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CLIMATE CHANGE AND THE U.S. AGRICULTURE AND FORESTRY SECTORS

HEARING

BEFORE THE

COMMITTEE ON AGRICULTURE
HOUSE OF REPRESENTATIVES

ONE HUNDRED SEVENTEENTH CONGRESS

FIRST SESSION

FEBRUARY 25, 2021

Serial No. 117–1

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CLIMATE CHANGE AND THE U.S. AGRICULTURE AND FORESTRY SECTORS

THURSDAY, FEBRUARY 25, 2021

HOUSE OF REPRESENTATIVES,
COMMITTEE ON AGRICULTURE,
Washington, D.C.

The Committee met, pursuant to call, at 12:58 p.m., via Webex, Hon. David Scott of Georgia [Chairman of the Committee] presiding.

Members present: Representatives David Scott of Georgia, Costa, McGovern, Adams, Spanberger, Hayes, Delgado, Rush, Pingree, Kuster, Bustos, Plaskett, O'Halleran, Carbajal, Lawson, Correa, Craig, Harder, Axne, Schrier, Panetta, Thompson, Austin Scott of Georgia, Crawford, DesJarlais, Hartzler, LaMalfa, Davis, Allen, Rouzer, Kelly, Bacon, Johnson, Baird, Hagedorn, Jacobs, Balderson, Cloud, Mann, Feenstra, Miller, Moore, Cammack, and Fischbach.

Staff present: Lyron Blum-Evitts, Melinda Cep, Ross Hettervig, Prescott Martin III, Félix Muñiz, Jr., Anne Simmons, Ashley Smith, Anna Brightwell, Josh Maxwell, Ricki Schroeder, Patricia Straughn, Erin Wilson, and Dana Sandman.

OPENING STATEMENT OF HON. DAVID SCOTT, A REPRESENTATIVE IN CONGRESS FROM GEORGIA

The CHAIRMAN. This hearing of the Committee of Agriculture entitled, *Climate Change and the U.S. Agriculture and Forestry Sectors,* will now come to order.

I want to welcome and thank everyone for joining this most important, timely, critical, and extraordinarily necessary hearing today. After brief opening remarks, Members will receive testimony from today's witnesses, and then the hearing will be opened up to questions and discussions. Members will be recognized in order of seniority, alternating between Majority and Minority Members, and in order of arrival for those Members who have joined us after the hearing was called to order. And as normal, when you are recognized, you will be asked to unmute your microphone, and will have 5 minutes to ask your questions or make a statement. If you are not speaking, I will greatly ask that you remain muted in order to minimize the background noise. In order to get in as many questions as possible, the timer will stay consistently visible on the screen to let you know how much time you have.

And now, ladies and gentlemen, let me open this up with a few remarks here myself.

This is perhaps the single-most important hearing that we must have right now, because agriculture is our single-most important industry overall, but especially right now, because nobody: our farmers, our agriculture industry, they more than any other entity or industry suffer more and benefit more from climate and weather. And I say it is our most important industry because of this: agriculture is the food we eat, it is the water we drink, it is the clothes we wear, and it is our shelter. Now, folks, we can do without a lot of things, but we definitely can't do without food, water, clothing, the necessities. And we have lost too many of our farms because we moved too late to get the right information in about these weather patterns. And so, I am so grateful for our Committee, our staff, that has assembled a wonderful panel. I am so thrilled to be able to approach this issue with my partner and my friend, Ranking Member Thompson. This is critical.

And so, I just want us to move with this with an open heart and an open mind, and to know that the American people are watching us. It is agriculture that is at the point of the spear when it comes to climate change. I am so grateful for the talented Members of this Committee who are willing to take this issue on and provide the critical leadership to deal with climate change, to secure our food supply, and save our farms.

[The prepared statement of Mr. David Scott follows:]

PREPARED STATEMENT OF HON. DAVID SCOTT, A REPRESENTATIVE IN CONGRESS FROM GEORGIA

Good morning, I'm excited to be here today for our first full Committee hearing and in particular to begin work on what is without a doubt the greatest challenge before us—climate change. I am also excited for the opportunity to work with my colleague, Ranking Member Thompson of Pennsylvania this Congress as he joins me in launching our first hearing together.

The U.S. agriculture sector is amongst the most productive in the world, contributing over $136 billion to the U.S. economy and directly supporting 2.6 million jobs. The U.S. forestry sector is another economic engine. In 2020, that sector manufactured $300 billion in forest products and employed approximately 940,000 people.

Over the past century, long-term changes in weather patterns have driven major changes across the globe, including the very landscapes that support these sectors. Since 1880, the average global temperature has increased about 2 °F. Increased temperatures have accompanied changes in rainfall patterns and more frequent climatic extremes. Most recently, the National Oceanic and Atmospheric Administration declared 2020 as the second warmest year on record, after 2016.

These changes introduce significant risks to agricultural production, forest resources, and the economy. These risks cannot be understated. According to USDA's Economic Research Service, climate change will likely affect risk-management tools, financial markets, and our global food security, among other important areas.

Our farmers, ranchers, and forest managers understand these risks, and they are the first to experience the pressures of a changing climate. But American producers are resilient, and many are already adopting production practices that not only improve productivity but store carbon and reduce emissions in the atmosphere. And yet there is tremendous opportunity to do more. It is incumbent on this Committee to ensure producers have the financial and technical resources they need to understand climate risks, consider mitigation strategies, and receive the support they need to make important investments in their operations.

I am excited to have such a broad range of witnesses to discuss these points today. I am also eager to hear how we may improve upon current policy and scale existing investments in proportion to the magnitude of the challenge. I look forward to your testimony.

With that I would like to invite our Ranking Member, Mr. Thompson, for any opening remarks.

The CHAIRMAN. With that, I want to turn it over to the Ranking Member, the distinguished Member from Pennsylvania, Ranking Member Thompson.

OPENING STATEMENT OF HON. GLENN THOMPSON, A REPRESENTATIVE IN CONGRESS FROM PENNSYLVANIA

Mr. THOMPSON. Well, good afternoon everybody, and I would like to thank the Chairman for holding today's hearing, and his flexibility due to the updated floor schedule.

The impact that climate has on agriculture production and on our natural resources is an issue of great importance to all of us on the House Agriculture Committee. Working with us—and Mr. Chairman, thank you for working with us on a mutually agreeable time that provides for greater Member participation. It is valued and very much appreciated. I would also like to thank the witnesses who juggled their schedules to join us today virtually, and I would like to thank all of our constituents, the stakeholders who are joining us today virtually as well.

Now, there is a saying I learned B.C. (Before Congress). If you are not at the table, you are probably on the menu. And for too long, the agriculture sector has been on the menu when it comes to climate. The hearing today begins to pull us up to the table.

I would like to start my remarks by making a very clear position: the climate is changing. The Earth's temperature is rising. I trust the science that globally industrial activity has contributed to the issue. Reducing global emissions is what we should be pursuing. It is the right thing to do, and it requires smart, prudent, and science-based policies.

But the apocalyptic narrative of the world coming to an end within a decade is not evidence-based and it is not supported by science. The self-proclaimed experts who continue to spout this impending doomsday scenario do nothing to advance the climate solutions discourse. They only cause unnecessary public angst and anxiety. It divides lawmakers when what we need is collaboration.

I imagine these climate grifters must rely on scare tactics to push their extreme agenda because it is burdensome, overreaching, and negatively affects jobs and rural economies. Not to mention the likelihood these policies could actually result in higher global emissions, and I will touch more on this in just a second.

Just over a decade ago, Congress rejected the Waxman-Markey Cap and Trade, and for those who weren't around or need reminding, this legislation was a national energy tax. Estimates vary, but experts predicted under Cap and Trade proposals, energy prices would increase as much as 125 percent. It was predicted that this policy would have resulted in American farm income dropping by $8 billion in 2012, $25 billion in 2024, and $50 billion in 2035. Decreases of 28, 60, and 94 percent respectively. This underscores the most troubling aspect of a national Cap and Trade system, or other similar approaches, which is that 40 to 60 million acres of land would likely have to shift from crop production and planted to trees.

It is worth noting, largely due to the innovations in free market principles, the United States has reduced emissions comparable to, if not better than, what Waxman-Markey called for in its out-year reduction targets.

Equally important, because it was not through government prescriptive measures, energy costs on average have come down. With Waxman-Markey energy prices would have skyrocketed. When Waxman-Markey failed, the Obama EPA chose a different route and pursued regulations to reduce emissions from the electricity sector known as the Clean Power Plan. Fortunately, that was stopped by the courts and eventually, the Trump EPA. Good thing, too. The government prescriptive Obama Clean Power Plan sought to reduce emissions 32 percent below 2005 levels by 2030. Without this regulation, and because of innovation and the market, power sector emissions hit that 32 percent reduction mark more than a decade sooner in 2019, without the utility bill increases that would have come with the Clean Power Plan.

Now, at a time when energy prices have decreased and manufacturing has strengthened, United States has led the world in reducing emissions. We have reduced carbon emissions more than the next 12 emission-reducing nations combined.

Now, let me quote the head of the International Energy Agency: " . . . in the last 10 years, the emissions reductions in the United States has been the largest in the history of energy . . . This is a huge decline of emissions." [1] Now, the question isn't whether or not climate change is real; the question is not whether or not to reduce emissions. The question is how to best approach it?

In just this past Congress, Democrats created a Select Committee on Climate Crisis, which used nearly an entire Congress only to deliver a staff report that simply rebranded Cap and Trade as the Green New Deal. Now, these climate approaches aimed to uproot the basic underpinnings of our farming, manufacturing, energy, and transportation systems, and requires changes for marginal or no benefits which would have significant implications for the profitability of U.S. agriculture and the U.S. economy, and specifically, the rural economy. More so, these recommendations can negatively impact food abundance and increase food prices all while displacing U.S. production with that of less efficient, more carbon intensive, foreign producers, leading to an increase in global emissions.

Now, these proposals were in direct conflict with the bipartisan principle that on-farm conservation should be locally led, voluntary, and incentive-based, principles that this Committee has put forward and really has been led by.

I truly believe our approach to overcoming this issue must favor pro-growth solutions over burdensome over-regulations. Innovation and research must be at the forefront of our solutions. As a matter of fact, there has been a lot of talk about legislation or Executive action to address climate change, but I believe many of these approaches are a solution in search of a problem. If we really want to reduce global emissions, hindering U.S. production is the opposite of what we should be doing. We should be taking steps to ensure the global competitiveness of our farmers.

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[1] **Editor's note:** this quotation originates from the facebook video feed, *Secretary Perry Holds a Joint Press Conference with IEA Executive Director Fatih Birol* and is available at *https://www.facebook.com/SecretaryPerry/videos/835183026823612/*.

Now, though often overlooked, the 2018 Farm Bill is arguably the greenest farm bill ever, and the farm bill is a climate bill. Some may scoff at that assertion, but let's talk about that bill. The farm bill's voluntary programs help farmers implement new practices that sequester carbon, reduce emissions, and adopt more energy-efficient farming practices. These programs have grown significantly in size and scope over the past 2 decades, providing $6 billion a year to farmers, ranchers, and forest owners to implement practices like soil health practices such as cover crops and no-till, that we can help draw down the carbon and store it in the soil.

The current conservation delivery system is the gold standard of the world. Our hard-working NRCS field staff, along with conservation districts, are delivering these benefits not only to farmers, but to the rural communities. I also believe that the private-sector can play a role in addressing the climate crisis. Companies like Land O'Lakes are leading in conservation finance, converting methane into energy, and working on private carbon markets.

Now, let me state for the record, I support private ecosystem markets as long as those markets are focused on benefits to the producers. I do not think the government should be intervening in those markets, and I hope we can concentrate more on proven solutions. I hope all of us can agree that a much greater expansion and more rapid deployment of high-quality broadband connectivity is essential in this regard. It is essential for our rural communities, and it is essential to data-driven climate solutions. Broadband isn't just needed in our homes; it is especially needed on our farms as well. Agriculture is science. It is technology. It is innovation. The demands of a 21st century farm economy and economically viable climate solutions depends on reliable connectivity.

Thanks to innovations in agriculture technologies, farmers are not the only conserving resources, they are doing so while producing more food, more fiber, and more feed. Productivity relative to resource use for agriculture is up a whopping 280 percent in the United States since the 1940s, while total farm inputs are mostly unchanged during this time period.

Now, I believe this is something that isn't talked about enough. U.S. producers are the shining star when it comes to resiliency and sustainability. U.S. producers are the answer to reducing global emissions, not the problem as so many activists would have you believe. However, without high-speed internet connectivity at both the farmhouse and the field, many of these new technologies that have helped create these efficiencies will never be realized to their fullest potential.

Continuing to build on the conservation success of American farmers will reap additional emission benefits and increase U.S. farming's competitive advantage globally. The men and women who farm our lands are the original stewards of that land. The left will give them no credit for all of the advancements they have made in protecting our natural resources. The wrong approach with burdensome regulations or policies that dramatically increase costs will harm rural economics, while displacing U.S. production with that of less efficient, foreign producers leading to an increase in global greenhouse gas emissions.

The question we have to ask ourselves is: who do we want supplying the world agriculture products? Is it the most efficient, low-emission producer that creates jobs in America, or the highest emitting sources that create jobs overseas? If you care about the American farmer, as well as addressing climate, the answer should be obvious.

Again, Mr. Chairman, thank you so much for holding this hearing today. I know you believe, as I do, that our farmers and ranchers can be part of the solution to the climate issues.

Thank you again to our witnesses, and I yield back.

The CHAIRMAN. Well, thank you, Ranking Member Thompson.

The chair would request that other Members submit their opening statements for the record so that we can move on and begin to hear from our wonderful panel.

[The prepared statements of Mr. Costa and Ms. Pingree follow:]

PREPARED STATEMENT OF HON. JIM COSTA, A REPRESENTATIVE IN CONGRESS FROM CALIFORNIA

As Chairman of the Livestock and Foreign Agriculture Subcommittee, I am committed to ensuring that farmers and ranchers have access to processing and connections to markets for their products. In the 116th Congress, I worked to establish the new RAMP–UP grant program to assist existing facilities in making improvements to come under Federal inspection. I also supported the recent House-passed provisions to reduce overtime costs for small and very small Federal establishments. And, I look forward to continuing to work with my colleagues to address this important issue, but these improvements cannot come at the expense of food safety. Given some discussion today on expanding sales of uninspected meat, I would like to submit two letters,* from food safety groups and from groups representing farmers and ranchers, outlining concerns with legislative efforts that would undermine current Federal food safety standards for meat and poultry.

PREPARED STATEMENT OF HON. CHELLIE PINGREE, A REPRESENTATIVE IN CONGRESS FROM MAINE

I want to thank Chairman Scott and Ranking Member Thompson for holding a hearing on the important topic of climate change and the agriculture and forestry sectors. We know that climate change is impacting agriculture. In Maine, average temperatures have increased about 3 °F since the beginning of the 20th century and the Northeast is warming faster than other regions of the country. All 16 counties in Maine were under a U.S. Department of Agriculture (USDA) Secretarial Disaster designation at some point in 2020 due to severe drought, which may have been exacerbated by climate change. This is a serious threat to our agriculture industry, which has an annual economic impact of $3.8 billion and supports more than 25,000 jobs.

We also know that agriculture affects our climate. There is no doubt that the primary driver of the climate change we are experiencing is anthropogenic emissions of greenhouse gases like carbon dioxide, nitrous oxide, and methane, and there is no doubt that the agricultural sector plays a measurable role in emitting these greenhouse gases. While U.S. agriculture has made efficiency gains that have reduced emissions per unit over the last several decades, agriculture contributed 9.6 percent of total U.S. greenhouse gas emissions in 2019-equivalent to 628.6 million metric tons of CO_2.

We need to do more to support farmers in adapting to, and mitigating their effect on, our changing climate. While the climate crisis poses a serious challenge for farmers, we can increase resilience, reduce greenhouse gas emissions, and sequester more carbon in the soil by providing these farmers with additional incentives and tools to shift to climate-smart practices, while ensuring they have the technical assistance necessary to successfully adopt them. I appreciate that there has been broad agreement on both sides of the aisle that science-based, farmer-driven, and voluntary policies offer the best path forward. These are the principles I used to de-

* **Editor's note:** the letters referred to are located on p. 329.

velop a bill I plan to reintroduce in the coming weeks, the Agriculture Resilience Act.

One of the themes of the hearing was the need for education: for farmers and for the Natural Resource Conservation Service (NRCS) professionals and extension agents that work with them. USDA's Northeast Regional Climate Hub is already helping Maine NRCS focus more on climate-smart practices through regionally specific, "farm smart" training. The Agriculture Resilience Act would build on these efforts by permanently authorizing and better resourcing the Climate Hubs. It would create a new technical assistance initiative devoting one percent of farm bill conservation funding to helping producers adopt practices that increase climate resilience and mitigate their emissions. Both of these policies were included in the policy recommendations of the Food and Agriculture Climate Alliance, an industry coalition that includes the American Farm Bureau Federation represented by Mr. Duvall. The bill would also support additional research, on-farm energy initiatives, opportunities to enhance farm viability and improve soil health, pasture-based livestock systems, and food waste reduction efforts, with the ultimate goal of making the U.S. agriculture sector achieve net zero emissions by 2040.

There has also been discussion among my colleagues about the diversity of American agriculture and how climate solutions cannot be one-size-fits-all. We know this in Maine—we are a state characterized by small- and medium-sized diversified farms. The University of Maine has taken a comprehensive look at the mitigation potential of Maine's agriculture and forestry sectors and identified potential strategies that would be most effective for the state, including applying biochar, reducing tillage, and using more effective manure management. If Maine farmers collectively adopt these practices, the UMaine researchers estimate that the sector could mitigate up to 786,000 tons of CO_2 equivalent per year in greenhouse gas emissions, or about double the sector's current emissions. This would come at the total cost of $26.3 million per year, or about 0.017 percent of the USDA's overall annual budget. I have included this report for the record with my statement.*

I look forward to working with my colleagues on the Agriculture Committee, our partners at USDA, and my fellow producers in Maine to make meaningful strides to mitigate climate change by helping farmers to be part of the solution.

[The CHAIRMAN.] Once again, I would like to welcome all of our witnesses, and thank you for being here today for this historic and very, very critical hearing.

First, we welcome Mr. Jim Cantore. Mr. Cantore is a senior meteorologist for The Weather Channel who has worked as a renowned forecaster for more than 30 years, forecasting the nation's weather day-to-day and reporting live from the field on severe weather events. He has also helped produce documentaries on meteorology, broadcasting in historic storms. Mr. Cantore holds an American Meteorological Society Television Seal of Approval and received an Emmy award in 2019 for his work on The Weather Channel's immersive mix reality storytelling.

Our next witness is Ms. Pamela Knox. Ms. Knox is the Director of the University of Georgia's Weather Network, as well as an agricultural climate—excuse me, I am convinced I can get that last word right—Agricultural Climatologist for the University of Georgia in the Department of Crop and Soil Science. She provides outreach and education on climate and its effect on crops and livestock in the southern United States. Ms. Knox also serves on the Technical Advisory Boards of the Southeast Regional Climate Center, or at NOAA and the Southeast Regions Climate Hub at USDA.

Our third witness today, who I am also so pleased to be able to invite and join us, is my good friend President Zippy Duvall. Zippy is President of the American Farm Bureau Federation. Mr. Duvall has served as President of Farm Bureau since 2016, and he is a

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* **Editor's note:** the report referred to is located on p. 333, and is available at: *https://crsf.umaine.edu/wp-content/uploads/sites/214/2020/09/UMaine-NCS-Interim-Report_1Sept20.pdf*.

third-generation farmer from Georgia. He owns a beef cow herd, raises broiler chickens, and grows hay. Prior to serving as the AFBF President, he was President of the Georgia Farm Bureau and served on Farm Bureau's Board of Directors. A gentleman I have had the privilege of working with for a number of years, even during my years in the Georgia State Senate.

Next, we will hear from Mr. Gabe Brown. Mr. Brown operates Brown's Ranch with his wife, Shelly, and son, Paul. Brown's Ranch is a diversified 5,000 acre farm and ranch near Bismarck, North Dakota, with a variety of cash crops, multi-species cover crops, and livestock that utilize grazing and no-till cropping systems. He is also a partner in the agricultural consulting company named Understanding Ag.

Our fifth and final witness today, we are pleased to welcome Mr. Michael Shellenberger. Mr. Shellenberger is the founder and President of Environmental Progress. He is an environmental journalist and the author of several books, including the recently published book, *Apocalypse Never*. Mr. Shellenberger was the co-founder and President of the Breakthrough Institute.

What a panel, and we are anxious to hear from you.

We will now proceed with our hearing and the testimony. Each will have 5 minutes. The time should be visible to you on your screen, and will count down to zero, at which point, your time will have expired.

Mr. Cantore, please begin now.

STATEMENT OF JIM CANTORE, SENIOR METEOROLOGIST, THE WEATHER CHANNEL, ATLANTA, GA

Mr. CANTORE. Chairman Scott, Ranking Member Thompson, and distinguished Members of the Committee, good afternoon. I am Jim Cantore and I am a meteorologist for The Weather Channel television network. I have been a weather forecaster for almost 35 years. I am here today on behalf of The Weather Channel to testify about the increasing impacts of climate change on the agricultural and rural communities of the United States, as well as the impact on the entire U.S. population.

Over the past several decades, scientists from all over the world have been studying changes in the Earth's atmosphere and weather patterns. Recent weather observations are confirming what computer models and scientific theory conclude.

First, climate is warming due to an increase in greenhouse gases, especially carbon dioxide in the atmosphere. Second, the changes are overwhelmingly caused by humans. Third, there is a definite link between increasingly extreme weather and the warming planet.

Carbon dioxide in our atmosphere has been steadily increasing, and in response, so have the temperatures. Since 1880, the average global temperature has been increasing at a rate of .14 °F per decade. However, since 1981, the increase is more than twice that rate.

These numbers may seem small, but much like our body temperature, the Earth's temperature is remarkably stable. Simply put, the planet has a fever, and it is getting worse. The statistics are alarming. The last 7 years have been the warmest on record.

Ice sheets and glaciers worldwide are melting and draining water into the ocean, raising the sea level. In New York City, the ocean sits roughly 1′ higher than when the Empire State Building was built in 1930. By the end of the century, the global average sea level will likely be over 1′ higher than it is today, but future pathways with high greenhouse gas emissions could raise those seas by over 3′ by 2100.

Flooding will be a daily occurrence with each high tide along the Eastern seaboard and Gulf Coast. We already see this in our country on sunny days in places like Miami, Florida and Charleston, South Carolina. Extreme temperatures and prolonged drought are increasing the risk of water shortages and wildfires over the western U.S. Extreme rainfall events are on the rise, increasing the chances for more serious flash flooding, and the strongest hurricanes are getting stronger, and potentially slowing down.

The costs are staggering. Billion-dollar disasters are on the rise, and we have a short video to take a look at one from last year that hit farmers particularly hard.

[Video shown.][2]

Mr. CANTORE. Our Weather Channel viewers are the very people who climate change is affecting the most. They are our farmers, our first responders, our airline pilots, our truckers, our working-class families. While the phrase *climate change* has long been politicized in this country, these Americans are now facing this today in real time what people thought might be a 22nd century problem. They are seeing their crops being washed away in 500 year floods, their livestock killed in monstrous wildfires, and landfalling hurricanes.

In conclusion, I used to question the roots of climate change theories. I, like many, doubted that climate change had its origins in human causes. But after covering severe weather for 3 decades, including more than 100 tropical systems, dozens of tornado outbreaks, and more floods than I can remember, I am here to tell you that climate change is real, and we are absolutely playing a role in this. Not every disaster is driven by climate change, but more and more, we are seeing things we have never seen before, and the link to climate change in many of these events is present.

Our country is suffering. Just ask the folks in Texas. While these changes are alarming, there is still time. With the government's help, our farmers will be able to adapt to changing temperatures and can even mitigate future warming. But we must act now to make the tough choices that will not only improve the lives of future generations, but those of all generations living today and tomorrow. And for those farmers whose life work is to feed this country and sustain one of the most time-honored industries of our great nation, we have a responsibility to help.

[The prepared statement of Mr. Cantore follows:]

Prepared Statement of Jim Cantore, Senior Meteorologist, The Weather Channel, Atlanta, GA

Chairman Scott, Ranking Member Thompson, and distinguished Members of the Committee. Good morning. I am Jim Cantore, and I am a meteorologist for The

[2] **Editor's note:** the video is retained in Committee file.

Weather Channel television network. I have been a weather forecaster for more nearly 35 years.

As farmers and the entire agriculture industry are aware, weather is the inescapable and ever-changing environment in which we live. As our climate changes, weather is becoming more volatile. As we witnessed last week across Texas and several other states, no person, business, community or entire state can escape its extremes. Dangerous cold, snow and ice revealed infrastructure failures, tested the human will for survival and sadly cost dozens of Americans their lives.

I am here today on behalf of The Weather Channel to testify about the increasing impacts of climate change on the agricultural and rural communities of the United States, as well as the impact on the entire U.S. population. Our job is to prepare Americans for these difficult times and help them navigate our changing Earth. Our responsibility as scientists is to follow the data. We are on the side of the American people, and it is up to us to explain the science in plain terms.

Over the past several decades, scientists from all over the world have been studying changes in [E]arth's atmosphere and weather patterns. Recent observations are confirming what computer models and scientific theory conclude:

- Earth's climate is changing faster than at any point in the history of modern civilization, primarily as a result of human activities that emit greenhouse gases into the atmosphere.
- The impacts are already being felt in the United States and are projected to intensify in the future—Americans will be dealing with even more extreme and costly weather in every season.
- The severity of these impacts will depend largely on actions taken to reduce greenhouse gas emissions and to adapt to the changes that will occur.

Carbon dioxide in our atmosphere has been steadily increasing and in response, so have the temperatures. Since 1880 the average global temperature has been increasing at a rate of 0.14 °F per decade. However, since 1981 the increase is more than twice that rate (0.32 °F). These numbers may seem small, but much like our body temperature, earth's temperature is remarkably stable . . . simply put, the planet has a fever and it is getting worse. The statistics are alarming:

- The last 7 years have been the warmest on record.
- Ice sheets and glaciers worldwide are melting and draining water into the ocean, raising the sea level. In New York City, the ocean is roughly 1′ higher than when the Empire State Building was built in 1930.
- By the end of this century, the global mean sea level will likely be over a foot higher than today, but if we continue to emit high levels of greenhouse gases, it could rise over 3′ by 2100. Flooding will be a frequent occurrence with each high tide along the eastern seaboard and Gulf Coast.
- Extreme temperatures and prolonged drought are increasing the risk of water shortages and wildfires over the western U.S.
- Extreme rainfall events are on the rise, increasing the chances for more serious flash flooding.
- And the strongest hurricanes are getting stronger.

I have seen these changes firsthand. Over my nearly 35 year career as a meteorologist at The Weather Channel, I have observed storms growing stronger, producing more precipitation and bringing destruction to areas that have never seen similar damage.

On October 8, 2016, I was covering Hurricane Matthew in Lumberton, North Carolina. My team and I came upon a motel where people had evacuated from the North Carolina and South Carolina coasts, as their local officials had instructed them. They came to Lumberton, thinking that this far inland—about 80 miles—they would be safe from the storm surge they were facing on the coastline. But what they encountered in Lumberton was excessive inland rainfall, over 18″ in the region. We had to help evacuate these people in boats to higher ground—due to this historic flood event. Again, Hurricane Matthew's inland devastation was evidence that many of these tropical systems are stronger, wetter and slower moving than we have seen in the past. This storm also left partially harvested cotton, soybean, and sweet potato farms across North Carolina submerged. Farmers who lost pigs and chickens barely recovered before Hurricane Florence hit in 2018. Devastating rainfall is a trend we are seeing with a likely climate link.

Also, in 2018, Hurricane Michael rapidly intensified to a category 5 upon landfall along the Gulf Coast. The hurricane-force winds lasted so long, and moved so far inland, the storm devastated the pecan crop in Georgia. That was the third year in a ***row*** the Georgia pecan crop had taken a hit from hurricanes—and Michael was the coup de grace. Even on the west side—the weak side—of the storm, across the Florida panhandle, there were massive timber losses—trees, snapped like twigs—where you could smell the pine in the air for miles. The crop losses in Georgia and Florida totaled more than $3 billion. Relief to farmers was slow, and so is the regeneration of this region's crops

Our Weather Channel viewers are the very people whom climate change is affecting the most. They are our farmers, our first responders, our airline pilots, our truckers, our working-class families. While the phrase "climate change" has long been politicized in this country, these Americans are now facing today, in real time, what people thought might be a 22nd century problem. They are seeing their crops being washed away in 500 year floods; their livestock killed in monstrous wildfires; their children being diagnosed with increasing respiratory illnesses due to a more hostile atmosphere.

In 2020 there were 22 weather/climate disaster events with losses exceeding $1 billion each to affect the United States. These events have been increasing over the last 40 years. The 1980–2020 annual average is seven events; the annual average for the most recent 5 years (2016–2020) is 16.

One of the most memorable of these events occurred last August when we saw one of the costliest severe thunderstorms in U.S. history damage over 700 miles of the upper Midwest—much of it farmland.

My colleague Dave Malkoff was on the ground in Benton County, Iowa as farmer Ben Olson was picking up the pieces of his destroyed corn crop. Early estimates from the Iowa Corn Growers Association put the loss at around 10 million acres, which is well over a billion bushels of corn. With a bushel selling for about $3 and 40¢ each, that's more than a $3 billion loss. And Mr. Olson and his neighbors are left with farms of rotting corn.

And whether or not your districts are directly affected by a disaster, you and your constituents are helping foot the bill. Billion-dollar natural disasters are on the rise in many parts of the country, climate change is playing a role. As policymakers, you are well aware of not only the cost of American lives and livelihoods, but also the detrimental impact these billion-dollar disasters have on our Federal and state budgets.

In Conclusion: I used to question the roots of climate change theories. I, like many, doubted that climate change has its origins in human causes. But after covering severe weather for 3 decades, including more than 100 tropical systems, dozens of tornado outbreaks, and more floods than I can remember, I am here to tell you that climate change is real and we are absolutely playing a role in this. Not every disaster is driven by climate change. But more and more we are seeing things we have never seen before, and a link to climate change in many of these events. And our country is suffering; just ask the folks in Texas. While these changes are alarming, there is still time. With the government's help, our farmers will be able to adapt to changing temperatures and can even mitigate future warming. But we must act now to make the tough choices that will not only improve the lives of future generations but those of all generations living today and tomorrow. And for those farmers whose life's work it is to feed this country and sustain one of the most time-honored industries of our great nation, we have a responsibility to help.

The CHAIRMAN. Thank you. Thank you so very much for that profound and extraordinarily excellent presentation. You grabbed it where it needed to be grabbed, Mr. Cantore. I hope I got that right. I will keep working on it as we move.

Next, we will now hear from Professor Knox. Please begin now.

STATEMENT OF PAMELA N. KNOX, DIRECTOR, UNIVERSITY OF GEORGIA WEATHER NETWORK; AGRICULTURAL CLIMATOLOGIST, UGA COOPERATIVE EXTENSION, ATHENS, GA

Ms. KNOX. Good afternoon, everyone. My name is Pam Knox, and it is an honor to speak to you all today. I thank Chairman Scott and Ranking Member Thompson, and all the Members of the Committee who are allowing me the chance to share my expertise.

I am an Agricultural Climatologist, and an extension specialist in the College of Agricultural and Environmental Sciences at the

University of Georgia. I am also the Director of the UGA Weather Network, which is a mesonet of 87 stations across the state that provides agricultural information to farmers and foresters in Georgia. You can see a picture of one of my stations behind me.

Before I took my current job, I worked as a USDA funded research scientist studying climate impacts on the Southeast, and livestock impacts of climate change across the U.S. I am also a former state climatologist for Georgia and Wisconsin.

What I want to talk about today is the importance of climate to agriculture and forestry. We know agriculture and forestry are highly affected by swings in weather and climate. Year-to-year changes in temperature and precipitation can be hard for farmers to deal with and making a bad choice of crops or management practices can be costly. In addition to the natural variations of the climate, the U.S. is also getting warmer, as Jim mentioned, due to increases in carbon dioxide, methane, and other greenhouse gases. Average temperatures in the U.S. have gone up by almost 2 °F in the last 60 years. Higher temperatures mean longer growing seasons, more heat stress on livestock and outdoor workers, more time for diseases and pests to threaten crops, and a more unpredictable water cycle. It also means more extreme events such as heatwaves, droughts, and floods that put farmers and foresters at risk by destroying crops and forests, and flooding fields and pastures.

Agriculture and forestry are being affected by climate, but they are also contributing to warming temperatures by adding greenhouse gases to the atmosphere and changing the surface of the land. Livestock production releases methane into the atmosphere. Using too much fertilizer adds nitrous oxide into the air, and also pollutes streams and lakes. Cutting down on forests and draining wetlands for crops in urban areas releases carbon dioxide and methane. On top of this, 30 to 40 percent of all the food produced is never used. This means that the fuel, water, and fertilizer that is used to produce it is wasted, and more greenhouse gases are produced as that food waste is dumped into landfills, and tractors and water pumps are run for no good reason.

Fortunately, agriculture and forestry can be powerful helpers in fighting climate change, too. Planting cover crops can prevent greenhouse gas emissions tied to fertilizers in irrigation by keeping water, carbon, and nutrients in the ground in the first place. Growing more trees and improving cropland productivity can pull carbon dioxide from the air. Many of these choices also help the farmers' bottom line by reducing the cost of fuel, agricultural chemicals, and the labor needed to apply them. A lot of these solutions don't need to be costly, either. They can be a real benefit to lower income and Black farmers with limited resources when you use these simpler solutions.

Climate change is already here, and farmers, ranchers, and foresters are already learning to adapt to the new conditions. Some farmers are taking advantage of the longer growing seasons by double-cropping, or growing new crops like satsumas and olives in Georgia, for example. Livestock producers are using shade structures or cooling barns to protect their animals from heat stress. Foresters are testing out new varieties of pine and other commercial tree varieties that can survive and thrive in the future. Many producers are also using smart irrigation techniques, and other climate-smart management practices to use water efficiently, while protecting and improving the soils.

But not all farmers know how to use these methods or can afford to follow them. So, information and training on best practices need to be available for them to make the best use of their land. Agencies like USDA, NOAA, NASA, and others have a long history of providing science-based, region-specific information and technologies to farmers, ranchers, and foresters across the country to help them monitor local climate and prepare for and respond to extreme weather and changes in climate. Other programs provide financial support for scientists studying the problems of extreme weather and climate change.

Knowledge, technology, and funding will all be needed to make a difference in fighting climate change.

In closing, while farms, ranches, and forests are all contributing to the increasing greenhouse gases in the atmosphere, and the rising temperatures that they produce, they also have the potential to help the U.S. reduce global warming by reducing emissions as well as absorbing gases from the environment. USDA and other agencies should be encouraged to work with farmers and scientists to find the best, most cost-effective ways to do this.

Thank you all for your attention, and I look forward to the discussion on this and hearing your comments.

[The prepared statement of Ms. Knox follows:]

PREPARED STATEMENT OF PAMELA N. KNOX, DIRECTOR, UNIVERSITY OF GEORGIA WEATHER NETWORK; AGRICULTURAL CLIMATOLOGIST, UGA COOPERATIVE EXTENSION, ATHENS, GA

Key Points

- Climate change is impacting agriculture and forestry by raising temperatures, which: affect the length of the growing season, degree days and chill hours; cause heat stress affecting livestock and outdoor workers; enhance evapotranspiration; and increase the likelihood of extreme events like floods and droughts, all of which have negative consequences on farm production.
- Agricultural and forest-based practices are affecting climate change by adding greenhouse gases to the atmosphere and altering the soil and land used for growing crops and livestock, adding to the rise in temperatures through release of methane and other greenhouse gases.
- Producers can reduce their emissions of greenhouse gases by using climate-smart agricultural practices such as using more cover crops and precision irrigation and by reducing food waste and overuse of fertilizers and other agricultural chemicals, which will help slow warming.
- Producers are already adapting to changes in climate by adding cover crops, changing crop and tree varieties, and adding new crops to their farms as well as adding cooling structures and irrigation; these actions can make their farms more resilient to changing climate and extreme weather.
- Farmers can benefit economically from conserving water, fuel, and labor now while they are helping to reduce climate change by managing their land and animals carefully.
- As farming and forestry become more technologically advanced, new management tools will require access to more and better local data to help producers make smart choices about how they manage their farms and forests for health, safety, and profit.

Introduction

I would like to thank Chairman Scott and the other Members of the House Agriculture Committee for the opportunity to testify at this hearing to explore the relationship between agriculture and forestry and climate change. It is an honor and privilege to be with you today. My name is Pamela Knox, and I am a Public Service Associate with Cooperative Extension at the University of Georgia. I am currently the Director of the University of Georgia Weather Network and an Extension Specialist in agricultural climatology. I have worked on projects specifically related to agriculture, forestry, and climate change for the last decade. Prior to my current position, I was a research scientist funded by the U.S. Department of Agriculture (USDA) to study the impacts of climate variability and change on crop production in the Southeast and on livestock production across the United States. I also worked with the USDA Southeast Regional Climate Hub to identify how climate variability and change affect management decisions and day-to-day activities on working lands across the region. I am currently a co-Principal Investigator on two projects related to identifying the rapid onset and expansion of drought using soil moisture monitoring; one is funded by USDA and the other by NOAA. I am a previous President of the American Association of State Climatologists and have served as State Climatologist in Wisconsin and as Assistant State Climatologist in Georgia. I am also a Certified Consulting Meteorologist and have served as the Chair of the American Meteorological Society's Board on Certified Consulting Meteorologists as well as their Board of Professional Continuing Education and on their Standing Committee on Applied Climatology. My testimony today is my opinion, based upon my background and experience in studying agriculture and climate.

Overview

According to the Bible and other ancient texts, agriculture is one of the earliest signs of civilization. Agriculture and forestry provide us with the food we eat, fiber we use to make clothing, and building materials and fuel that we use to provide shelter and keep us warm. In the United States in 2019, agriculture contributed over $1.1 trillion to the GDP, a 5.2 percent share of the economy.[1] In addition, agriculture provided 10.9 percent of total U.S. employment.

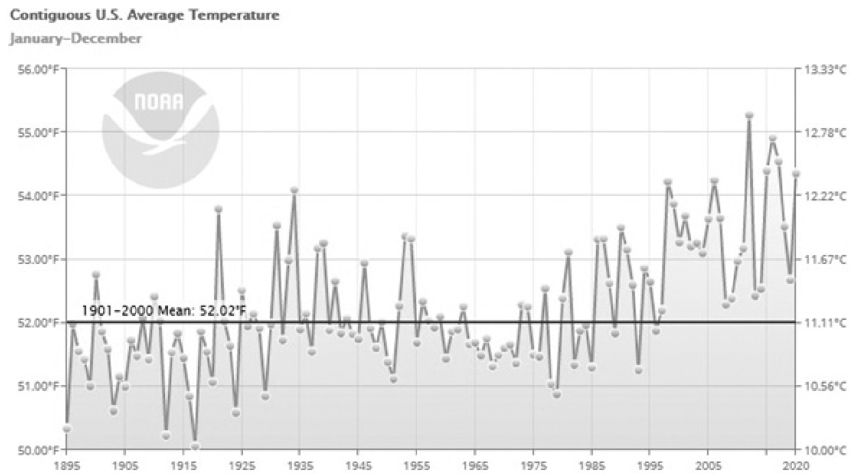
Of all the sectors of the U.S. and the world economy, agriculture is arguably the one most affected by swings in weather and climate. Natural cycles of climate variability in the past have led to changes in agricultural activity as temperatures have risen and fallen and rain has come and gone. In periods when the local climate is favorable, those communities have expanded. Where drought, frosts, and extreme heat have occurred, agriculture has contracted and sometimes failed, leading to famine and migration as the citizens moved elsewhere or died out. Agriculture has also affected the communities around it by changing the nature of the land cover from forests to bare fields, affecting the local energy balance, temperature, and water cycle. In areas where agriculture expanded beyond the capacity of the local climate to sustain it, the land lost its ability to provide for those who lived there.

Agriculture has also benefited from the rise of the Industrial Revolution, which provided agricultural producers with the mechanical ability to farm larger acreage, reduce the impacts of pests and diseases, and increase yield through the use of fertilizers and other agricultural chemicals. This has allowed us to feed a growing population. These benefits did not come without costs, however, since use of mechanical equipment requires fuel and factory production. Agricultural chemicals, when used improperly, have hurt natural ecosystems and contributed to the growth of toxic algae and diseases in water downstream. The cost of using this modern equipment has also put economic strain on lower-income and minority farmers who often have difficulty getting access to the most recent technology and information needed to maximize their potential yields. Clearing of land has reduced forest cover in some areas and released carbon dioxide and other greenhouse gases into the atmosphere, resulting in changes to the [E]arth's energy balance.

Since 1895, annual average temperature in the United States has changed quite a bit from year to year (*Figure 1*), making planning for farmers difficult since what happened last year is probably not what they will experience this year. The annual average temperature has also changed on longer time scales due the influence of both natural cycles and human contributions to the global energy balance. Natural cycles include both shorter-term cycles such as the El Niño Southern Oscillation (ENSO) related to ocean temperatures in the eastern Pacific Ocean, and longer-term cycles in the global atmosphere and ocean. Those natural cycles occur on top of an upward trend that has been linked in numerous studies to increasing greenhouse gases in the atmosphere, which act as a blanket that holds the [E]arth's heat near

[1] *https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/.*

Figure 1. Contiguous United States Annual Average Temperature from 1895–2020 [2]



the surface instead of allowing it to escape to space. In the 57 year average lifetime of a farmer in the United States,[3] the average temperature has risen by approximately 2 °F. Overnight low temperatures have increased more than daytime high temperatures,[4] which may be due to increases in humidity over time or to differences between the structures of daytime and nighttime atmospheric layers near the ground.[5] This is important for agriculture because warmer nights hurt early-morning workers and prevent steers from gaining weight due to 24-hour warmth.[6]

The annual average precipitation of the contiguous United States has also increased during that farmer's lifetime (*Figure 2*). As temperatures rise, the atmosphere can hold more water vapor than before. The result: as the water cycle has strengthened, both humidity and temperature have increased. That has not eliminated the year-to-year swings that occur naturally due to ENSO and other internal cycles in the global climate system, so farmers still need to be able to respond to the short-term changes in rainfall, including droughts and floods, as well as plan for long-term changes that the warmer climate will bring. Precipitation is also becoming more variable, with more rain on the wettest days and longer dry spells between rainstorms.[7]

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[2] NOAA National Centers for Environmental information, *Climate at a Glance: National Time Series,* published February 2021, retrieved on February 10, 2021 from *https://www.ncdc.noaa.gov/cag/*.

[3] *2017 Census of Agriculture,* USDA National Agricultural Statistics Service.

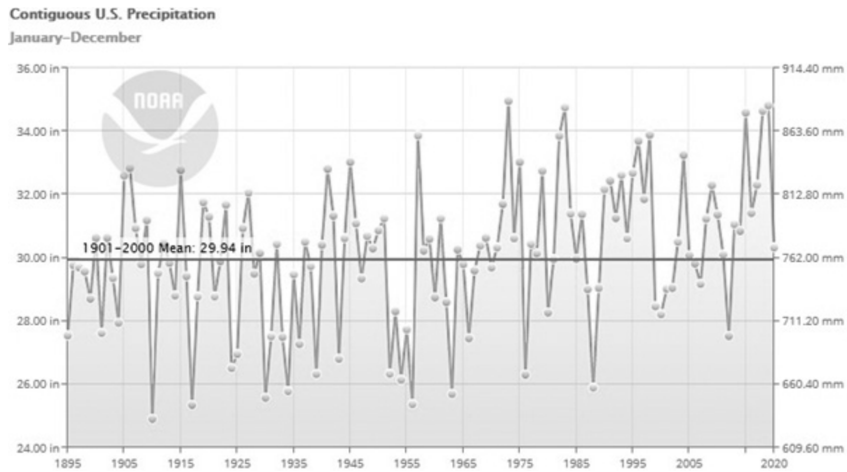
[4] *https://science2017.globalchange.gov/chapter/6/*.

[5] *https://phys.org/news/2016-03-nights-warmer-faster-days.html*.

[6] *https://www.climate.gov/news-features/blogs/beyond-data/climate-change-rule-thumb-cold-things-warming-faster-warm-things*.

[7] *https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation*.

Figure 2. Contiguous United States Annual Average Precipitation[8]



Changes in temperature and precipitation are also affecting the frequency and intensity of extreme events, including heat waves, floods, droughts, and severe weather like hurricanes and derechos, such as the one that devastated parts of Iowa last August. Floods have become more frequent and damaging due to a more active water cycle and increases in vulnerable infrastructure. This infrastructure was built to design standards for the past climate, which may not reflect what we are seeing now or will occur in the future. Droughts have become more frequent and often start and grow more quickly than in the past due to warmer temperatures and longer dry spells between rain events. We call these quickly developing droughts "flash droughts," an area I study in my work. These droughts have a special impact on agriculture because crops and forage need regular amounts of water to grow and thrive, and if they do not get it, they can lose health and potential yields very quickly.

Hurricanes and tropical storms so far do not seem to be increasing in number overall (although there is a lot of year-to-year variability based on natural cycles). However, recent research has shown that hurricanes are moving more slowly over land than they have in the past and are intensifying more rapidly just before they make landfall, which increases the damage they can do to coastal areas and crops that lie along the path of the storms after they come onshore.[9] Extreme wind events such as tornadoes and derechos also do not appear to be increasing in number,[10] although they may cause more damage than in previous years due to increases in shade trees and vulnerable infrastructure.[11]

A warmer climate multiplies the risk from these events in the future by expanding the peak season for extreme events and expanding the area where they can occur toward the north. Winter storms might be expected to be less likely due to warmer temperatures, but the increase in the strength of the water cycle could make them produce more snow or ice, causing problems for farmers worried about the transportation of milk from farms to dairies and cutting off electricity needed for milking or power. Even if the frequency of the storms does not change, the increased use of sophisticated technology could make them more vulnerable to extreme weather in the future. Recent events such as the cold outbreak in the central United States last week have shown us that we are not even able to respond adequately to weather and climate extremes similar to ones we know have happened in the past; responding to the more variable and more extreme weather that we expect to see in the future as shown by climate models will be even more costly, disruptive, and challenging.

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[8] NOAA National Centers for Environmental information, *Climate at a Glance: National Time Series,* published February 2021, retrieved on February 10, 2021 from *https://www.ncdc.noaa.gov/cag/*.

[9] *https://www.gfdl.noaa.gov/global-warming-and-hurricanes/*.

[10] *https://blogs.ei.columbia.edu/2016/12/01/increasing-tornado-outbreaks-is-climate-change-responsible/*.

[11] *https://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm*.

How Climate Change is Impacting Agriculture and Forestry

Changes that we are seeing in our climate now are affecting agriculture and forestry in many ways. Rising temperatures are leading to warmer days and even warmer nights, which reduce heating costs in winter but increase cooling costs in summer. It also increases heat stress on both livestock and outdoor workers who are exposed to those high temperatures. Warmer overnight temperatures also harm some crops such as corn. The higher temperatures also lead to longer growing seasons, which Knox and Griffin (2014) estimated at roughly a 1 week increase in the growing season for every 1 °F rise in temperature.[12] The longer growing seasons provide opportunities for growing new crops and double-cropping but also lead to longer seasons for pests and diseases that affect the crops, forests, and animals. Warmer temperatures are also shifting climate zones to the north, changing the mix of crops and tree species that can be grown in any area or what times of year they can be grown successfully. The exact amount of temperature change that will occur cannot be predicted because there are so many unknowns to consider, including what choices humans make about greenhouse gas emissions in the future, but a range of increases from roughly 4° to 9 °F is projected to occur by 2100 by most climate models, depending on the scenario chosen.[13] These changes will not be uniform across the globe; some areas may see greater temperature rises than others, but all areas will be affected.

More variations in the water cycle provide both positive and negative impacts on agriculture. Northern parts of the United States are benefiting from more rainfall and a longer growing season now *versus* early in the 20th century. Crops such as corn are expanding into areas that previously could grow only wheat, for example. But the increase in the heaviest rain is leading to more erosion and flooding, both of which hurt farmers who are concerned with soil health and transportation of products to market. In dry years, longer intervals between rain events puts extra stress on crops and forests, especially where the water-holding capacity of soils is low. In the western United States, warmer temperatures have caused more precipitation to fall as rain and less as snow, which significantly affects the availability of irrigation water for crops as well as city water supplies because there is less storage of water in mountain snowpacks. Droughts are also expected to become more frequent and longer in a warmer world because the higher temperatures increase evaporation from soil, streams, and lakes, and increase evapotranspiration from plants. Even if the total amount of precipitation does not change, more evapotranspiration will lead to higher water demands by crops and more evaporation from lakes and reservoirs will make water shortages more frequent. Increases in heat spells are also expected to lead to more rapid onset of droughts and more frequent flash droughts that primarily affect crops and increase the occurrence of forest fires in the western United States.

The increase in carbon dioxide (CO_2) in the atmosphere is expected to have some fertilization effect on plants, since they take in CO_2 as they grow. However, that effect is limited by the plant's ability to use the CO_2 and the availability of other required elements, including water and nutrients. Scientists have also noted that some weeds grow much more quickly in enhanced CO_2 environments than crops do. That could lead to more competition between crops and weeds, resulting in an increased need for herbicides, so the benefits from increased carbon dioxide are limited.

In recent years we have had many examples of the devastation that extreme weather can have on agriculture and forestry. Hurricane Florence (September 2018) caused tremendous damage to the coastal Carolinas, primarily due to flooding from rains of up to 36″ in Elizabethtown, North Carolina.[14] The widespread flooding due to the slow-moving storm caused tremendous damage to sweet potatoes and other crops in eastern North Carolina and also caused the deaths of 3.4 million chickens and turkeys and 5,500 hogs. Hurricane Michael (October 2018) intensified just before landfall, bringing devastating winds through an area stretching from the Florida Panhandle to the northeast through southern Georgia and on into the Carolinas and Virginia. It was still a hurricane as it passed through central Georgia on October 10, and the UGA Weather Station in Donalsonville in far southwestern Georgia reported a wind gust of 115 mph as the eyewall passed over the airport location. Losses to agriculture and forestry in Georgia and Florida were estimated at over

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[12] P. Knox and M. Griffin, *Using Analog Methods to Illustrate Possible Climate Change for Agricultural Producers, https://ams.confex.com/ams/94Annual/webprogram/Paper232055.html*.

[13] *National Climate Assessment,* 2018, *https://nca2018.globalchange.gov/chapter/2/*.

[14] S.R. Stewart and R. Berg, *National Hurricane Center Tropical Cyclone Report on Hurricane Florence,* May 30, 2019, *https://www.nhc.noaa.gov/data/tcr/AL062018_Florence.pdf*.

$3.3 billion.[15] The storm hit about a week before most cotton was expected to be harvested, completely shredding many fields; it also flattened pine plantations and pecan groves that had been in farm families for generations, leading to years of losses of income for those families as they tried to reestablish their groves by planting new trees. Storms like the 2020 Midwestern Derecho also show the vulnerability of agriculture and forestry to severe thunderstorms and extreme weather, although it has not yet been determined whether these storms will become more frequent in the future.[16]

How Agriculture and Forestry Are Impacting Climate Change

The growth of agriculture and forestry over time have resulted in many benefits to our citizens, including better access to food, fiber, and building materials. But agriculture and forestry have had negative impacts on our citizens and our climate as well. Food waste due to inefficient use of farm production and citizen consumption results in 30–40 percent of food being thrown away in the United States,[17] even though many lower-income families do not have adequate access to the food they need. This leads to increased emissions of methane from landfills where the food is dumped. It also wastes the fertilizer, fuel, and water that was used to produce that food in the first place and the time and energy of people that are involved in producing and transporting that food from farm to market. Using too much fertilizer also results in the release of nitrous oxide, another greenhouse gas, which further increases global temperatures.

Livestock production allows ranchers and farmers to raise high-quality protein on land that often cannot be used for other economic activities. However, methane emissions from cattle produce 14 percent of greenhouse gas (GHG) emissions globally per year, although it is only four percent of all GHG emissions in the United States.[18] A lot of agricultural production goes towards providing the feed these animals use, and that production also emits greenhouse gases through the use of diesel fuel, fertilizers, and changes in land use from wetlands to cultivated crops.

Overuse of fertilizer, especially in areas with frequent heavy rains, causes problems with toxic water both locally, in rivers downstream from the fertilized fields, and in the Gulf of Mexico and ocean estuaries. This affects the livelihood of fishermen there by reducing the catch of commercial species as well as harming local ecosystems. It also reduces the health of the stream and estuary ecosystems and can lead to higher costs to treat the water for human and animal consumption and industrial uses.

Overall, the inefficient use of water and fertilizer and waste of food leads to serious economic consequences for agricultural producers, since they are the ones who pay for the diesel fuel to run equipment and pumps, and the chemicals needed to fertilize their crops and protect from weeds, pests, and diseases. Methods to make farms more efficient are often costly and put an extra burden on lower-income and minority farmers who cannot afford the cost of the added enhancements, leading to reduced production and even less money coming in.

How Agriculture and Forestry Can Reduce Emission of Greenhouse Gases

Agriculture and forestry have a large role to play in reducing the effects of greenhouse gases. The best way to reduce greenhouse gases in the atmosphere is to prevent their emission in the first place. Then there is no need to remove them from the atmosphere later. In 2018, agriculture produced 9.9 percent of the U.S. emissions of greenhouse gases by economic sector.[19] Worldwide, agricultural emissions account for 24 percent of all greenhouse gas emissions. These emissions come from numerous sources, including livestock production, release from agricultural soils, and rice production.

There are many ways that agriculture and forestry can help reduce the output of greenhouse gases. One of the biggest potential new ways to reduce emission of these gases is through reduction of food waste and packaging, which reduces methane emission from landfills where the unused food is buried and also reduces the amount of fuel, fertilizer, and transportation costs used to produce the food that is not used. It also reduces the amount of land that needs to be cleared for new crops. Improved diets for livestock and anaerobic digesters to recover methane from animal waste can reduce the amount of methane emitted. Using soil-preserving methods such as growing cover crops helps keep carbon, nutrients, and water in the soil, re-

[15] J.L. Beven, R. Berg, and A. Hagen, *National Hurricane Center Tropical Cyclone Report on Hurricane Michael, May 17, 2019, https://www.nhc.noaa.gov/data/tcr/AL142018_Michael.pdf.*
[16] *https://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm#climatechange.*
[17] *https://www.usda.gov/foodlossandwaste/why.*
[18] *https://www.ucdavis.edu/food/news/making-cattle-more-sustainable/.*
[19] *https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.*

ducing the need for fertilizers and running diesel-powered irrigation pumps. Making production more efficient by using tools like smart irrigation and better management of nitrate fertilizers also reduces the emission of greenhouse gases. The use of solar- and wind-powered pumps, where feasible, can also help cut the costs of fuel. Using new methods of cultivating rice using less water-intensive methods may also help to decrease methane emissions. Changing diets to eat lower on the food chain can also help reduce emissions.

Farming and forestry can also help by removing carbon dioxide and other greenhouse gases from the atmosphere. Growing forests and improving cropland productivity both pull carbon dioxide from the air as "carbon sinks." Many of the methods that reduce emission of these gases also help make the land better at removing carbon dioxide. For example, using no-till methods of farming keeps more water and nutrients in the soil and increases the health of the soil and of the plants in those fields, allowing them to suck up more carbon dioxide. Protection of existing forests and planting of new trees can also help to remove carbon dioxide from the atmosphere and cool the local climate. These practices also have other benefits such as protection of biodiversity, erosion control, and ecotourism, all of which can also benefit farmers.

Many of these solutions can be implemented now and many farmers are already doing so. For example, the number of cover crop acres in the United States increased by 5 million acres from 2012 to 2017, according to the *2017 Census of Agriculture.*[20] There is also ongoing research funded by USDA and other agencies into how to make these practices even better and easier for producers to implement. Because there are so many different types of agricultural production, there is no "one size fits all" solution. Many of these newer methods of production will result in economic savings for the producers immediately without large capital outlays. This is particularly important for lower-income and minority farmers and will be valuable to producers regardless of how the climate changes because the newer methods reduce the use of costly fertilizers, fuel for field work and irrigation, and other expensive inputs.

How Agriculture and Forestry Can and Are Adapting to Changing Climate

Since the climate is already changing and will continue to change for the foreseeable future based on greenhouse gases that have already entered the atmosphere or will be emitted in the future, farmers will also have to adapt to warmer temperatures, longer growing seasons, and more variable rainfall. In fact, many farmers have already started to take advantage of these changes. A longer growing season can lead to the enhanced ability to produce two crops instead of one ("double-cropping"), or to choose different varieties with higher yield that take longer to grow. That allows producers to diversify and create multiple income streams from the different crops they grow. Farmers are also experimenting with new crops that expand their options for selling locally at premium prices. For example, in Georgia producers are now starting to grow satsuma mandarins in the southern parts of the state, and olive groves and pomegranates have also been introduced to expand market options. In the northern part of the United States, some areas that are seeing increased rainfall are now growing corn where it was not previously possible due to the dry conditions. Expansion of other crops towards the north may also occur where appropriate soils and rainfall permit them to grow. However, more research is needed on whether the changes in climate that are occurring are compatible with how those crops grow.

Livestock producers are also adapting to a warmer climate by protecting their animals from heat stress using shade structures, or in some cases, keeping their dairy herds in air-cooled barns. New breeds like White Angus have been introduced to see if they can withstand high levels of heat stress better than current breeds. New hybrids of commercial crops and fruit such as peaches, which need a certain amount of cold weather to produce good yields, are being developed to grow in the new, warmer conditions. Foresters are also testing out different species of pine and other commercial varieties of trees to make sure that those forests will thrive under the climate conditions that are expected to occur as those trees mature. Many of these approaches require research to learn how to make the best choices, but farmers are already taking the lead on testing new varieties and new crops to determine their market values and growth patterns.

[20] *https://www.farmprogress.com/cover-crops/census-finds-cover-crop-acreage-increases-50-nationwide.*

What USDA and other agencies are already doing to prepare for changes in climate and extreme weather

The USDA has a long history of providing science-based, region-specific information and technologies to agricultural and natural resource managers across the United States, both alone and with other Federal and state agencies. This information helps land managers to make better choices based on scientific principles. The USDA also provides decision tools and guidance on how to use them so farmers from a wide range of backgrounds can use them effectively. In 2013, the USDA Climate Hubs were chartered to "provide a link between research activities and practical, actionable information that producers can use to make climate-smart management decisions".[21] They are led by *Agricultural Research Service* [1] and *Forest Service* [2] senior Directors with contributions from many other programs including the *Natural Resources Conservation Service,*[3] *Farm Service Agency,*[4] *Animal and Plant Health Inspection Service,*[5] and the *Risk Management Agency.*[6] The hubs currently address how working lands can be managed to become more resilient to extreme weather including hurricanes, wildfires, floods, and droughts. For example, the Southeast Regional Climate Hub has produced a series of crop-specific hurricane preparedness and recovery guides [22] that are being used to help producers plan for how to deal with hurricanes, which have severely impacted agriculture in the Southeast over the last 5 years. They also provide advice for what to do after a hurricane moves through the region. Other hubs provide information on dealing with drought and other types of extreme weather and climate that affect many different types of agricultural production. As an Extension specialist I use the information from all these sources to help producers make more informed choices about what crops to grow and how to manage them based on the current climate and what is predicted in the future.

Other programs within USDA provide financial support for scientists who are looking for better solutions to problems related to extreme weather and climate change. I have benefited from several grants from the National Institute of Food and Agriculture (NIFA), including one to put together training materials for extension agents and producers on livestock and climate across the United States and another looking at the impacts of drought and a warming climate on crop production in the Southeast. Other initiatives have focused on forestry and tools to help foresters pick the tree varieties that will do best in the future climate. USDA is currently providing funds for a project that I am co-Principal Investigator on that studies the impacts of "flash" drought. We are evaluating a variety of low-cost sensors that can be used by farmers in the Southeast to make water-smart decisions which will target efficient water use. This will also reduce fuel use and decrease the amount of fertilizer runoff into streams and, eventually, the ocean by using water wisely only when and where it is needed.

In addition to USDA, there are many other Federal agencies working in the area of monitoring climate and preparing for and responding to weather extremes as well as preparing for future impacts. One of these groups is NASA; you will hear more about their activities from one of the other experts in this panel. The agency that I work with most often is the National Oceanic and Atmospheric Administration (NOAA), which provides information on real-time weather and climate conditions across the U.S. and the world. NOAA scientists and employees also work with many constituent groups on when to expect extreme weather conditions. They also work with emergency managers to prepare for extreme events as well as study extreme weather and climate events from the past to learn better ways to respond to them next time.

In addition to Federal agencies, there are many state and local agencies and private organizations that are also working in the area of agriculture, forestry, and climate change. I am proud to be an Extension specialist at the University of Georgia. Surveys of farmers show that nearly half (47.8%) of farmers surveyed in a recent study found university Extension to be the most trustworthy source of climate change information.[23] Extension agents serve a critical role in translating the

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[21] *https://www.climatehubs.usda.gov/about-us.*
[1] *https://www.ars.usda.gov/.*
[2] *https://www.fs.fed.us/.*
[3] *https://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home/.*
[4] *https://www.fsa.usda.gov/.*
[5] *https://www.aphis.usda.gov/aphis/home/.*
[6] *https://www.rma.usda.gov/*
[22] *https://www.climatehubs.usda.gov/hubs/southeast/topic/hurricane-preparation-and-recovery-southeast-us.*
[23] *Journal of Extension, https://www.joe.org/joe/2018june/a7.php.*

science of climate variability and change into actionable decisions that local farmers can use to improve crop yields today and prepare for variations in climate in the future. We work with both academic and industry scientists and farmers, including those from both large and small farms, to identify developing critical conditions that may affect their crops and to help them plan for future impactful events.

Cooperative efforts between these groups have already produced important information about the relationship between agriculture and climate. The *Fourth National Climate Assessment*[24] includes an entire chapter on Agriculture and Rural Communities that addresses many of the issues I have mentioned above and relates it to rural communities and the economies there, which are mainly driven by agriculture. USDA also released a new publication, *Climate Indicators for Agriculture,* which describes how changing climate is affecting agricultural indicators such as chill hours, growing degree days, extreme rainfall, and heat stress.[25]

Recommendations to enhance efforts to assist agricultural producers respond to climate change

Based on the climate changes that have already occurred and will continue to change in the future, there are many ways that Congress can act to assist producers in both adapting to the ongoing changes and reducing the emission and concentration of greenhouse gases in the atmosphere. In general, Congress can encourage the use of research incentives to scientists to produce more targeted and applied ways of doing smart agriculture. This should not be done in a vacuum but should be done through collaboration with farmers using the expertise and assistance of Cooperative Extension and other groups that work at the intersection between science and production.

To facilitate the use of smart agriculture, farmers should be equipped with improved access to resources like the internet so they can access tools and information that relate climate to agriculture and forestry. This will help farmers improve their farm and woodlot management choices and show them how to use the information effectively. Congress can also encourage access to needed agriculture-specific data such as the agricultural weather networks (“mesonets”) that are already in place in some states and encourage their expansion to other agricultural areas that have fewer resources. This will help producers make effective decisions which will conserve resources and save money. This information should also be shared with other countries because improvements in agricultural production and better capture of carbon using water, fuel, and agricultural chemicals more efficiently will benefit the global climate system far more than just doing it in the United States alone.

In conclusion, I would like to highlight the following four points:

1. ***The time to act is now.***

   Reducing greenhouse gas emissions and responding to the changing climate is not something that can wait until we have perfect answers. We will never have perfect knowledge since science is constantly making new discoveries and farmers are innovating their own production methods at the same time. If we wait, we will waste time while we put more greenhouse gases into the air that will require removal. The climate will get more extreme as a result of those additional gases. It’s better not to emit the greenhouse gases in the first place. As our mothers reminded us, an ounce of prevention is worth a pound of cure. The longer we wait, the more unpredictable and extreme the climate is likely to become. Technology is always changing, and we can and must incorporate those changes into our management plans in the future, but we can take concrete steps now that will also save farmers money by reducing the costs of production. You can think of this as a ship captain responding to the sight of an iceberg ahead. If we respond to it now, we can make smaller, less drastic changes that will keep the ship safe, while if we wait, much more wrenching changes will be needed the closer we get to the iceberg in the future.

2. ***Economically, many farmers will benefit from these activities regardless of how the climate is changing.***

   Conserving water, fuel, and agricultural chemicals like fertilizer and herbicides makes good financial sense for farmers. Improving the health of the soils on farms, rangelands, and in forests will provide additional benefits to producers like better fertility and water-holding capacity, making them more

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[24] *4th National Climate Assessment,* 2018, chapter on agriculture, *https://nca2018.globalchange.gov/chapter/10/.*

[25] *Climate Indicators for Agriculture, https://www.usda.gov/sites/default/files/documents/climate_indicators_for_agriculture.pdf.*

resilient to extreme climate events like drought. It is especially true for producers who own the land rather than renting it, because they receive more tangible economic benefits from improving the soil, since they may be able to use less water and fertilizer over time. This is especially important for producers who want to keep the farms in their families over many generations, because they need to maintain the soil's health over many years of production as well as minimize production costs to keep more money on the farm. Climate-smart and sustainable agriculture also benefits local water supplies, municipalities, and ecosystems because resources are not being wasted or degraded.

Note that not every solution will work for every producer. Farm size, type of crop or crops, availability of money to use on farm equipment, and expertise all vary widely across the U.S. The use of irrigation to reduce vulnerability to drought may help some commodity farmers but be too expensive for small farmers unless simpler, lower-cost alternatives are developed and encouraged. In some parts of the country, like the Southeast, we usually have enough water for crops compared to other parts of the United States, but it sometimes needs to be supplemented to provide a boost to crops during a hot, dry spell. This water often only needs to be moved short distances to keep the crops growing and requires the use of much smaller infrastructure than the big irrigation projects out West that move water long distances to get it to the crops that need it. By working with scientists and producers to find the best ways to keep their crops alive in a cost-effective way, the farmers will be able to respond to the climate variations we are seeing now as well as adapt to and become more resilient to future climate change. This is especially important because climate models have a harder time predicting what the future precipitation patterns will be than they do temperature patterns, and so flexibility in how farmers adapt is particularly important. These low-cost, local solutions will especially benefit Black and small-scale farmers because they will allow crops to survive with lower costs than some bigger water projects, although those also have a place in some parts of the country.

3. ***Good management requires good data and useful tools.***

The best-managed farms use data to monitor their production and determine where and when to apply water and agricultural chemicals and decide when to harvest. Good data can also tell them when their livestock are under stress and use appropriate measures to keep them healthy. Tools such as smart irrigation schedulers and precision agriculture can cut costs and reduce the waste of fuel, water, and fertilizer by allowing producers to apply the right amount at the right time to maximize benefits to the crops without overusing them. In the future, agriculture will become even more technologically advanced. Use of machine learning and artificial intelligence will require good input data, the availability of computers and internet access, and access to equipment that can take advantage of this knowledge.

Traditional sources of weather data such as the National Weather Service collect information that is useful for farmers, but stations are widely separated and often do not capture measurements that are agriculturally important such as soil temperature, soil moisture and solar radiation. This is where supplemental weather observations from individual stations and networks of agricultural stations in mesonets can be of tremendous importance. The House has already recognized the importance of these mesonets in the NOAA pilot program enacted under section 511 of the Water Resources Development Act, which was included in the FY21 Appropriations package. Mesonets like the one that I manage at the University of Georgia provided tremendous added value to agricultural producers by increasing the density of observations, especially in rural areas where traditional weather observations are rare. They also provide data that cannot be obtained from more traditional sources. Production tools based on these data, such as irrigation schedulers, warning systems for development of critical pests and diseases, and trackers of crop development stages can provide highly useful and important information that farmers can use to minimize expenses and maximize yield.

To access weather and climate information and use tools effectively, farmers must have access to both the weather data and to the tools that use the data to make crop predictions. That is especially difficult in rural areas where access to the internet is limited, especially by low-income and Black farmers. To make maximum use of this information, rural broadband access must be improved. New agricultural tools need to be identified by scientists working together with producers to make sure that they are useful, reliable, and easy to use. Farmers must also learn how to use these tools effectively so that they can apply them to their management practices. Extension and the climate hubs have an important role to play in making sure this information is useful and is reaching the farmers who need it. Use of the data along with the agricultural tools that use them provide both short-term economic benefits to farmers by reducing wasted money, fuel, and labor as well as long-term benefits by reducing emission of greenhouse gases.

4. ***Farmers and foresters must be an integral part of the process.***

No one knows better how to farm than the farmers themselves. Innovation in farming has improved productivity dramatically over time, and farmers will continue to work to improve efficiency and manage crops better and more economically. But farmers and foresters must work with scientists to make sure they are not just doing what they have always done before, if there is something better based on science. They also need to know what the future weather and climate risks to farming and forestry are so that they manage their land appropriately. Scientists have the expertise to test new innovations carefully and demonstrate which ones are the most economical and beneficial. But scientists need to work with producers to make sure that the innovations are also practical and cost-effective and address the issues that farmers have to deal with on a daily basis.

The USDA Climate Hubs along with other Federal climate centers have an important role to play in both developing new tools and information sources for producers and in telling the farmers and foresters how to use these products effectively. This can be done through publications, web resources, and workshops, but they need to incorporate the input of practicing farmers and foresters as well as scientists. Extension also has an important role to play in this process, since extension agents work in the fields with farmers and see first-hand what problems the farmers are facing and how available information is used as well as what is missing. By serving as a liaison between the scientists and the producers, extension agents bring together academic and practical experience which will produce the most effective solutions for agricultural systems responding to both climate variations like drought and extreme weather like hurricanes, forest fires, and floods, both now and in the future. That way scientists and farmers and foresters can work together to help solve the problem of climate change in a way that benefits us all.

Thank you again for the opportunity to provide you with this look at the relationship between agriculture and forestry and climate change in the United States. I look forward to hearing your comments and answering your questions on this topic.

The CHAIRMAN. Thank you very much, Professor Knox.

And now, Mr. Zippy Duvall, please start now.

STATEMENT OF ZIPPY DUVALL, PRESIDENT, AMERICAN FARM BUREAU FEDERATION, WASHINGTON, D.C.

Mr. DUVALL. Well, good afternoon, Chairman Scott, Ranking Member Thompson, and all the Members of the Committee. I want to begin by thanking you for all the help you give our American farmers and ranchers over the last year and during this difficult time of the pandemic. It came on top of an already distressed farm economy, and we are all glad to see some positive turns.

Keeping our farmers and ranchers in production is vital to our food security and our national security. As you know, farmers and ranchers work hard to keep food on our plates, while continuing to make great strides in sustainability, which brings us to the topic of today.

American agriculture accounts for approximately ten percent of the total U.S. greenhouse gas emissions, far less than transportation, electricity generation, and other industry sectors. Total carbon sink efforts from forestland, grassland management, and management of cropland all offset approximately 12 percent of the total U.S. emissions.

To continue to make these gains in carbon sequestration, we need to increase investment in agricultural research. We need new technologies to help us capture more carbon in our soil. Farmers continue to produce more food, fiber, and energy more efficiently than ever before. Over the last two generations, we have tripled our production without using more resources from our land. In fact, we would have to add 100 million more acres than 1990 to match the same production of 2018.

Our advancements in sustainability are due to adoption of technologies and our farmers terrific participation in voluntary, incentive-based conservation programs. United States farmers have enrolled more than 140 million acres in Federal conservation programs. That equals the total landmass of California and New York State together.

Our farms and our land are our heritage. Every farmer I know wants to leave his land, air, and water and his ranch and farm business in better shape and better condition than he found it. To achieve that goal, Congress must protect agriculture from undue burdens and to respect farmers' and ranchers' ability to innovate and solve problems. We must work with Congress to explore new markets and new opportunities for agriculture.

Farm Bureau's Grassroot Development Process supports market-based incentives for adopting practices and planting crops that keep carbon in our soil. We welcome the opportunity to participate in an emerging carbon market.

To expand these opportunities, we convened a wide group of stakeholders to explore policy options that respect farmers and ranchers as partners, while also assuring that our rural communities can thrive. That effort became known as the Food and Agriculture Climate Alliance. It consists of organizations representing a cross section of farmers and ranchers, forest owners, food sectors, state governments, and environmental advocates. We are working together to develop and promote shared climate policy priorities. The Alliance is united under three principles that guide all 40 recommendations. First, we support voluntary market- and incentive-based policies. Second, we want to achieve science-based outcomes. And third, we want to promote the resilience and help our rural economy better adapt to climate changes.

We hope the work of, and the recommendations of the Alliance ensure, farmers and ranchers will be respected and supported. We must ensure that public policy does not threaten the viability of our farms, and the long-term resilience of our rural communities. Americans have a new appreciation for the importance of agriculture after seeing empty shelves during the pandemic last year, and I am proud to assure that Americans in America that the commitment of the farmers and ranchers is unwavering, and we will still be farming. So, let's make sure that public policy doesn't stand in the way of our ability to continue to fulfill that commitment.

Thank you, Mr. Chairman, for holding this hearing today. I look forward to the questions.

[The prepared statement of Mr. Duvall follows:]

PREPARED STATEMENT OF ZIPPY DUVALL, PRESIDENT, AMERICAN FARM BUREAU FEDERATION, WASHINGTON, D.C.

Mr. Chairman and Members of the Committee, my name is Zippy Duvall. I am a third-generation farmer and President of the American Farm Bureau Federation, and I am pleased to offer this testimony, on behalf of the American Farm Bureau Federation and Farm Bureau members across this country.

America's farmers and ranchers play a leading role in promoting soil health, conserving water, enhancing wildlife, efficiently using nutrients, and caring for their animals. For decades they have embraced innovation thanks to investments in agricultural research and adopted climate-smart practices to improve productivity, enhance *sustainability, and*[1] provide clean and renewable energy. In fact, the use of ethanol and biodiesel in 2018 reduced greenhouse gas emissions by an amount equivalent to taking 17 million cars off the road.

Livestock and crop production are the heart of American agriculture, providing the food we enjoy every day. The daily choices we make on our farm and ranches are driven by our commitment to sustainability. Farmers have embraced technologies that reduce emissions and increase efficiency, making U.S. agriculture a leader in sustainability. Building upon the strong foundation of voluntary stewardship investments and practices, including those in the farm bill, we look forward to working with policymakers to further advance successful sustainable practices in U.S. agriculture. Throughout this process, lawmakers must ensure that any governmental analysis characterizing U.S. crop and livestock systems reflects U.S. agriculture's leadership globally in sustainable farming practices.

All told, agriculture accounts for approximately 10% of total U.S. greenhouse gas (GHG) emissions, far less than transportation, electricity generation, and industry sectors. Farmers continue to produce more with greater efficiency. In fact, U.S. agriculture would have needed nearly *100 million more acres in 1990 to match 2018 production levels.*[2]

Carbon sequestration, achieved through the management of forestry, grasslands, wetlands, cropland and settlements contributed to GHG removals equivalent to 12% of total U.S. emissions. With increased investment in agricultural research we can develop the new frontier technologies to capture even more carbon in our croplands, our forests and our grasslands. We can definitely reduce our carbon footprint. With cutting-edge science, we may be able to achieve net zero emissions in some sectors of agriculture.

U.S. farmers and ranchers have long been at the forefront of climate-smart farming, utilizing scientific solutions, technology, and innovations to raise crops and care for livestock. These efforts are designed to protect soil and water, efficiently manage manure, produce clean and renewable energy, capture carbon, and improve sustainability. Over two generations, we've been able to increase productivity by 287 percent, while using the same resources. To say we're doing more with less is an understatement.

Total carbon sink efforts from forestland management, land converted to forestry, grasslands, and wetland management more than offset agriculture's contribution to total emissions. However, many of agriculture's carbon sequestration efforts are not directly assigned to the agriculture sector. It is certain that if the carbon sequestration efforts of U.S. farmers and ranchers were assigned to agriculture, especially our forests, our contributions to GHG emissions would be lower. It is worth noting that U.S. farmers have enrolled more than 140 million acres in Federal conservation programs—that's equal to the total land area of California and New York combined. Millions more acres are dedicated to non-Federal conservation programs.

More productive livestock operations allow ranchers, pork producers, and dairy farmers to maintain their total contribution to GHG emissions at less than 3%. Innovation plays an important role, from methane digesters to advances in nutritional balance that lead to lower per-unit GHG emissions. In fact, we have seen a 25% reduction in per unit of GHG emission for our dairy industry, an 18% reduction in swine and close to a 10% drop for our beef cattle producers.

U.S. farmers and ranchers contribute significantly fewer GHG emissions than their counterparts around the world. EPA data shows agriculture's global contribution to GHG emissions was 24% in 2010, more than double U.S. farmers' and ranchers' contributions to total U.S. emissions in 2019. This significant difference is largely driven by U.S. farmers' enthusiastic adoption of technology. American farmers and ranchers are pioneers of sustainability, and any policy debate should recognize

[1] *https://www.fb.org/land/fsf.*
[2] *https://www.fb.org/market-intel/ghg.*

their contributions, efficiency gains, and the considerable impact of their carbon sequestration efforts.

With trade challenges and the impacts of the COVID–19 pandemic, America's farmers and ranchers are facing difficult headwinds. As we continue to work with Congress, we must explore new markets and opportunities for agriculture. We also recommend working with our international trade partners to make certain that national sustainability standards do not become trade barriers to our agricultural exports.

At the American Farm Bureau, our policy is crafted by our grassroots members, hardworking farmers and ranchers, who recognize the value of a voluntary, market-based system of incentives for planting crops or adopting farming practices that keep carbon in the soil. That is why we welcome opportunities for farmers and ranchers to participate in emerging carbon markets.

To further promote and expand these opportunities, the American Farm Bureau felt it was important to convene a wide group of stakeholders to further explore policy options for farmers, ranchers and rural communities. What came out of that effort is now known as the Food and Agriculture Climate Alliance which consists of organizations representing a cross-section of farmers, ranchers, forest owners, the food sector, state governments and environmental advocates that are working together to develop and promote shared climate policy priorities.

The alliance united around three principles that guide our 40 recommendations: Support voluntary, market- and incentive-based policies; advance science-based outcomes; promote resilience and help rural economies better adapt to changes in the climate. We hope the work and recommendations of the alliance ensure farmers and ranchers will be respected and supported as society pushes for more climate-smart practices. Advocating for the right policies—voluntary, market- and incentive-based solutions—will allow us to build on our sustainability advances and recognize farmers as partners in this effort, while helping to prevent a move toward the punitive policies discussed a decade ago.

Farm Bureau will continue to work to ensure that farm families maintain their ability to respond and adapt to climatic events and that public policies do not threaten the long-term resiliency of our rural communities. Congress must protect American agriculture and production practices from undue burden, and respect farmers' and ranchers' ability to innovate and solve problems.

American farm families want to leave the land better than when it was first entrusted to our care. That is the story of my family's farm in Georgia and the story of millions of farms across this country. We want to protect the planet, feed and clothe people, and promote vibrant communities. Working with our partners, land-grant universities, policymakers, and the farmers and ranchers we represent Farm Bureau intends to continue finding solutions for the challenges of the future.

Mr. Chairman, I commend you for convening this hearing and for all your hard work on behalf of agriculture across the country. I will be pleased to respond to questions.

The CHAIRMAN. Well, thank you so much, President Duvall, for your excellent remarks there.

Now, Committee, before we continue with introducing the witnesses today, and with the consent of my colleagues, I would like to share with you now a very brief clip from the documentary entitled, *Kiss the Ground.* My dear friend, Congresslady Jayapal of the State of Washington brought this film to my attention. I watched it on Netflix. I was very impressed with what they had to say, and I have invited them to show this very impressive film. It will introduce you to the possibilities of how we must balance our climate, replenish our water supplies, deal with the carbon, and most importantly, continue being the champions of feeding the world by taking care of our soil.

Please start the clip now, would you?

[Video shown.][3]

[3] **Editor's note:** the video is retained in Committee file.

The CHAIRMAN. Thank you very much for that, and what a very informative message. I would encourage as many of you to see the complete film, *Kiss the Ground.* It is now airing on Netflix.

And now, we will return to hearing the testimony of the remaining two witnesses who are here with us today.

Mr. Brown, you may begin your testimony now.

STATEMENT OF GABE BROWN, CO-OWNER/OPERATOR, BROWN'S RANCH, BISMARCK, ND

Mr. BROWN. Thank you, Honorable Chairman Scott and Members of the Committee, for allowing me the opportunity to speak to you today.

Since 1991, my family and I have owned and operated a ranch near Bismarck, North Dakota. As a farmer and rancher, I have been affected by the extreme variability in weather. Drought, flooding, extreme cold and heat: the change in our climate is affecting everyone and every farm. Agriculture is often vilified as being a major contributor to climate change, but you can help agriculture become a major part of the solution.

First slide, please.

[Slide.]

Mr. BROWN. On the left side of this picture are my soils today. On the right side are my neighbor's. These samples were taken only a few feet apart. The only difference is management, or as I like to call it, stewardship. In 1993, my soil organic matter levels were at 1.7 percent. Today, they are near seven percent. My neighbor's are at or below 1.7 percent. Today, my soils can infiltrate over 30″ of water per hour, while my neighbor's can infiltrate less than ½″ per hour.

So, how did farmers like me take large amounts of carbon out of the atmosphere and use it to regenerate our soils? The answer is we use six proven time-tested ecological principles. These principles will work on every farm in every one of your districts.

Next slide, please.

[Slide.]

Mr. BROWN. We start with context. We are not planting orchards in the desert. That is out of context. We are making our farms more resilient, but programs like crop insurance are not rewarding farmers for positive outcomes, and they are not based on environmental constraints. We are serious about not only reducing and eliminating tillage, but also significantly reducing all synthetic fertilizers and pesticides as they harm soil biology, our ecosystems, and our health.

I am holding a pint jar of treated soybean seed. The neonicotinoids on this seed has the capability of killing 72 million bees. This has to stop.

Next slide.

[Slide.]

Mr. BROWN. Allan Savory said it well when he said "It's not drought that causes bare ground, it is bare ground that causes drought." We are keeping our soils covered with diverse living cover crops and grain crops, thus continuing to pump carbon into the soil, while protecting our soils from erosion, conserving moisture, and holding nitrates, phosphates, and other nutrients on our farms. We are prioritizing diversity. This Committee can help every farm, ranch, and CRP land to significantly increase the biodiversity of plants, insects, and soil biology.

We realize the importance of grazing animals. Our richest, healthiest soils were formed in partnership with grazing ruminants. Proper use of grazing ruminants is one of the keys to carbon sequestration.

Next slide, please.

[Slide.]

Mr. BROWN. Down to 36″ and beyond, adaptive regenerative grazing is seeing total carbon gains significantly higher than rotational or continuous grazing.

Next slide.

[Slide.]

Mr. BROWN. This is the Chihuahuan Desert. Many think that with only 6″ to 8″ of annual rainfall, it was always a desert.

Next slide.

[Slide.]

Mr. BROWN. The dark colored soil near the surface is carbon. This means it was recently a vast grassland. The erosion you see took only 60 years. You can drive through this desert, and then you open a gate to Alejandro Correo's ranch.

Next slide.

[Slide.]

Mr. BROWN. The difference is stewardship. He is using livestock to regenerate his soils and increase biomass. Where his neighbors need 300 acres to feed one cow per year, he only needs 30. As a result, regenerative farmers are substantially increasing the profitability of our farms and ranches, thus helping to revitalize our rural communities while producing food that is higher in nutrient density. We have done this while reducing our reliance on government programs. These programs should be a hand up or a reward for positive results.

While more resources are needed, just increasing funding isn't going to solve it. We need to put that funding into what actually regenerates landscapes. We must make the adoption of regenerative ag available for all farmers from all backgrounds.

From farmers to scientists to environmentalists to the government, we hear: "I didn't know." Well, at one time, I didn't know either. We must educate, not only farmers and ranchers, but all society as to these concepts which are rooted in indigenous knowledge.

It is not just about emission reductions. It is about our land's resilience and ability to function. Regenerating our soil ecosystem is the most cost-effective national investment we can make to mitigate climate change and heal society. The current system is broken. We need to change the way we see things. Regenerative agriculture is a win for all, and this Committee, Mr. Chairman, can help lead the way.

Thank you for your time, and I look forward to your questions.

[The prepared statement of Mr. Brown follows:]

PREPARED STATEMENT OF GABE BROWN, CO-OWNER/OPERATOR, BROWN'S RANCH, BISMARCK, ND

Thank you, Honorable Chairman Scott, and Members of the Committee, for allowing me the opportunity to testify before you today.

My name is Gabe Brown. I own and operate a 5,000 acre ranch near Bismarck, North Dakota with my wife, son and our family. We have farmed this land since 1991 and began by using conventional methods, but crop failures due to erratic weather, increased costs and rising debt led us to adopt a series of regenerative soil health practices. These practices have provided multiple benefits. Regenerative practices have made our farm profitable over the past 3 decades, and also increased our soil carbon over six-fold since we first started taking on-farm measurements in 1993.

Today I make the case for wide-scale adoption of regenerative agriculture by sharing the essential opportunities afforded to me. Regenerative agriculture mitigates climate change while increasing resilience against current and future climatic uncertainty including flooding, fire and drought. It is essential to soil, plant, animal, human, community, and economic health. Regenerative agriculture does this by restoring our land and soil, the biology and the ecological cycles and processes which are foundational to human and planetary health and stability.

As a farmer and rancher, I have been affected by the extreme variability in weather. 2020 was the second driest year ever recorded where I live and ranch in Burleigh County, North Dakota. Just this month the local weather station recorded the most consecutive days of $-25°$. From drought to flooding, from extreme cold to extreme heat, the change in our climate is affecting everyone and everything, especially farmers.

In 1997, I had the good fortune of hearing Don Campbell, a rancher from Alberta, Canada present at a conference and Don made this statement, "If you want to make small changes, change the way you do things; if you want to make major changes, change the way you **see** things."

This statement changed my life. I realized that the resiliency of my farm was up to me. The ability of my farm to cope with climate change was up to me.

As a farmer educator, I travel all over this country and have visited hundreds of properties. With my colleagues, I am currently involved with farmers and ranchers managing over 22 million acres in the U.S. The realities that these land managers are facing on the ground are alarming. One thing, however, remains constant, when a farmer or rancher changes how they *see* things, real regeneration starts happening

I want to be clear: farmers and ranchers are the heart of this country and so many of them are incredible stewards of our land. However, land use, particularly the **shift to our modern systems of agriculture in the United States and across the world has been one** of the biggest **drivers** of many issues we face today such as drought, flooding, soil loss and erosion, and the depletion of water resources, often attributed broadly to "climate change". Through mismanagement, our land and our soil is now heavily degraded and in many cases barely functioning, or worse, completely desertified.

Today, climate change is exacerbating the equally serious problem of degraded land. Scientists estimate that "75% of land is degraded". IPBES

It's not just a question of carbon or greenhouse gases. We've broken the hydrological cycle, carbon storage capacity, and nutrient cycle. Much of our land's soil is degraded to such a state and not functioning as it once did.

We have to come to grips with the reality that the current state or our soils is dire. We are losing 1.7 billion tons of soils annually (Cornell University). That is 4 tons of topsoil per acre per year on ag land (USDA).

Continuing on this trajectory should no longer be an option.

The Economic Toll of Modern Agriculture in the U.S.

- The average debt increase for farmers is 4.1% a year since 1990 (USDA).
- Percentage of net farm income from government support is increasing at an alarming rate; it's projected at almost 40% in 2020 (USDA).
- The cost of inputs, including fertilizers, herbicides, pesticides, *etc.* is rising for farmers due to the degradation of our soils.
- Crop insurance payouts continue to rise, adding a burden to taxpayers.
    - The cost of crop insurance has been an average $7 billion a year since 2013 (USDA–RMA).

However, U.S. agriculture can and must be a major part of the solution. We can rebuild our soils through regenerative agriculture. Rebuilding our soils means rebuilding resilience, strength, and freedom for our nation.

Whether your primary concern is a farmer's bottom line, rural economic recovery, climate mitigation, sequestering carbon, reversing biodiversity collapse, cleaning our water and air, rehydrating our land so aquifers charge and springs flow again, providing land access for minorities and beginning farmers, or addressing the health crisis, regenerative agriculture provides the solution.

In 1991, my wife, Shelly, and I purchased a degraded ranch near Bismarck, ND. Soil tests showed that Soil Organic Matter levels (Soil Organic Matter is about 58% Carbon) were from 1.7% to 1.9%. Soil scientists tell me that historically, soil organic matter levels were between 7% to 8% in my region. This meant that approximately 75% of the soil carbon had been washed away or released into the atmosphere due to previous farming practices. This rate of soil carbon loss is all too common throughout the United States. Soils in North America have lost, on average, 20% to 75% of their carbon stock.

I also performed water infiltration tests. They showed that my soils could only infiltrate ½″ of water per hour. This meant that any rain event in which I received more than that amount the water either ponded on the soil surface or ran off, in the case of any sloped land, carrying with it precious topsoil and nutrients. Top soil loss and artificial nutrient run off becomes problematic downstream with fish kills, water quality issues, and more.

On Farm Soil Comparison: Regenerative *vs.* Conventional

In the picture you see before you, on the left-hand side of the screen are my soil's today (well aggregated and higher carbon levels). On the right-hand side of the screen are my neighbor's soils (compacted and mostly devoid of carbon). These samples were taken only feet apart. They are the same soil type. The only difference is management, or as I prefer to call it, stewardship.

Today, organic matter levels on my farm are from 5.7% to 7.9%. My neighbors are 1.7%

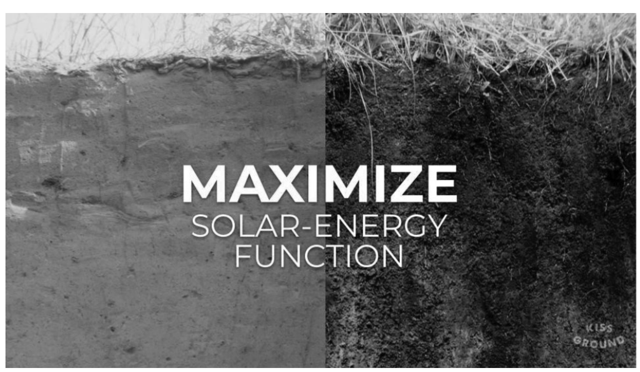
Today, my soils can infiltrate 30″ of water per hour, while my neighbor is still lagging around ½″ per hour.

- That is a 60-fold increase. In places around this country riddled with flooding, this could create massive reductions in damage and allow for us to retain precious water *versus* having it runoff carrying pollutants and sediment.
- As I am often quoted saying, "it is not about how much rain falls, it's how well you absorb and retain it"

Today, I do not use any synthetic fertilizer, pesticides, or fungicides. As a result of lower expenses and increased production my profits have increased tenfold.

So how does soil regeneration work?

The soil system evolved to be self regenerating and self healing, otherwise there would never have been soil to begin with. So, rebuilding soil is all about helping nature to do it using a system running on carbon energized by the sun—basically, maximizing photosynthesis—the ability for plants to use the energy from the sun to take carbon from the atmosphere and pump into the soil as liquid energy (glucose and water).



Building Functioning Soil

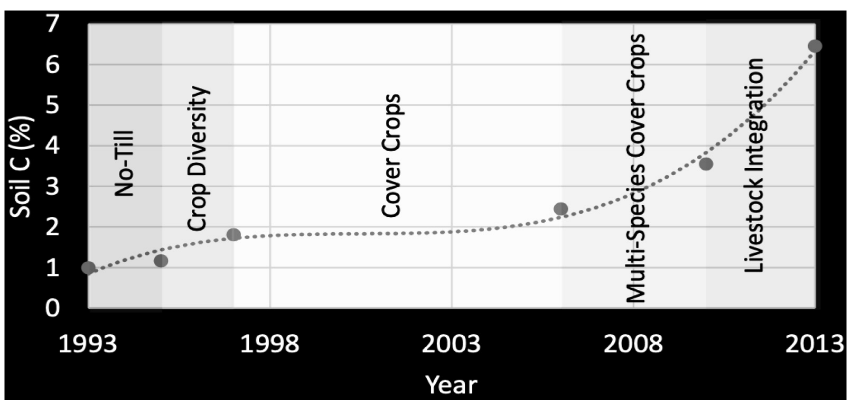
Nature also evolved to create functioning soil. Plants share their sugars with the microbes in the soil who not only make minerals and nutrients available to plants but also create glues that bind the soil particles together forming aggregates. This is what causes the primary difference between soil and dirt where soils contain organic matter (*i.e.,* carbon-based compounds) and dirt is only mineral—sand, silt and clay.

Healthy soil performs like a sponge.

Healthy soils are able to hold 20x their weight in water due to the pore space between aggregates which also allows for faster infiltration rates. The substances building the aggregates, the glues from the microorganisms, and the organic matter within the aggregates are carbon based and often very stable (meaning it can remain as soil carbon for years). Thus, the CO_2 in our atmosphere can and must become the glue that rebuilds our soils so they can function again.

How Regenerative Soil Health Practices Build Soil Carbon Over Time

Gabe Brown's Soil Carbon Data



Carbon Bank/Markets: *if we move this direction please take in mind these four areas of concern.*

1. *Integrate other outcome areas while building out carbon models so they aren't separate (**i.e.,** hydration, biomass, evapotranspiration, biodiversity, **etc.**)*
2. *Large scale ground truthed calibration with real-time satellite data so it is based on outcomes.*
3. *Make sure at least 50% of all monies from carbon (or other services) make it to the farmer.*
4. *Make sure all corresponding data like precipitation, humidity index, **etc.** are included in the baseline so equal setting is created for every state and region.*

Regenerating healthy soil is the solution.

- The Benefits:
  - Massive carbon sequestration potential.

1. Adaptive "Regenerative" grazing cases have shown the top 12″ of soil are adding 4.76 tons (short U.S.) C/acre/year and 17.46 (short U.S.) tons CO_2/acre/year.

- Increase water holding capacity and absorption.

  1. 1% increase of Soil Organic Matter means 18–25 thousand more gallons per acre held.

- Biodiversity

  1. Life in the soil means more life on the land (birds, bees, game, *etc.* return)
  2. 1 teaspoon of healthy soil holds more organisms than people on [E]arth.

- Resilience/risk mitigation

  1. My colleagues and I work with hundreds of farmers totaling 22 million acres of land. The average we are seeing is only ½″ of water infiltrated per hour.
  2. My farm started at this same rate and now can absorb 30″ rainfall per hour.

- Healthy plants and Farmer Profits

  1. Healthy soils make healthy plants that are pest and disease-resistant and require less input costs because the life in the soil makes the nutrients available to the plant.

     a. In partnership with General Mills, Understanding Ag tested 45 farms that averaged 9,000 pounds of nitrogen in the top foot of the soil profile.

     b. **In most cases, soils are not deficient in nutrients, they are deficient in biology.**

     c. Biologically active soils can help farmers reduce input costs. 7k acre farms, like Rick Clark's in Indiana, are saving $860k a year on input costs.

Why are farmers moving toward regenerative?*—They want out of this endless cycle of debt and dependence. They want freedom. They want to see their sons and daughters interested in carrying on the legacy of their family farm. At the very least they want to provide for their families and keep them safe. The shift is huge, once they start working with nature instead of against her, their lives completely change. We work with every type of farmer, large, small, organic, conventional, wealthy, and in debt. We work with every race, religion, and creed. We work with White, Black, Latino, Asian, and Native American farmers. Regenerative agriculture came about because farmers were hurting, this is an incredibly interconnected movement from the soil up.*

> *The demand to successfully transition to regenerative agriculture is here and it is growing. And it means each of you can work to make sure that option is available to all farmers. At the very least encourage, and if needed, facilitate early adoption.*

To move to regenerative on a massive scale with any type of farming and ranching we have to prioritize these six principles.

- ○ Context

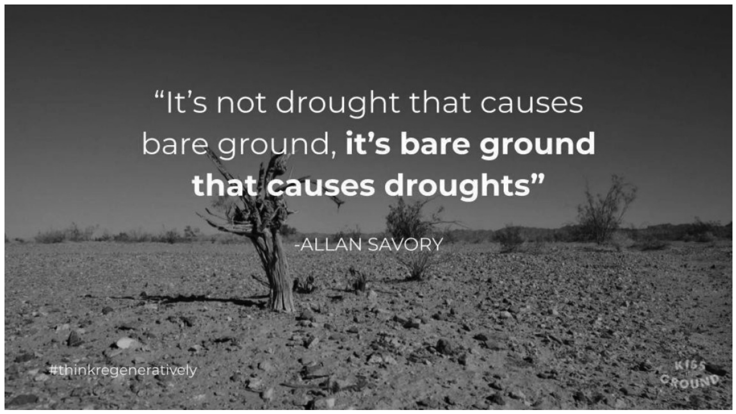
  - Nature always acts in context. It does not try to grow plants or raise animals out of context of where they should not be growing or living.
  - Programs like crop insurance are currently not based on positive outcomes and don't work in context, often leading to continued nationwide degradation of our soils.

    - ○ We need to monitor for real outcomes as to benefit farmers building resilience into their operations.
    - ○ Crop insurance needs to integrate environmental contexts so we aren't creating unnecessary harm.

  - Our financing and loan system for farmers is often out of context keeping farmers on an arbitrary hamster wheel of trying to pay back principal balances. It could be changed to an investment model that helps farm and ranch operations move to regenerative.

Orchards in the desert. Example of bad context.

- Least Disturbance
  - We have to get serious about reducing and eliminating tillage.
  - We have to reduce chemicals. Nature does not use copious amounts of chemicals.
    - The chemicals, herbicides, fungicides, insecticides, even the fertilizer we are putting on our crops are damaging our soils.
- Living Root
  - Living roots in the soil as long as possible throughout the year. Nature always wants a living plant to take carbon out of the atmosphere, through photosynthesis convert it to carbon compounds that it can pump into the soil to feed microbes. That is what makes rebuilding soil possible.
  - We need a massive mobilization of multispecies cover crops and mentorship from experienced individuals to ensure their success. We need 75% of our cropland covered in the offseasons as soon as possible.
  - We need viable options like roller crimpers for termination of diverse cover crops.
  - CRP can be beneficial but it is highly underutilized for actual regeneration. It needs diverse mixes of species not monocultures of shallow-rooted grasses that have poor nutrient quality. It needs to include regenerative grazing.
- Soil Armor
  - Walk through the forest, there is a carpet of leaves. Walk through a healthy prairie and every inch is covered in plants, deep-rooted grasses, and forbs. Nature always wants to cover the soil to protect it from wind erosion, water erosion, and evaporation to keep building soil aggregates.
  - We have to think holistically. We have prioritize every square foot of soil and how well the soil is performing *versus* leaving thousands of acres bare and exposed while investing in small infrastructure projects and thinking we've accomplished our goal. (without armor, every bare inch of soil becomes vulnerable to water droplets that act like bombs to soils aggregates exploding them and leaving dispersed state soil easily compacted and able to wash away).



- Increase biodiversity
  - Where in nature do you have a monoculture? The answer is only where human intervention has dictated it. Nature thrives on diversity, yet what do we do? We plant monocultures, corn, soybeans, wheat, cotton, rice, and the list goes on.
  - As policymakers, you can help change this! Every working farm, ranch, or land in CRP can significantly increase the biodiversity of plants, animals, insects, and soil biology.
  - This pint jar of soybean seed that I am holding has been treated with neonicotinoids and has the capability of killing 72,350,000 honeybees from the amount of chemical alone.
- Animal Integration
  - Ecosystems do not function properly without animals. Many of our richest, healthiest soils evolved with, and were formed in partnership with, grazing ruminants. Proper use of grazing ruminants are one of the keys to taking massive amounts of carbon out of the atmosphere, especially in more brittle environments that were originally grassland systems maintained by large herds and the indigenous people of this land.
  - We must work together to bring back animals into our farming systems. We have to understand the profound opportunities and the differences of Adaptive "regenerative" grazed land *versus* "rotational" grazing or "continuous" grazing.
    - Compare soil carbon data—**total soil carbon tons per acre.**

Horizon	Adaptive (Regenerative)	Rotational	Continuous
6″	4.67	1.64	1.36
12″	4.00	1.88	1.37
18″	2.95	1.03	0.40
24″	2.04	1.02	0.54
30″	1.71	0.38	0.40
36″	1.42	0.41	0.34

TSC.

And, we can do this faster than we ever thought possible! As my associate Dr. Allen Williams says, "outcomes that used to take us 15–20 years we are now seeing occurring in 3–4 years.". What he is saying is that the advances in how quickly farmers can regenerate landscapes, all while reducing input costs, continues to improve.

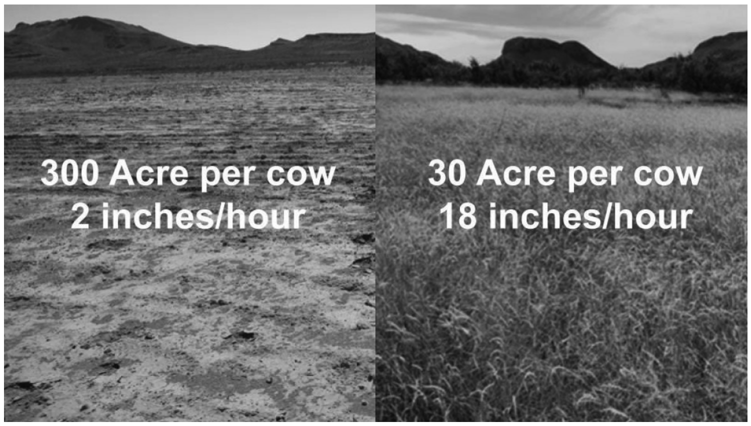
This is the Chihuahuan desert in Texas. Many think that with only 6–8″ of annual rainfall it was always a desert[.]

But take a close look at this picture. See the dark-colored soil near the surface? That is carbon. This was recently a vast grassland.

- ◦ This is erosion and is happening more and more across the whole country. Look closely to see the barbed wire going across this gully. This erosion occurred in just the past 60 years.
- ◦ I want to ask you all to take this back to your own states and districts. Think about places you grew up in or how your grandparents described the landscape, I want you to become present to the rates of land degradation that are happening all around us now. Climate change is exacerbating it but the management of the land is of the utmost importance.
  - Look for dried up streams or riverbeds. Look for bare land that once was vast prairie
  - It's all connected. We are drying ourselves up and leaving our land vulnerable.

You drive through this desert and then you open a gate to enter Alejandro Corrillo's ranch.

The difference is simply stewardship. Alejandro has used livestock as a tool to regenerate his soils and increase biomass. Where 12 years ago he needed 300 acres to feed one cow per year, he now only needs 30 acres per cow. *Note: Regenerative grazing in less brittle environments like Alabama see ranches going from 11 acres needed per cow/year to 2 in under 3 years.*



By practicing Regenerative Agriculture we can use nature's proven, time-tested principles to take massive amounts of carbon out of the atmosphere and build it back into the soil.

4 Short Case Studies

I want to very quickly share four case studies to show that this is not an anomaly for my ranch in North Dakota or Alejandro's in Texas. Yes, this can happen with farmers in your district.

Rick Clark (5th generation Farmer Indiana—Regenerative Organic)

- 7k acres growing alfalfa, yellow field peas, cattle, soy, corn, and wheat
- By moving to no-till and cover crop and planting into crimped cover crop "planting green", he eventually removed all chemical inputs (no synthetic fertilizer, pesticides or fungicides "farming nacked")
- Savings on inputs approximately $860k annually (based regional averages).
- His water infiltration rate has improved to 5″ rainfall per hour.
- 4 bushel a year increase (for past 4 years) for corn. 1.5 increase for soy.

Adam Grady (11th Generation North Carolina)

- 1,600 acres cattle, pasture pigs, sheep, corn beans, pasture turkey, corn, and soy.
- Moved from tillage to no-till and cover w/livestock integration
    - *"In our second year, we saved over $200k by reducing input costs such as seed, pesticides, herbicides, fungicides, and fertilizer as well as reducing labor, and fuel costs.*

      We had also reduced Glyphosate consumption by 80% and were glyphosate free by year 3."

      ADAM GRADY Dark Branch Farms.
- Was able to seed 2 week[s] after hurricane Florence waters receded while neighbors were still flooded.
- Was able to pay off his farm debt after only 3 years of farming regeneratively.

Adam Chappel (Arkansas)

- the 8k acre cotton farm was spending $100 an acre on herbicides, "there was no way for us to be profitable".
- Switched to no-till and cover cropping now they are making 100–250 an acre profit.
- "I don't care what you call it, I call it profitable farming"—Adam Chappel

Dr. John Boyd (4th Generation Farmer Virginia)

- 1,300 acres growing corn, soy, wheat, beef cattle, goats, pigs, vegetables, and hemp.
- Transitioning to regenerative practices has lead to
    - Much native biodiversity being restored.

    - Major water and input savings.
- Working with Tribal communities reintroducing hedgerows of elderberries into lands and pastures.
- As founder of the National Black Farmers Association, John works to help black farmers access NRCS soil health programs and get education in regenerative management.

This hearing is about climate change. But those of us who farm and ranch, it is so much more.

By practicing Regenerative Agriculture we can use nature's proven, time-tested principles to not just take massive amounts of carbon out of the atmosphere but we can use it to build back our soils, for farms, families and futures.

- We can restore the water cycle and replenish underground clean water sources making droughts less frequent.
- We can infiltrate water more quickly and hold more water thus alleviating flooding.
- We can hold nutrients on the landscape, thus preventing nitrates and phosphates from entering our watersheds.
- We can make farming and ranching profitable again by reducing inputs and stacking enterprises.
- We can revitalize our rural communities by diversifying farm production.
- We can produce food that is higher in nutrient density thus significantly lowering healthcare costs[.]
- We can Regenerate America[.]

Mr. Chairman, you and your Committee Members have the opportunity to foster this change. You can develop, adjust, or expand policy that will allow agriculture to be part of the solution. More resources are needed, but just increasing funding isn't adequate. It all starts with education and a "change in how we see things." We must educate farmers and ranchers as to these regenerative principles. But it's not just the farmers, this is systemic, the crop advisors, the field agents, and all society, need more education on the ecological approach and how and *why* regeneration of the land can and must happen.

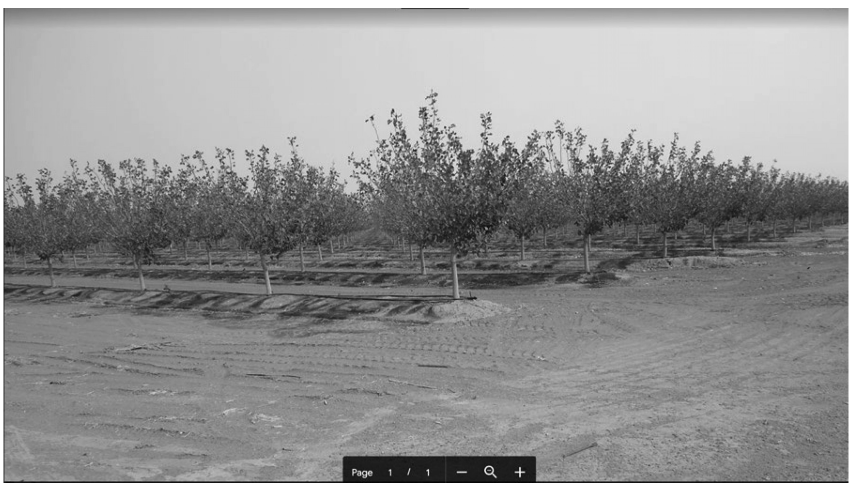
From farmers, to soil scientists, to leading environmentalists, to government officials, you hear a resounding phrase, "I didn't know". Well, I didn't know either. This is an opportunity for all of us to learn.

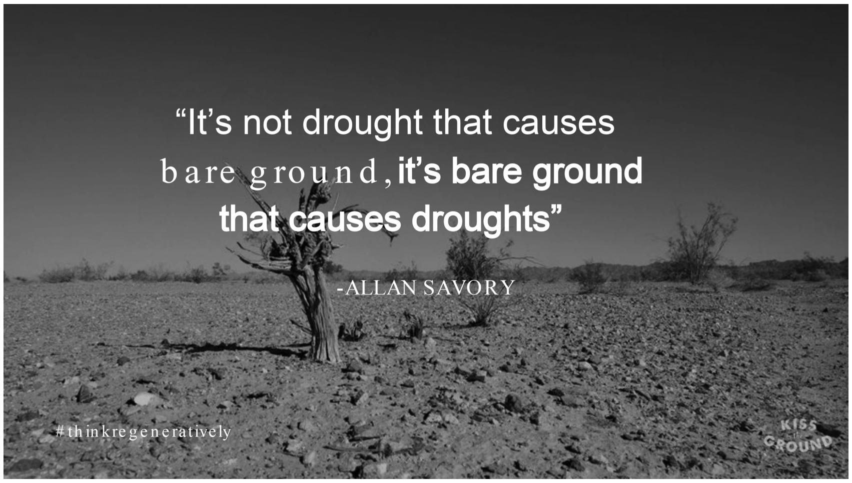
While many of these concepts are rooted in indigenous knowledge, many of them are being relearned and shaped by our current context and are emerging with science. We are living in a time like no other, we need science, technology, indigenous wisdom, and holistic thinking working together to move us toward regeneration.

Building back healthy soil is the most cost-effective regional, state, and national investment. From risk mitigation to farmer prosperity, to human health, to carbon sequestration, it's a win, win, win, win, and this Committee, Mr Chairman, can help lead the way.

Thank you for your time and I look forward to your questions.

ATTACHMENT





Total Soil Carbon Increases (tons per acre)

Measurement Depth	Adaptive (Regenerative)	Rotation	Continuous
6"	4.67	1.64	1.36
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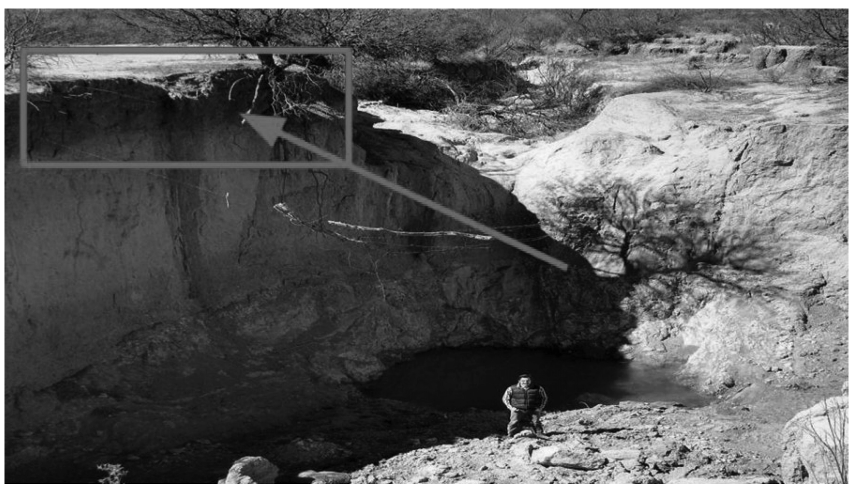

The CHAIRMAN. Thank you for your excellent testimony.

And now, we will hear from Mr. Shellenberger. Please begin now.

STATEMENT OF MICHAEL D. SHELLENBERGER, FOUNDER AND PRESIDENT, ENVIRONMENTAL PROGRESS, BERKELEY, CA

Mr. SHELLENBERGER. Thank you very much. Thank you very much for inviting me. It is a pleasure to be here.

I will just jump right in by sharing special slides that I have prepared for the Committee.

So, let's see. As background, because I am going to present some information that may surprise some people, just my credentials. *Time Magazine* "Hero of the Environment" and Green Book Award winner. I have been working with James Hanson, the climate scientist, and others to protect nuclear power plants, but I also have a new book out on the environment called, *Apocalypse Never.* While I am an environmental advocate and a climate advocate, I am also concerned by a growing alarmism, which I think is not conducive to sober and sound climate or environmental policy.

I want to draw attention to some important positive trends that many people don't know about. American farmers are world leaders in innovation, productivity, environmental protection. You can see here, our crop yields continue to rise dramatically over the last 30 years, whether it is soy, wheat, corn. You can see that globally we produce enough food for two billion people right now. I think a lot of us experienced the fact that we have too much food available. It is a new problem in human history to have so much food. We produce 25 percent more food than we need every year. The result is that extreme poverty has declined dramatically. Globally, just ten percent of all humans live in extreme poverty today, down from about 50 percent just a few decades ago. Life expectancy has increased 40 years, and you can see that soil erosion has declined in the United States 40 percent, while yields have risen. A very impressive achievement. We have increased meat production. We have doubled meat production, even while reducing greenhouse gas emissions. Incredible success that we don't hear enough about this.

A big part of the reason is that we have cut the feeding time for various animals, including chickens, while doubling their weight.

You can see the big problem with degraded soils are in developing and poor countries, which I will come back to, but they are experiencing soil loss at twice the rate of wealthy and developed economies like the United States.

The evidence is clear: technological change and agricultural modernization will significantly outweigh climate change in the United States and around the world. This is a very important report that was produced by the United Nations Food and Agriculture Organization in 2018 called, *The Future of Food and Agriculture.*[4] Just to help you understand what you are looking at here, you can see that what it is showing is that whether you are an irrigated system or rain fed system, and whether you are in the business-as-usual scenario, the sustainability scenario, or a scenario of greater inequality, what really matters is technological change. Just think of it as fertilizers, mechanization, and irrigation are the big three, but certainly better seed types massively outweigh the changes to temperature. This is important because climate change is real. It is a serious problem. We should do something about it, but we are not helpless, and if farmers continue to do what they know how to do, which is to adapt, we are going to do very well.

And in fact, the U.S. Government's fourth National Climate Assessment says very clearly that we can adapt to climate change through innovation and adaptation. They point to different seed types, crop rotations, cover crops, irrigation, managing heat stress, pest and disease management as the keys. If every nation raised its agricultural productivity to the level of its most successful farmers, global food yields would rise as much as 70 percent, and they could rise another 50 percent if nations increase the number of crops per year to their full potential.

I think that one of the most important things that the United States can do is to work with the World Bank and other institutions to help poor and developing nations to modernize agriculture for economic development, environmental and public health reasons. We saw with the coronavirus pandemic, assuming that the conventional explanation of the coronavirus pandemic is accurate, it was a spillover of a zoonotic virus, perhaps from a bat, and perhaps through a pangolin from low yield farming in south China. We need to modernize meat production, pull meat production away from forest frontiers. We need to help countries to do that. It is in all of our interests to modernize meat production agriculture, and there are good environmental reasons. You can see that because we have become so much more efficient globally, we have actually reduced the amount of land that we use for meat production, which is the single-largest use of the Earth's surface by humankind, by an area almost the size of Alaska. We know that the most efficient meat production in North America requires 20 times less land than the most efficient meat production in Africa. You can see there a scaled-up picture of that efficiency. We know that industrial meat production is far more efficient than pasture meat production, and

[4] **Editor's note:** the report referred to is retained in Committee file and is available at: *http://www.fao.org/3/I8429EN/i8429en.pdf.*

produces a fraction of the carbon emissions, just by concentrating that meat production. In Brazil, we could save an area twice the size of Portugal——

The CHAIRMAN. Thank you.

Mr. SHELLENBERGER.—and restore a rainforest without impeding agricultural expansion.

I will just close by saying carbon emissions in the United States have been going down for many years. We are on track to meet our climate agreements. Deaths for natural disasters have gone down. There was some talk of increased costs of extreme weather events. In fact, as a share of GDP, they have gone down significantly.

I would just say——

The CHAIRMAN. Thank you.

Mr. SHELLENBERGER.—to somebody that is concerned about climate change and other issues, we should just consider the fact that we are in the midst of a very serious drug overdose epidemic, which killed about 81,000 people last year in contrast to extreme weather, which only killed 413.

Thanks very much.

[The prepared statement of Mr. Shellenberger follows:]

PREPARED STATEMENT OF MICHAEL D. SHELLENBERGER, FOUNDER AND PRESIDENT, ENVIRONMENTAL PROGRESS, BERKELEY, CA

Good morning Chairman Scott, Ranking Member Thompson, and Members of the Committee. My name is Michael Shellenberger, and I am Founder and President of Environmental Progress, an independent and nonprofit research organization.[1] I am an invited expert reviewer of the next assessment report by the Intergovernmental Panel on Climate Change (IPCC), a *Time Magazine* "Hero of the Environment," and author of the 2020 book on the environment, *Apocalypse Never,* published by HarperCollins.

I will make four points in my testimony:

1. American farmers are world leaders in innovation, productivity, and environmental protection.
2. Technological change and agricultural modernization will significantly outweigh climate change in the U.S. and around the world.
3. Vegetarianism is not important for protecting the environment or reducing greenhouse gas emissions.
4. The U.S. should directly and through the World Bank and other institutions help poor and developing nations to modernize agriculture for economic development, environmental, and public health reasons.

I will draw upon the best-available science as well as upon my interviews with scientists to present the evidence supporting these three claims and recommendation.

I. The American farmer Is a World Leader in Innovation, Productivity, and Environmental Protection

Urbanization, industrialization, and energy consumption have been overwhelmingly positive for human beings as a whole. From preindustrial times to today, life expectancy extended from thirty to seventy-three years.[2] Infant mortality declined

[1] Environmental Progress is an independent nonprofit research organization funded by charitable philanthropies and individuals with no financial interest in our findings. We disclose our donors on our website: *http://environmentalprogress.org/mission*.

[2] James C. Riley, "Estimates of Regional and Global Life Expectancy, 1800–2001," *Population and Development Review* 31, no. 3 (2005), 537–543, accessed January 16, 2020, *www.jstor.org/stable/3401478;* "World Population Prospects 2019: Highlights," United Nations, accessed January 14, 2020, *https://www.un.org/development/desa/publications/world-population-prospects-2019-highlights.html*.

from 43 to 4 percent.[3] From 1981 to 2015, the population of humans living in extreme poverty plummeted from 44 percent to ten percent.[4]

Our prosperity is made possible by using energy and machines so fewer and fewer of us have to produce food, energy, and consumer products, and more and more of us can do work that requires greater use of our minds and that even offers meaning and purpose to our lives.

The declining number of workers required for food and energy production, thanks to the use of modern energy and machinery, increases productivity, grows the economy, and diversifies the workforce. Former farm workers who move to cities spend their money buying food, clothing, and other consumer products and services, resulting in a workforce and society that is wealthier and engaged in a greater variety of jobs.

The human population growth rate peaked in the early 1960s alongside rising life expectancy and declining infant mortality.[5] Total population will peak soon.[6] And thanks to rising agricultural productivity, the share of humans who are malnourished declined from 20 percent in 1990 to 11 percent today, about 820 million people.[7]

Farms and cities are thus deeply connected. Cities concentrate human populations and leave more of the countryside to wildlife. Cities cover just more than half a percent of the ice-free surface of the [E]arth.[8] Less than half a percent of Earth is covered by pavement or buildings.[9] At the same time, humankind's use of land for agriculture is likely near its peak and capable of declining soon.[10]

As wealthy nations develop and farms become more productive, grasslands, forests, and wildlife are returning. Globally, the rate of reforestation is catching up to a slowing rate of deforestation.[11] The key is producing more food on less land. While the amount of land used for agriculture has increased by eight percent since 1961, the amount of food produced has grown by an astonishing 300 percent.[12]

Though pastureland and cropland expanded 5 and 16 percent, between 1961 and 2017, the maximum extent of total agriculture land occurred in the 1990s, and declined significantly since then, led by a 4.5 percent drop in pasture land since 2000.[13] Between 2000 and 2017, the production of beef and cow's milk increased by

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[3] Max Roser, *et al.,* "Child & Infant Mortality," Our World in Data, 2019, accessed January 16, 2020, *https://ourworldindata.org/child-mortality*. The World series for 1800 to 1960 was calculated by Max Roser on the basis of the Gapminder estimates of child mortality and the Gapminder series on population by country. For each estimate in that period a population weighted global average was calculated. The 2017 child mortality rate was taken from the 2019 update of World Bank data.

[4] "PovcalNet: an online analysis tool for global poverty monitoring," The World Bank, accessed January 16, 2020, *http://iresearch.worldbank.org/PovcalNet/home.aspx*.

[5] Max Roser, Hannah Ritchie and Esteban Ortiz-Ospina, "World Population Growth," *Our World In Data,* May 2019, accessed January 16, 2020, *https://ourworldindata.org/world-population-growth*.

[6] Max Roser, Hannah Ritchie and Esteban Ortiz-Ospina, "World Population Growth," *Our World In Data,* May 2019, accessed January 16, 2020, *https://ourworldindata.org/world-population-growth*.

[7] For 1990 data: U.N. Food and Agriculture Organization, "Undernourishment around the world," *The State of Food Insecurity in the World,* 2006 (Rome: FAO, 2006), *http://www.fao.org/3/a0750e/a0750e02.pdf*.

For 2018 data: FAO, "Suite of Food Security Indicators," FAOSTAT, accessed January 28, 2020, *http://www.fao.org/faostat/en/#data/FS*.

[8] Xiaoping Liu, *et al.,* "High-resolution multi-temporal mapping of global urban land using Landsat images based on the Google Earth Engine Platform," *Remote Sensing of Environment* 209 (2018): 227–239, *https://doi.org/10.1016/j.rse.2018.02.055*.

[9] Christopher D. Elvidge, *et al.,* "Global distribution and density of constructed impervious surfaces," *Sensors* 7, no. 9 (2007): 1962–1979, *https://dx.doi.org/10.3390%2Fs7091962.*

[10] Niko Alexandratos and Jelle Bruinsma, "World agriculture towards 2030/2050: the 2012 revision," Agricultural Development Economics Division, Food and Agriculture Organization of the United Nations, June 2012, accessed January 16, 2020, *http://www.fao.org/3/a-ap106e.pdf*. The UN FAO projects that arable land and permanent crop area will stay nearly flat through 2050, as detailed from its report on the subject.

[11] FAO, "Data," FAOSTAT, accessed October 26, 2019, *http://www.fao.org/faostat/en/#data*. The FAO finds reforestation in Europe, Asia, North America, and the Caribbean. Central America, South America, Africa, and Oceania are still deforesting. The global rate of deforestation has been cut by over half since 1990, from 7.3 million to 3.3 million hectares per year as reforestation accelerated.

[12] Global FAO, "Data," FAOSTAT, accessed October 26, 2019, *http://www.fao.org/faostat/en/#data*. Per FAO, global per capita kilocalorie production was 2196 in 1961, and 2884 in 2013. Along with the population rise from 3.1 to 7.2 billion between 1961 and 2013, global food production has tripled. Global land for agriculture increased from 4.5 to 4.8 billion hectares over the same period

[13] Global FAO, "Data," FAOSTAT, accessed October 26, 2019, *http://www.fao.org/faostat/en/#data*.

19 and 38 percent, respectively, even as total land used globally for pasture shrank.[14]

The replacement of farm animals with machines massively reduced land required for food production. By moving from horses and mules to tractors and combine harvesters, the United States slashed the amount of land required to produce animal feed by an area the size of California. That land savings constituted an astonishing ¼ of total U.S. land used for agriculture.[15]

Today, hundreds of millions of horses, cattle, oxen, and other animals are still being used as draft animals for farming in Asia, Africa, and Latin America. Not having to grow food to feed them could free up significant amounts of land for endangered species, just as it did in Europe and North America.

Energy is required for all of this agricultural modernization. Thanks to fertilizers, irrigation, petroleum-powered tractors, and other farm machines, the power densities of farms rise ten-fold as they evolve from the labor-intensive techniques used by small farmers in poor nations to the energy-intensive practices used on California's rice farms.[16]

American farmers embraced the digital revolution starting in the 1990s. It was then that they started using GPS for auto-steering combines and other farm machinery, significantly reducing both overlaps and gaps in fields. Farmers mapped soils and used new equipment to apply chemicals at precise and variable rates specific to different soils. GPS also opened up precision agriculture, as it is called. Special equipment can space seeds precisely, while genetic engineering helps farmers guard against insects and weeds with fewer and less toxic chemicals.

Conventional agriculture is used on 99 percent of U.S. cropland and is responsible for significant environmental improvements to farming. The total amount of pesticides applied to U.S. crops declined 18% between 1980 and 2008 and is today 80 percent lower than their 1972 peak.[17] Total fertilizer use in the U.S. peaked in 1981 and hasn't risen since, despite an increase in total crop production of 44 percent, according to the Environmental Protection Agency.[18]

The use of water per unit of agricultural production has been declining as farmers have become more precise in irrigation methods. Irrigation water used per bushel of corn has declined by nearly half since 1980, while greenhouse gases declined 31 percent.[19]

High-yield farming is also better for soils. Eighty percent of all degraded soils are in poor and developing nations of Asia, Latin America, and Africa. The rate of soil loss is twice as high in developing nations as in developed ones. Thanks to the use of fertilizer, wealthy European nations and the United States have adopted soil conservation and no-till methods, which prevent erosion. In the United States, soil erosion declined 40 percent in just fifteen years, between 1982 and 1997, while yields rose.[20]

II. Technological Change and Agricultural Modernization Will Significantly Outweigh Climate Change in the U.S. and Around the World

In 2019 the Intergovernmental Panel on Climate change warned that warming of 1.5 °C above pre-industrial temperatures would cause "long-lasting or irreversible" harm. *The New York Times* reported that planetary warming threatens to worsen resource scarcity, and "floods, drought, storms and other types of extreme weather threaten to disrupt, and over time shrink, the global food supply."[21]

But there is little to no scientific basis for claims that climate change will reduce agricultural productivity globally. "It's difficult to see how we could accommodate eight billion people or maybe even half of that," said Swedish agronomist Johan

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[14] Global FAO, "Data," FAOSTAT, accessed October 26, 2019, *http://www.fao.org/faostat/en/#data*.

[15] USDA, *Changes in Farm Production and Efficiency: A Summary Report,* Statistical Bulletin 233 (Washington, D.C.: USDA, 1959), 12–13.

[16] Vaclav Smil, *Power Density* (Cambridge: The MIT Press, 2016), 168.

[17] Jorge Fernandez-Cornejo, *et al.,* "Pesticide Use Peaked in 1981," USDA Economic Research Service, June 2, 2014. *ers.usda.gov*.

[18] Environmental Protection Agency, "Report on the Environment," accessed February 18, 2021. *www.epa.gov*.

[19] Field to Market, "Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the U.S.," December 2016. *www.field tomarket.org*.

[20] USDA, "Changes in Erosion 1982–1997," United States Department of Agriculture, January 4, 2001, *https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs143_013911;* FAO, "Data," FAOSTAT, accessed January 27, 2020, *http://www.fao.org/faostat/en/#data*. FAO data on crop yields show almost every major crop increasing in yield in the United States between 1982 and 1997.

[21] Christopher Flavelle, "Climate Change Threatens the World's Food Supply, United Nations Warns," *New York Times,* August 8, 2019, *https://www.nytimes.com*.

Rockström of the Potsdam Institute in Germany, if temperatures rise four or more degrees above preindustrial levels.[22] But when I asked Rockström by telephone for the scientific studies supporting his claim, he said, "I must admit I have not seen a study."[23]

In fact, scientists have done that study—two are Rockström's colleagues at the Potsdam Institute—and they found that food production could increase even at 4° to 5 °C warming above preindustrial levels, and they found that technical improvements, such as fertilizer, irrigation, and mechanization, mattered more than climate change.[24]

Food production would only decline in the U.S. and North America if the American farmer stopped innovating and adapting, which is counter to the nature of farmers. IPCC finds that there would be net agricultural productivity declines "without adaptation" and that the productivity of agriculture in some parts of North America will improve with warmer temperatures. Some of the yield increases in recent decades came from rising temperatures in Canada and greater precipitation in the U.S. Where water is not a limiting factor, rising temperatures will increase productivity in North America, unless farmers stop innovating and adapting.[25]

There is very good reason to believe that American farmers will adapt well to climate change. "The North American agricultural industry has the adaptive capacity to offset projected yield declines and capitalize on opportunities under 2° warming," IPCC writes, including through genetically modified seeds. Many of these practices bring other economic and environmental benefits. Low- and no-till farming reduces soil erosion, allows for the retention of moisture, and reduces greenhouse gases.[26]

The U.S. Government's Fourth National Climate Assessment supports IPCC's findings. It similarly suggests that the risks of climate change to U.S. farmers will be mitigated by innovation and adaptation. Farmers can adapt by changing what they produce, altering productive inputs including seed type, and using new technologies. Farmers can alter crop rotations, use different cover crops, and deploy irrigation. Farmers can manage heat stress among life stock by changing breeds and diets, providing shade, and altering patterns of feeding and reproduction. The Assessment points to pest and disease management, climate forecasting tools, and crop insurance as proven effective ways to reduce risk and increase productivity and efficiency.[27]

Human beings around the world today produce 25 percent more food than we consume, and experts agree surpluses will continue to rise in a warmer world so long as poor nations gain access to fertilizer, irrigation, roads, and other key elements of modern agriculture.[28] The FAO projects that even farmers in the poorest regions today, like sub-Saharan Africa, may see 40 percent crop yield increases from technological improvements alone.[29] It concludes that food production will rise 30 percent

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[22] Gaia Vince, "The Heat is On Over the Climate Crisis. Only Radical Measures Will Work," *Guardian,* May 18, 2019, *https://www.theguardian.com.*

[23] Johan Rockström (director of the Potsdam Institute for Climate Impact Research) in discussion with the author, November 27, 2019.

[24] Hans van Meijl, *et al.,* "Comparing impacts of climate change and mitigation on global agriculture by 2050," *Environmental Research Letters* 13, no. 6 (2018), *https://iopscience.iop.org/article/10.1088/1748-9326/aabdc4/pdf.*

[25] Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1444, 1462.

[26] Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: *North America.* In: CLIMATE CHANGE 2014: IMPACTS, ADAPTATION, AND VULNERABILITY. PART B: REGIONAL ASPECTS. CONTRIBUTION OF WORKING GROUP II TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1463.

[27] US Global Change Research Program, U.S. Government, "Fourth National climate Assessment, Chapter 10: Agriculture and Rural Communities," 2017.

[28] United Nations Food and Agriculture Organization (FAO), *The future of food and agriculture—Alternative pathways to 2050* (Rome: Food and Agriculture Organization of the United Nations, 2018), 76–77.

[29] Food and Agricultural Association of the United Nations (FAO), *The future of food and agriculture—Alternative pathways to 2050* (Rome: United Nations, 2018), 76–77.

by 2050 except in a scenario it calls Sustainable Practices is adopted, in which case it would rise 20 percent.[30]

Roughly 40 percent of the planet has seen "greening"—more forest and other biomass growth—between 1981 and 2016. Some of this greening is due to a reversion of former agricultural lands to grasslands and forests, and some of it is due to deliberate tree planting, particularly in China.[31] This is even true in Brazil. While the world's attention has been focused on the Amazon, forests are returning in the southeast, which is the more economically developed part of Brazil. This is due to both rising agricultural productivity and environmental conservation.[32]

Part of the reason the planet is greening stems from greater carbon dioxide in the atmosphere, and greater planetary warming.[33] Scientists find that plants grow faster as a result of higher carbon dioxide concentrations. From 1981 to 2016, four times more carbon was captured by plants due to carbon-boosted growth than from biomass covering a larger surface of Earth.[34]

All else being equal, it would be best for global temperatures to remain stable. We should not want them to either rise or decline. The reason is because we have built our civilization based on current temperatures.

But all else isn't equal. The cause of climate change is rising energy consumption, and that energy consumption has been necessary for the 90 percent decline in natural disaster deaths, the 25 percent and rising global food surplus, and the 30 percent decline in the global burden of disease.

Some have suggested that climate change will make diseases like COVID–19 more frequent or more severe, but the main factors behind the novel-coronavirus pandemic had nothing to nothing to do with climate change and everything to do with the failure of the Chinese regime to protect public health.

Governments and farmers have known what "biosecurity" measures to take for decades, and enacted them, partly, in response to the 2005 avian flu (H5N1) epidemic. These measures include hardened facilities to prevent, for example, bats, from entering buildings; the regular testing of animals and workers; and disallowing live animals from being transported and sold at markets.[35]

Other scientists find similar outcomes. The UN Food and Agriculture concludes that food production will rise 30 percent by 2050 unless "sustainable practices" are adopted—in which case it would rise just 10 to 20 percent.[36] And a paper published in *Nature* in 2019 found that "agro-ecological" farming, which has long been promoted by European governments, U.S. NGOs, and the UN, does not improve the agricultural productivity of small African farmers.[37]

In the summer of 2020, politicians and the news media pointed to climate change as the cause of historic, high-intensity "megafires" in California and Oregon, but leading forest scientists said fire suppression and the accumulation of wood fuel, not climate change, were what made California's fires more intense.

"Climate dries the [wood] fuels out and extends the fire season from 4–6 months to nearly year-round but it's not the cause of the intensity of the fires," said U.S.

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[30] FAO, *The future of food and agriculture—Alternative pathways to 2050* (Rome: United Nations, 2018), accessed December 16, 2019, *http://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en*.

[31] Jing M. Chen, *et al.,* "Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink," *Nature Communications* 10, no. 4259 (October 2019): 1–7, *https://www.nature.com/articles/s41467-019-12257-8.pdf*.

[32] Alberto Barretto, *et al.,* "Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975–2006 period," *Global Change Biology* 19 (2013): 1804–15, *https://doi.org/10.1111/gcb.12174*. "The significant reduction in deforestation that has taken place in recent years, despite rising food commodity prices, indicates that policies put in place to curb conversion of native vegetation to agriculture land might be effective. This can improve the prospects for protecting native vegetation by investing in agricultural intensification."

[33] Jing M. Chen, *et al.,* "Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink," *Nature Communications* 10, no. 4259 (October 2019): 1–7, *https://www.nature.com/articles/s41467-019-12257-8.pdf*.

[34] Jing M. Chen, *et al.,* "Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink," *Nature Communications* 10, no. 4259 (October 2019): 1–7, *https://www.nature.com/articles/s41467-019-12257-8.pdf*.

[35] "Should We Domesticate Wild Animals to Prevent Disease Pandemics? An Interview with Peter Daszak," *Environmental Progress,* May 21, 2020.

[36] United Nations Food and Agriculture Organization (FAO), *The future of food and agriculture—Alternative pathways to 2050* (Rome: Food and Agriculture Organization of the United Nations, 2018), p. 76–77.

[37] Marc Corbeels, *et al.,* "Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa," July 16, 2020. For examples of efforts to promote agroecology see Shiny Varghese, "Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition," Institute for Agriculture and Trade Policy, June 26, 2019.

Forest Service scientist Malcolm North. "The cause of that is fire suppression and the existing debt of wood fuel." North estimates that there is five times more wood fuel in California's forests, on average, than before Europeans arrived.

A large, well-managed forest turned a high-intensity fire into a low-intensity one, proving that how forests are managed outweighs the higher temperatures and longer fire season caused by climate change. In 2013, after a high-intensity megafire known as the Rim Fire in the Stanislaus Forest reached Yosemite National Park, where prescriptive burning had occurred, it *became* [1] a surface fire. Similarly, the high-intensity Rough Fire of 2015 turned into a surface fire after it reached Sequoia National Park, whose managers had been using prescribed burns for decades.

The evidence for the efficacy of what foresters call "fuel treatment," through selective logging, prescribed burning, or both, can also be found on U.S. Forest Service lands. In 2014, areas where there had been selective logging and prescribed burning survived the high-intensity King megafire Eldorado National Forest. Similarly, the 2018 Carr fire burned through areas where there had been treatment of wood fuels over the last 3 decades. Even so, areas that had prescribed fire within the last 5 years, particularly the last 3 years, did better. Such cases are powerful evidence that selective logging and prescribed burning could allow many forests in California and elsewhere to survive climate change.

III. Vegetarianism Is Not an Important Factor for Protecting the Environment

In 2019, the Intergovernmental Panel on Climate Change (IPCC) published a special report on food and agriculture. "Scientists say that we must immediately change the way we manage land, produce food and eat less meat in order to halt the climate crisis," reported CNN.[38] Americans and Europeans need to reduce consumption of beef and pork by 40 percent and 22 percent, respectively, said experts, in order to feed ten billion people.[39] If everyone followed a vegan diet, which excludes not only meat but also eggs and dairy products, land-based emissions could be cut by 70 percent by 2050, said IPCC.[40]

But the headline number in the IPCC's 2019 report, a 70 percent reduction in emissions by 2050, referred only to agricultural emissions, which comprise a fraction of total greenhouse emissions.[41] As such, converting to vegetarianism might reduce *diet*-related personal energy use by 16 percent and greenhouse gas emissions by 20 percent, found a study, but *total* personal energy use by just two percent, and total greenhouse gas emissions by four percent.[42]

As such, were IPCC's "most extreme" scenario of global veganism to be realized—in which, by 2050, humans completely cease to consume animal products and all livestock land is reforested—total carbon emissions would decline by just ten percent.[43]

Another study found that if every American reduced her or his meat consumption by ¼, greenhouse emissions would be reduced by just one percent. If every American became vegetarian, U.S. emissions would drop by just five percent.[44]

Study after study comes to the same conclusion. One found that, for individuals in developed nations, going vegetarian would reduce emissions by just 4.3 percent,

[1] *https://fireecology.springeropen.com/articles/10.1186/s42408-019-0041-0*.

[38] Isabelle Gerretsen, "Change food production and stop abusing land, major climate report warns," *CNN*, August 8, 2019, *https://www.cnn.com*.

[39] Jen Christensen, "To help save the planet, cut back to a hamburger and a half per week," *CNN*, July 17, 2019, *https://www.cnn.com*.

[40] Cheikh Mbow, *et al.*, "Food Security," in Valerie Masson-Delmont, *et al.* (eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems,* IPCC, 2019, accessed January 21, 2020, *https://www.ipcc.ch/srccl*.

[41] Cheikh Mbow, *et al.*, "Food Security," in *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (IPCC, 2019), 487

[42] Janina Grabs, "The rebound effects of switching to vegetarianism. A microeconomic analysis of Swedish consumption behavior," *Ecological Economics* 116 (2015): 270–279, *https://doi.org/10.1016/j.ecolecon.2015.04.030*.

[43] Cheikh Mbow, *et al.*, "Food Security," in *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (IPCC, 2019), 487. In "business-as-usual", global greenhouse emissions will rise to 86 gigatons/year by 2050, and emissions from agriculture will rise to 11.6 gigatons/year. The "upper-bound" scenario of 100 percent veganism would reduce emissions by 8.1 gigatons/year from this baseline.

[44] Gidon Eshel, "Environmentally Optimal, Nutritionally Sound, Protein and Energy Conserving Plant Based Alternatives to U.S. Meat," *Nature: Scientific Reports* 9, no. 10345 (August 8, 2019), *https://doi.org/10.1038/s41598-019-46590-1*.

on average.[45] And yet another found that, if every American went vegan, emissions would decline by just 2.6 percent.[46]

Plant-based diets, researchers find, are cheaper than those that include meat. As a result, people often end up spending their money on things that use energy, like consumer products. This phenomenon is known as the rebound effect. If consumers respent their saved income on consumer goods, which require energy, the net energy savings would only be .07 percent, and the net carbon reduction just two percent.[47]

None of this means that people in rich nations can't be persuaded to change their diets. For example, since the 1970s, Americans and others in developed nations have been eating more chicken and less beef. The global output of chicken meat has grown fourteen-fold, from eight metric megatonnes to 109 metric megatonnes, between 1961 and 2017.[48]

The good news is that the total amount of land humankind uses to produce meat *peaked* in the year 2000. Since then, the land dedicated to livestock pasture around the world, according to the Food and Agriculture Organization of the U.N., has decreased by more than 540 million square miles, an area 80 percent as large as Alaska.[49]

All of this happened without a vegetarian revolution. Today, just two to four percent of Americans are vegetarian or vegan. About 80 percent of those who try to become vegetarian or vegan eventually abandon their diet, and more than half do so within the first year.[50]

Developed nations like the United States saw the amount of land they use for meat production peak in the 1960s. Developing nations, including India and Brazil, saw their use of land as pasture similarly peak and decline.[51] Part of this is due to the shift from beef to chicken. A gram of protein from beef requires two times the energy input in the form of feed as a gram from pork, and eight times a gram from chicken.[52] But mostly it is due to efficiency. Between 1925, when the United States started producing chicken indoors, and 2017, breeders cut feeding time by more than half while more than doubling the weight.[53]

Meat production roughly doubled in the United States since the early 1960s, and yet greenhouse gas emissions from livestock *declined* by 11 percent during the same period.[54] Producing a pound of beef in the U.S. today requires ⅓ less land, ⅕ less feed, and 30 percent fewer animals as the 1970s.[55]

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[45] Elinor Hallström, *et al.,* "Environmental impact of dietary change: a systematic review," *Journal of Cleaner Production* 91 (March 15, 2015), *https://doi.org/10.1016/j.jclepro.201y4.12.008*. The best estimate of emissions reductions of going vegetarian was 540kg, while average developed nation CO_2e (Annex I) is 12.44t CO_2e.

[46] Robin R. White and Mary Beth Hall, "Nutritional and greenhouse gas impacts of removing animals from U.S. agriculture," *Proceedings of the National Academy of Sciences* 114, no. 48 (2017), *https://doi.org/10.1073/pnas.1707322114*.

[47] Janina Grabs, "The rebound effects of switching to vegetarianism. A microeconomic analysis of Swedish consumption behavior," *Ecological Economics* 116 (2015): 270–279, *https://doi.org/10.1016/j.ecolecon.2015.04.030*.

[48] FAO, "Livestock Primary," FAOSTAT, *http://www.fao.org/faostat/en/#data/QL*.

[49] FAO, *World Livestock: Transforming the livestock sector through the Sustainable Development Goals* (Rome: FAO, 2018), Licence: CC BY–NC–SA 3.0 IGO, *http://www.fao.org/3/CA1201EN/ca1201en.pdf*.

[50] Charles Stahler, "How many people are vegan?" Vegetarian Resource Group, based on March 7–11, 2019 Harris poll, accessed December 31, 2019, *https://www.vrg.org/nutshell/Polls/2019_adults_veg.htm;* Kathryn Asher, *et al.,* "Study of Current and Former Vegetarians and Vegans: Initial Findings, December 2014," Humane Research Council and Harris International, accessed October 30, 2019, *https://faunalytics.org/wp-content/uploads/2015/06/Faunalytics_Current-Former-Vegetarians_Full-Report.pdf*.

[51] FAO, "Land Use," FAOSTAT, accessed January 27, 2020, *http://www.fao.org/faostat/en*.

[52] A. Shepon, *et al.,* "Energy and Protein Feed-to-Food Conversion Efficiencies in the U.S. and Potential Food Security Gains from Dietary Changes," *Environmental Research Letters* 11, no. 10 (2016): 105002, *https://doi.org/10.1088/1748-9326/11/10/105002*. Beef has a protein conversion efficiency of 2.5%, pork of 9%, and poultry of 21%.

[53] Vaclav Smil, *Should We Eat Meat? Evolution and Consequences of Modern Carnivory* (Oxford: John Wiley & Sons, Ltd., 2013), 92. When the U.S. started producing chickens indoors, in 1925, it took 112 days for one to reach maturity. By 1960 it took half as long and chickens gained ⅓ more weight. By 2017, chickens grown indoors only required just 48 days to reach maturity and they had more than doubled in weight since 1925.

[54] FAO, "Data," FAOSTAT, *http://www.fao.org/faostat/en/#data/RL*, cited in Frank Mitloehner, "Testimony before the Committee on Agriculture, Nutrition and Forestry U.S. Senate," May 21, 2019, accessed November 3, 2019, *https://www.agriculture.senate.gov/imo/media/doc/Testimony_Mitloehner_05.21.2019.pdf*.

[55] J.L. Capper, "The environmental impact of beef production in the United States: 1977 compared with 2007," *Journal of Animal Science,* December 1, 2011.

American cow milk production in the U.S. today requires 90 percent as much land and 79 percent fewer animals as it did in 1944.[56] Fewer animals means ⅔ less methane, a potent greenhouse gas, per glass of milk today as compared to 1950.[57]

Last fall I visited a milking operation owned by Matt Swanson near Turlock, California. I was amazed as I watched dozens of cows calmly eat and get milked as they slowly turned on a giant merry go-round. The machine was labor-saving, allowing for under a half dozen workers to oversee an operation with hundreds of milking cows.

IV. The U.S. Should Directly and Through the World Bank and Other Institutions Help Poor and Developing Nations To Modernize Agriculture for Economic Development, Environmental, and Public Health Reasons

The use of land as pasture for beef production is humankind's single largest use of Earth's surface. We use twice as much land for beef and dairy production as for our second largest use of Earth, which is growing crops. Nearly half of Earth's total agricultural land area is required for ruminant livestock, which includes cows, sheep, goats, and buffalo.[58]

During the last 300 years, an area of forests and grasslands almost as large as North America was converted into pasture, resulting in massive habitat loss and driving the significant declines in wild animal populations. Between 1961 and 2016, pastureland expanded by an area almost the size of Alaska.[59]

While people in developing countries increased their per capita meat consumption from 10 kilograms per year to 26 kilograms between 1964 to 1999, people in the Congo and other Sub-Saharan African nations experienced no change in per capita meat consumption.[60]

Activists argue that factory farms are far worse for the natural environment than free-range beef, but pasture beef requires *fourteen to nineteen times* more land per kilogram than industrial beef, according to a review of fifteen studies.[61] The same is true for other inputs, including water. Highly efficient industrial agriculture in rich nations requires less water per output than small farmer agriculture in poor ones.[62] Pasture beef generates 300 to 400 percent more carbon emissions per kilogram than industrial beef.[63]

This difference in emissions comes down to diet and lifespan. Cows raised at industrial farms are typically sent from pastures to feedlots at about 9 months old, and then they are sent to slaughter at fourteen to eighteen months. Grass-fed cattle spend their entire lives at pasture and aren't slaughtered until between eighteen to twenty-four months of age. Since grass-fed cows gain weight more slowly and live longer, they produce more manure and methane.[64]

In addition to their longer lifespans, the roughage-heavy diets typical of organic and pasture farm systems result in cows releasing more methane. These facts combined tell us that the global warming potential of cows fed concentrates is 4 to 28 percent lower for cows fed roughage.[65]

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[56] J.L. Capper, *et al,* "The environmental impact of dairy production: 1944 compared with 2007," *Journal of Animal Science,* June 2009.

[57] Frank Mitloehner, "Testimony before the committee on agriculture nutrition and forestry U.S. Senate," May 21, 2019.

[58] FAO, "Land Use" FAOSTAT, 2017, *http://www.fao.org/faostat/en/#data/RL*.

[59] FAO, "Land Use," FAOSTAT, accessed January 27, 2020, *http://www.fao.org/faostat/en*. To be exact, 1.42 million km^2.

[60] World Health Organization, "Availability and changes in consumption of meat products," accessed January 23, 2020, *https://www.who.int/nutrition/topics/3_foodconsumption/en/index4.html*.

[61] Durk Nijdam, Geertruida Rood and Henk Westhoek, "The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes," *Food Policy* 37 (2012): 760–770, *https://doi.org/10.1016/j.foodpol.2012.08.002*.

[62] David Gustafson, *et al.,* "Climate adaptation imperatives: Global sustainability trends and eco-efficiency metrics in four major crops—canola, cotton, maize, and soybeans," *International Journal of Agricultural Sustainability* 12 (2014): 146–163, *https://doi.org/10.1080/14735903.2013.846017*.

[63] Durk Nijdam, Geertruida Rood and Henk Westhoek, "The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes," *Food Policy* 37 (2012): 760–770, *https://doi.org/10.1016/j.foodpol.2012.08.002*.

"Production of 1 kg of extensively farmed beef results in roughly three to four times as many greenhouse gas emissions as the equivalent amount of intensively farmed beef."

[64] Lupo, C.D., Clay, D.E., Benning, J.L., & Stone, J.J. (2013). *Life-Cycle Assessment of the Beef Cattle Production System for the Northern Great Plains, USA.* JOURNAL OF ENVIRONMENT QUALITY, 42(5), 1386. doi:10.2134/jeq2013.03.0101

[65] M. de Vries, C.E. van Middelaar, and I.J.M. de Boer, "Comparing environmental impacts of beef production systems: A review of life cycle assessments," *Livestock Science* 178 (August 2015): 279–288, *https://doi.org/10.1016/j.livsci.2015.06.020*.

Attempting to move from factory farming to organic, free-range farming would require vastly more land, and thus destroy the habitat needed by endangered species. "You simply can't feed billions of people free-range eggs," a farmer told a journalist. "It's cheaper to produce an egg in a massive laying barn with caged hens. It's more efficient and that means it's more sustainable"[66]

Modernized agricultural techniques and inputs could increase rice, wheat, and corn yields five-fold in sub-Saharan Africa, India, and developing nations.[67] Experts say sub-Saharan African farms can increase yields by nearly 100 percent by 2050 simply through access to fertilizer, irrigation, and farm machinery.[68]

If every nation raised its agricultural productivity to the levels of its most successful farmers, global food yields would rise as much as 70 percent.[69] If every nation increased the number of crops per year to their full potential, food crop yields could rise another 50 percent.[70]

The most efficient meat production in North America requires twenty times less land than the most efficient meat production in Africa. Replacing wild animal meat with modern meats like chicken, pork, and beef would require less than one percent of the total land used globally for farming.[71]

The technical requirements for creating what experts call "the livestock revolution" are straightforward. Farmers need to improve breeding of animals, their diet, and the productivity of grasses for foraging. Increasing meat production must go hand-in-hand with increasing agricultural yields to improve and increase feed. In Northern Argentina, farmers were able to reduce the amount of land used for cattle ranching by 99.7 percent by replacing grass-fed beef with modern industrial production.[72]

The dominant form of climate policy in international bodies and among nations around the world emerged from 1960s-era environmental policies aimed at constraining food and energy supplies. These policies are correctly referred to as Malthusian in that they stem from the fears, first articulated by the British economist Thomas Malthus in 1798, that humans are at constant risk of running out of food.

Real world experience has repeatedly disproven Malthusianism. If it hadn't, there wouldn't be nearly eight billion of us. Worse, Malthusian ideas have been used to justify unethical policies that worsen socioeconomic inequality by making food and energy more expensive, including closing down nuclear plants.[73]

The same report which found that agricultural modernization outweighs climate change also found that climate policies were more likely to hurt food production and worsen rural poverty than climate change itself. The "climate policies" the authors refer to are ones that would make energy more expensive and result in more bio-

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[66] Jonathan Safran Foer, *Eating Animals* (New York: Little Brown, 2009), 95–96.

[67] A. Bala, "Nigeria," *Global Yield Gap and Water Productivity Atlas,* accessed January 16, 2020, *http://www.yieldgap.org/en/web/guest/nigeria;* Nikolai Beilharz, "New Zealand farmer sets new world record for wheat yield," *ABC News,* April 3, 2017, *https://www.abc.net.au;*

Matthew B. Espek, *et al.,* "Estimating yield potential in temperate high-yielding, direct-seeded U.S. rice production systems," *Field Crops Research* 193 (2016): 123–132, *https://doi.org/10.1016/j.fcr.2016.04.003*. While average yields for some crops like wheat have plateaued, there is still more room for them to increase. In 2017, a farmer in New Zealand produced an astonishing eight times more wheat than the Australian average, and five times more than the global average.

[68] FAO, *The future of food and agriculture—Alternative pathways to 2050* (Rome: Food and Agriculture Organization of the United Nations, 2018), 76–77.

[69] Nathaniel D. Mueller, *et al.,* "Closing yield gaps through nutrient and water management," *Nature* 490 (2012): 254–257, *https://doi.org/10.1038/nature11420*.

[70] Deepak K. Ray, "Increasing global crop harvest frequency: recent trends and future directions," *Environmental Research Letters* 8 (2013), *https://doi.org/10.1088/1748-9326/8/4/044041*.

[71] World average yield for chicken 14 m^2/kg, pork 17m^2/kg, and 43 m^2/kg for beef.

John E. Fa, Carlos A. Peres and Jessica J. Meeuwig, "Bushmeat Exploitation in Tropical Forests: an Intercontinental Comparison," *Conservation Biology* 16 (2002): 232–237, *https://doi.org/10.1046/j.1523-1739.2002.00275.x*.

5 million tons of bushmeat extracted in the Congo and Amazon basins.

Emiel V. Elferink and Sanderine Nonhebel, "Variations in land requirements for meat production," *Journal of Cleaner Production* 15, no. 18 (2007): 1778–1786. *https://doi.org/10.1016/j.jclepro.2006.04.003*.

[72] Ricardo Grau, Nestor Gasparri, and T. Mitchell Aide, "Balancing food production and nature conservation in the subtropical dry forests of NW Argentina," *Global Change Biology* 14, no. 5 (2008): 985–997, *https://doi.org/10.1111/j.1365-2486.2008.01554.x*.

[73] Michael Shellenberger, *Apocalypse Never: Why Environmental Alarmism Hurts Us All,* HarperCollins, 2020, p. 222–249.

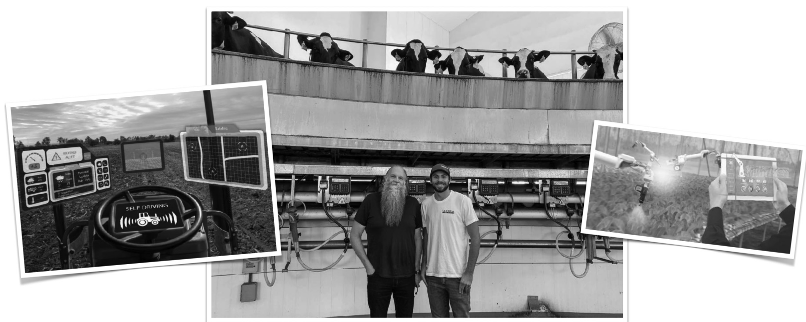
energy use (the burning of biofuels and biomass), which in turn would increase land scarcity and drive up food costs. The IPCC comes to the same conclusion.[74]

Policymakers should explicitly reject policies that significantly raise food and energy prices, directly or indirectly. Republicans and Democrats alike should affirm their commitment to human flourishing and prosperity, both of which depend on cheap food and energy, which depend on the rising productivity of inputs to agriculture and electricity generation, including labor, land, and capital.

But we should go beyond that and seek to help our brothers and sisters in poor nations to modernize agriculture, industrialize, and modernize their economies, for economic and environmental reasons. Such a partnership will be good for America and good for the planet.

Thank you for inviting my testimony.

ATTACHMENT

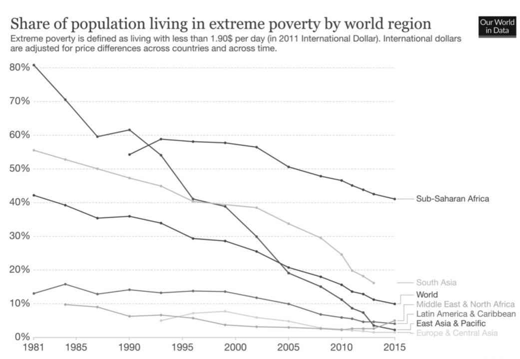


Good News About Farming & the Environment

Data to Accompany Testimony to the House Agriculture Committee

ENVIRONMENTAL PROGRESS

Michael Shellenberger :: February 25, 2021



From 1981 to 2015, the global population living in extreme poverty fell from **44% to 10%**

ENVIRONMENTAL PROGRESS

Source: Oxford University's Our World in Data

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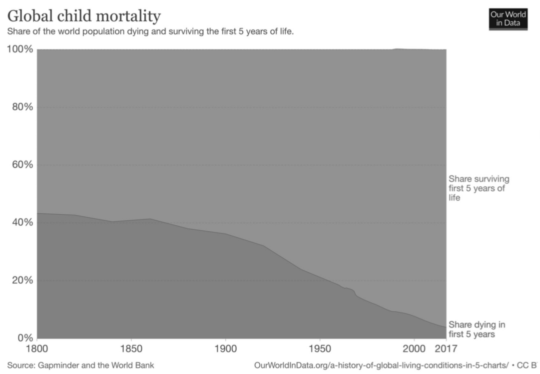
[74] "This occurs because . . . land-based mitigation leads to less land availability for food production, potentially lower food supply, and therefore food price increases." Cheikh Mbow, *et al.*, "Chapter Five: Food Security," in V. Masson-Delmotte, *et al.*, eds., *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (IPCC, 2019), *https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf*.

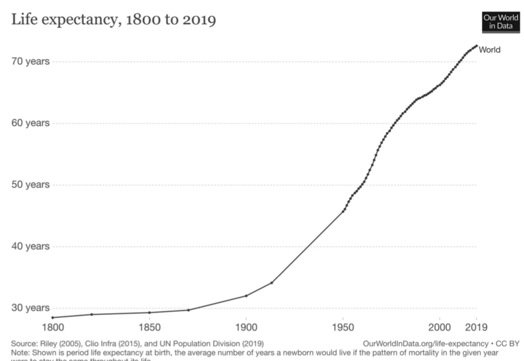


…and a decline in infant and child mortality from **43% to 4%**

ENVIRONMENTAL PROGRESS

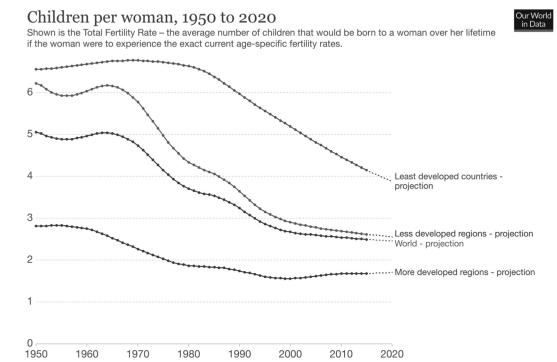
Source: Nikos Alexandratos and Jelle Bruinsma, "World Agriculture Towards 2030/2050: The 2012 Revision," ESA Working Paper no. 12-03, Agricultural Develop- ment Economics Division, Food and Agriculture Organization of the United Nations, June 2012, http://www.fao.org/3/a-ap106e.pdf.

Urbanization, industrialization, and energy consumption have contributed to an extension of life expectancy of **over 40 years…**



ENVIRONMENTAL PROGRESS

Source: Nikos Alexandratos and Jelle Bruinsma, "World Agriculture Towards 2030/2050: The 2012 Revision," ESA Working Paper no. 12-03, Agricultural Develop- ment Economics Division, Food and Agriculture Organization of the United Nations, June 2012, http://www.fao.org/3/a-ap106e.pdf.

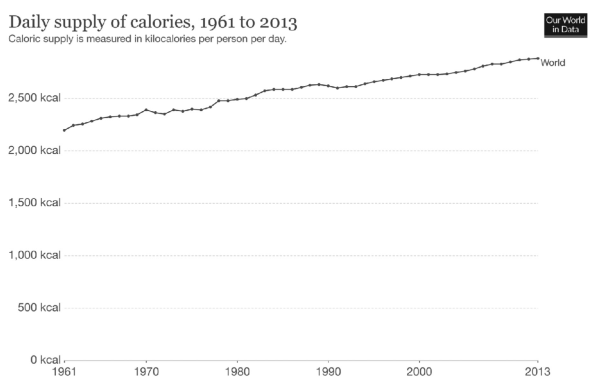


In 1994, the U.N. held its last Family Planning meeting

Between 1996 and 2006, United Nations family planning spending **declined by 50%**

ENVIRONMENTAL PROGRESS

Source: Robert J. Mayhew, *Malthus: The Life and Legacies of an Untimely Prophet;* Oxford University's Our World in Data



We already produce enough food for **10 billion** people, a **25% surplus**

ENVIRONMENTAL PROGRESS

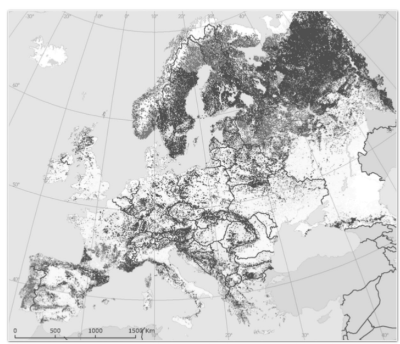
Source: OurWorldInData.org/food-supply; UN Food and Agriculture Organization (FAO)

"In Europe between 1990 and 2015, the area covered by forests and woodlands increased by **90,000 square kilometres** - an area roughly the size of Portugal."

ENVIRONMENTAL PROGRESS

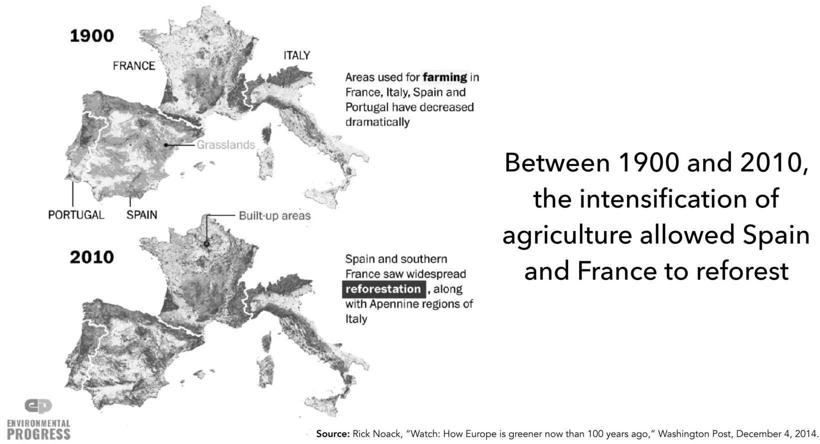
Source: Johnny Wood, "Europe's forests are booming. Here's why," local Commission on Adaptation," August 6, 2019. https://gca.org

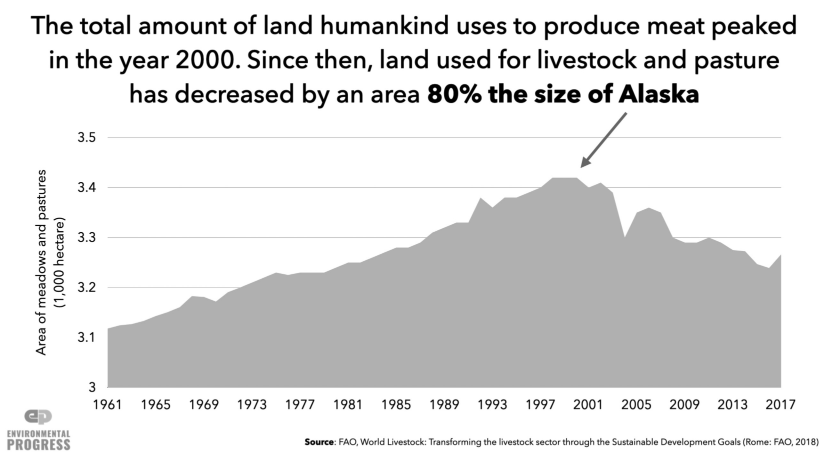
More than 40% of Europe is tree covered



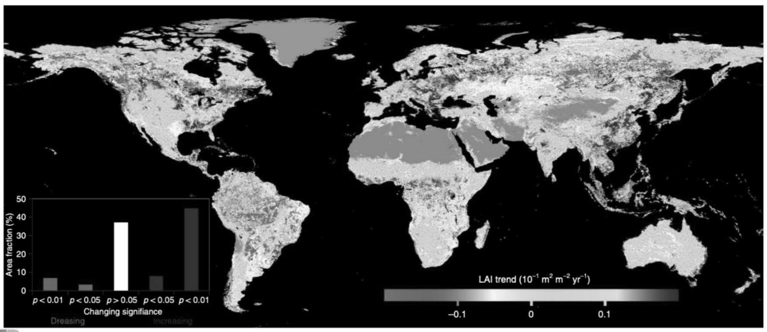
ENVIRONMENTAL PROGRESS

Source: Eurostat, "Over 40% of the EU is covered with forests" March 21, 2018, https://ec.europa.eu. Image from from European Environment Agency, https://www.eea.europa.eu/


1900
FRANCE
ITALY
Areas used for farming in France, Italy, Spain and Portugal have decreased dramatically
Grasslands
PORTUGAL
SPAIN
Built-up areas
2010
Spain and southern France saw widespread reforestation, along with Apennine regions of Italy
Between 1900 and 2010, the intensification of agriculture allowed Spain and France to reforest
ENVIRONMENTAL PROGRESS
Source: Rick Noack, "Watch: How Europe is greener now than 100 years ago," Washington Post, December 4, 2014.


The total amount of land humankind uses to produce meat peaked in the year 2000. Since then, land used for livestock and pasture has decreased by an area 80% the size of Alaska
Area of meadows and pastures (1,000 hectare)
3.5
3.4
3.3
3.2
3.1
3
1961 1965 1969 1973 1977 1981 1985 1989 1993 1997 2001 2005 2009 2013 2017
ENVIRONMENTAL PROGRESS
Source: FAO, World Livestock: Transforming the livestock sector through the Sustainable Development Goals (Rome: FAO, 2018)

Roughly 40 percent of the planet has seen "greening" between 1981 and 2016



ENVIRONMENTAL PROGRESS

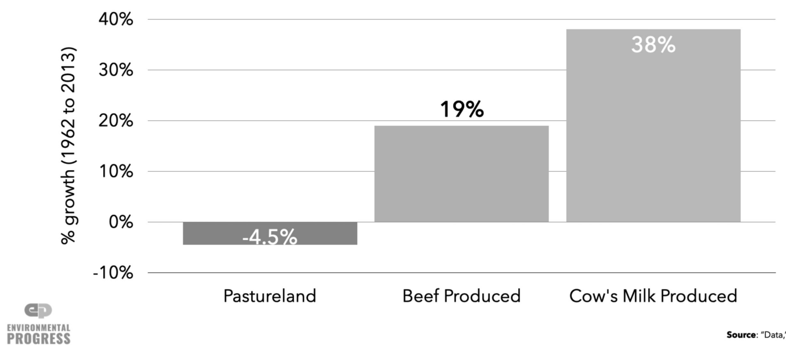
Source: Jing M. Chen, Weimin Ju, Philippe Ciais et al., "Vegetation Structural Change Since 1981 Significantly Enhanced the Terrestrial Carbon Sink," *Nature Communications* 10, no. 4259 (October 2019): 1–7, https://www.nature.com/articles/s41467-019-12257-8.pdf.

While land used for agriculture has increased by **8%** since 1962, the amount of food produced has grown by an astonishing **300%**

ENVIRONMENTAL PROGRESS

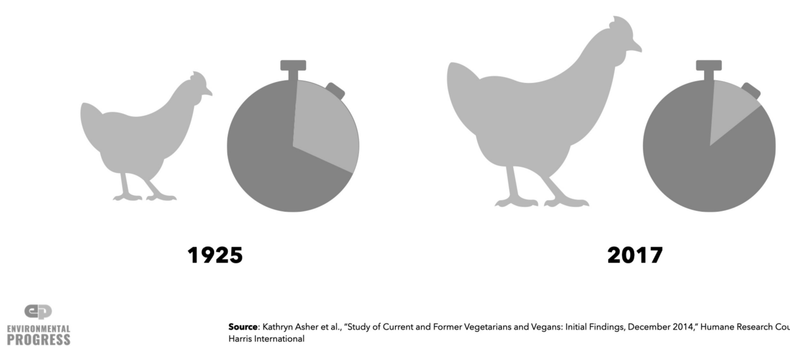
Source: Per FAO, global per capita kilocalorie production was 2,196 in 1961 and 2,884 in 2013. Along with the global population increase from 3.1 billion to 7.2 billion between 1961 and 2013, global food production has tripled. The amount of global land used for agriculture increased from 4.5 billion to 4.8 billion hectares over the same period. "Data," FAO.

Between 2000 and 2017, the production of beef and cow's milk increased even as total land used for pasture shrank



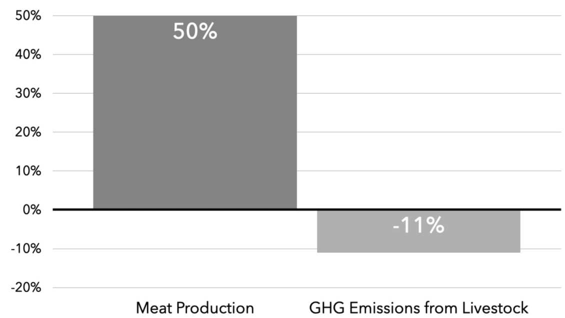
Source: "Data," FAO.

Between 1925 and 2017, U.S. breeders cut feeding time by **more than half** while **more than doubling** the weight



Source: Kathryn Asher et al., "Study of Current and Former Vegetarians and Vegans: Initial Findings, December 2014," Humane Research Council and Harris International

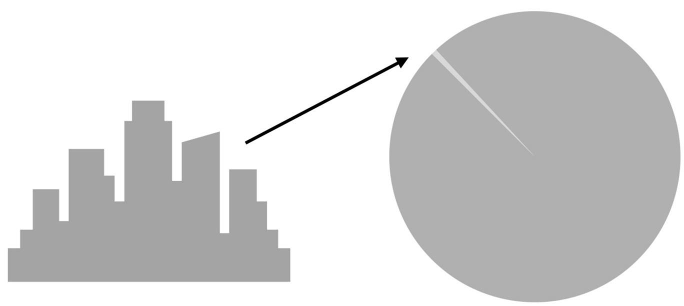
Meat production in the U.S. roughly **doubled** since the early 1960s, yet greenhouse gas emissions from livestock declined by **11%**



ENVIRONMENTAL PROGRESS

Source: FAO, cited in Frank Mitloehner, "Testimony before the Committee on Agriculture, Nutrition and Forestry US Senate"

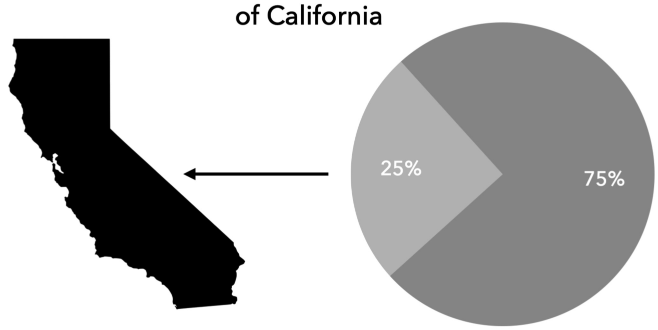
Cities cover **~0.6%** of the ice-free surface of the earth, even less of which is covered buildings and concrete



ENVIRONMENTAL PROGRESS

Source: Xiaoping Liu, Guohua Hu, Yimin Chen et al., "High-Resolution Multi-temporal Mapping of Global Urban Land Using Landsat Images Based on the Google Earth Engine Platform," *Remote Sensing of Environment* 209 (May 2018): 227–39, https://doi.org/10.1016/j.rse.2018.02.055; Christopher D. Elvidge, Benjamin T. Tuttle, Paul C. Sutton et al., "Global Distribution and Density of Constructed Impervious Surfaces," *Sensors* 7, no. 9 (2007): 1962-79, https://dx.doi.org/10.3390%2Fs7091962.

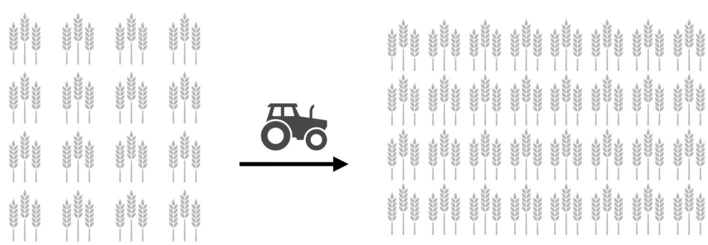
The replacement of farm animals by machines reduced the amount of land to produce animal feed by **25%**, an area the size of California



ENVIRONMENTAL PROGRESS

Source: *Changes in Farm Production and Efficiency: A Summary Report*, United States Department of Agriculture, Statistical Bulletin 233 (Washington, DC: USDA, 1959), 12–13.

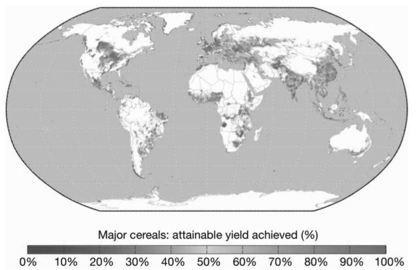
Experts say Sub-Saharan African farms can increase yields by nearly 100% by 2050 simply through access to irrigation, fertilizer, and farm machinery



ENVIRONMENTAL PROGRESS

Source: FAO, *The future of food and agriculture–Alternative pathways to 2050* (Rome: Food and Agriculture Organization of the United Nations, 2018), 76–77.

If every nation raised its agricultural productivity to the levels of its most successful farmers, global food yields would rise as much as **70%**



Yields could rise an additional **50%** if nations increased number of crops per year to their full potential

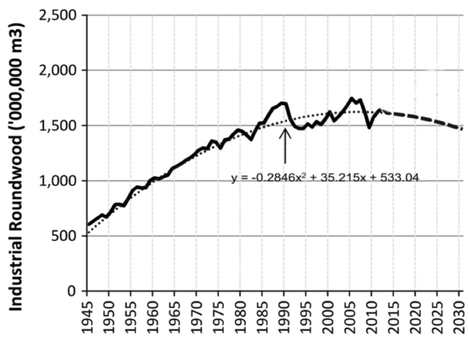
ENVIRONMENTAL PROGRESS

Source: Nathaniel D. Mueller, James S. Gerber, Matt Johnston et al., "Closing Yield Gaps Through Nutrient and Water Management," *Nature* 490 (2012): 254–57, https://doi.org/10.1038/nature11420; Deepak K. Ray, "Increasing Global Crop Harvest Frequency: Recent Trends and Future Directions," *Environmental Research Letters* 8 (2013), https://iopscience.iop.org/article/10.1088/1748-9326/8/4/044041/pdf.

The increasing productivity of farms is resulting in reforestation, which is catching up to declining rates of deforestation

ENVIRONMENTAL PROGRESS

Source: FAO and UNEP. 2020. The State of the World's Forests 2020. Forests, biodiversity and people. Rome. https://doi.org/10.4060/ca8642en

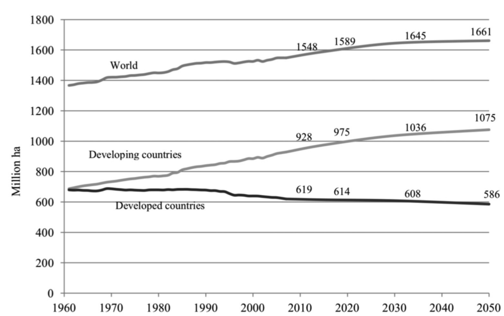


Humankind's use of wood has peaked and could soon decline significantly

ENVIRONMENTAL PROGRESS

Source: Russell Warman, "Global Wood Production from Natural Forests Has Peaked," *Biodiversity and Conservation* 23, no. 5 (2014): 1063-78, https://doi.org/10.1007/s10531-014-0633-6.

Humankind's use of land for agriculture is likely near its peak and capable of declining soon

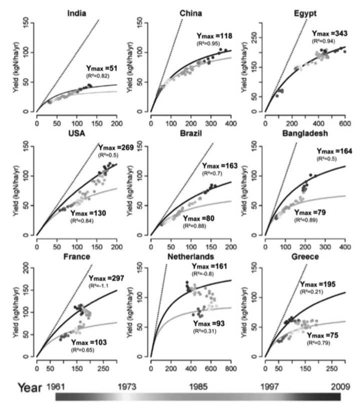


ENVIRONMENTAL PROGRESS

Source: Nikos Alexandratos and Jelle Bruinsma, "World Agriculture Towards 2030/2050: The 2012 Revision," ESA Working Paper no. 12-03, Agricultural Develop- ment Economics Division, Food and Agriculture Organization of the United Nations, June 2012, http://www.fao.org/3/a-ap106e.pdf.

Nations get better at using nitrogen fertilizer over time

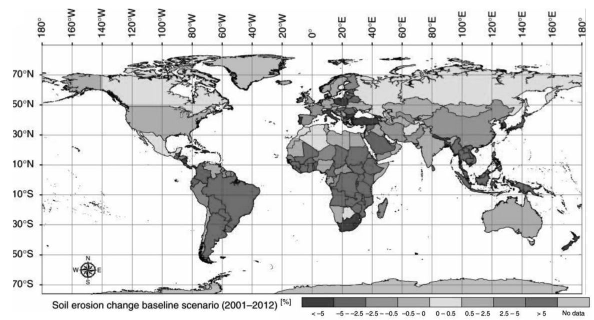
Since the early 1960's, the Netherlands has doubled its yields while using the same amount of fertilizer



ENVIRONMENTAL PROGRESS

Source: Nikos Alexandratos and Jelle Bruinsma, "World Agriculture Towards 2030/2050: The 2012 Revision," ESA Working Paper no. 12-03, Agricultural Develop- ment Economics Division, Food and Agriculture Organization of the United Nations, June 2012, http://www.fao.org/3/a-ap106e.pdf.

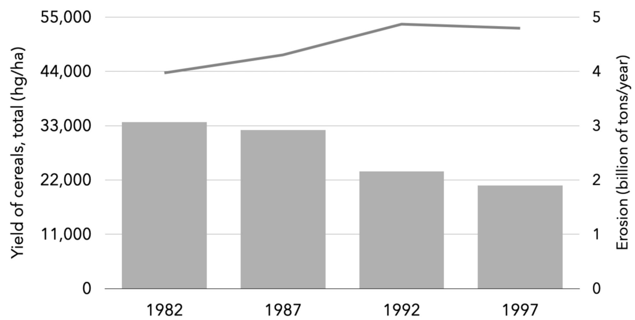
80% of all degraded soils are in developing and poor nations, which experience soil loss at **twice** the rate of developed nations



ENVIRONMENTAL PROGRESS

Source: Borrelli, Pasquale et al. "An assessment of the global impact of 21st century land use change on soil erosion." *Nature communications* vol. 8,1 2013. 8 Dec. 2017, doi:10.1038/s41467-017-02142-7

In the United States, soil erosion declined **40%** in just 15 years while yields rose



Source: "Changes in Erosion 1982–1997," U.S. Department of Agriculture, Janu- ary 4, 2001, https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref /?cid=nrcs143_013911. FAO data on crop yields show almost every major crop increasing in yield in the United States between 1982 and 1997. "Data," FAO.

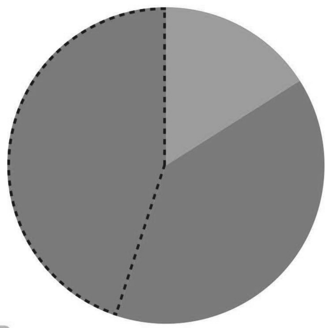
ENVIRONMENTAL PROGRESS

4% of Americans are vegetarian or vegan

Source: FAO, World Livestock: Transforming the livestock sector through the Sustainable Development Goals (Rome: FAO, 2018)

ENVIRONMENTAL PROGRESS

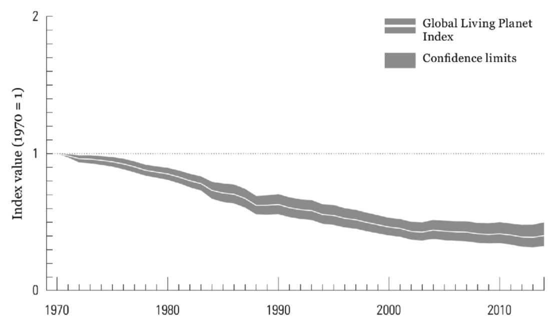
Over 80% of those who try a vegetarian or vegan diet abandon it, and more than **half** do so in the first year



ENVIRONMENTAL PROGRESS

Source: Kathryn Asher et al., "Study of Current and Former Vegetarians and Vegans: Initial Findings, December 2014," Humane Research Council and Harris International

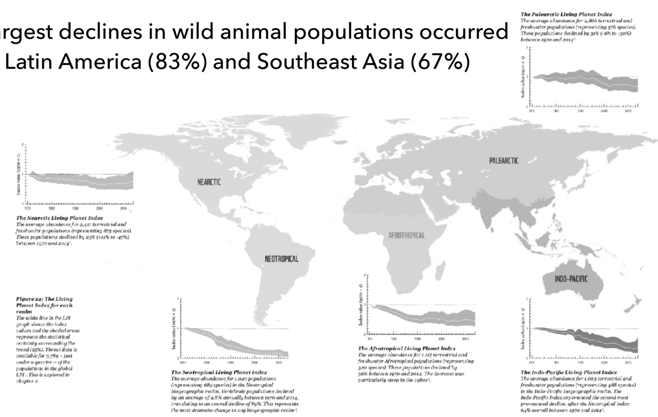
The population of wild mammal, bird, fish, reptile, and amphibian species declined by roughly half between 1970 and 2010



ENVIRONMENTAL PROGRESS

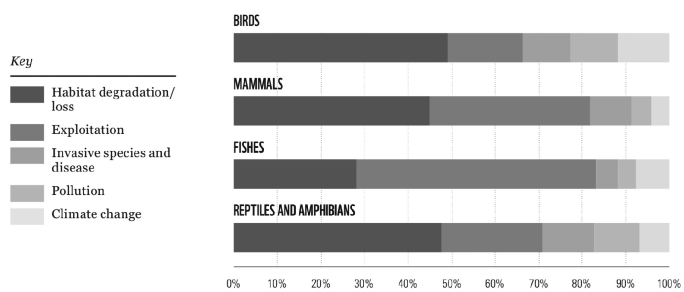
Source: "Living Planet Index," 2018, Zoological Society of London and WWF, www .livingplanetindex.org.

The largest declines in wild animal populations occurred in Latin America (83%) and Southeast Asia (67%)



Source: "Living Planet Index," 2018, Zoological Society of London and WWF, www .livingplanetindex.org.

Habitat loss and degradation and overexploitation remain the most significant drivers of biodiversity decline



Source: "Living Planet Index," 2018, Zoological Society of London and WWF, www .livingplanetindex.org.

Today, more than **1/4** of Earth's land surface is used for meat production

The spread of pasture for cattle and other domesticated animals continues to threaten many endangered species, such as the critically endangered mountain gorilla

ENVIRONMENTAL PROGRESS

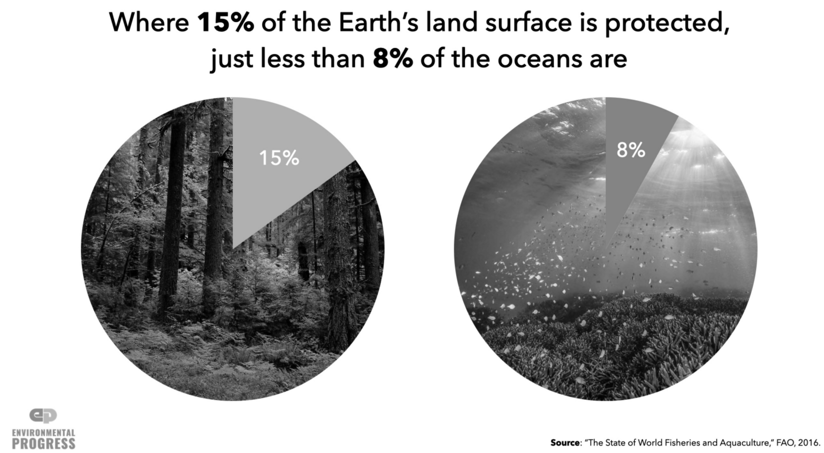
Source: Vaclav Smil, *Should We Eat Meat?*

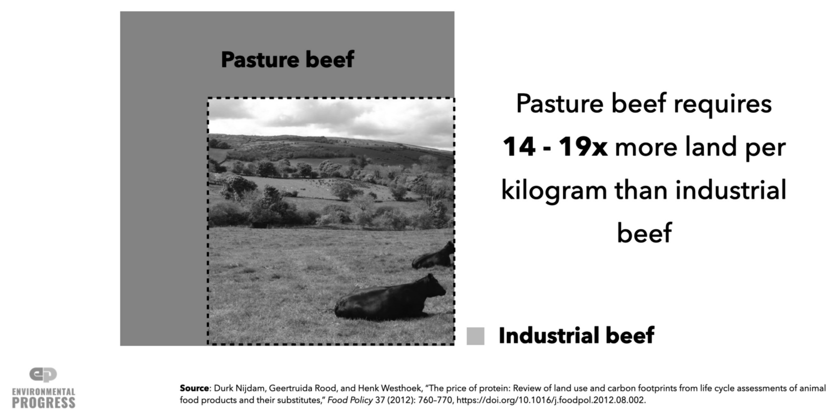
Over the last 300 years, an area of forests and grasslands almost the size of **North America** was converted into pasture

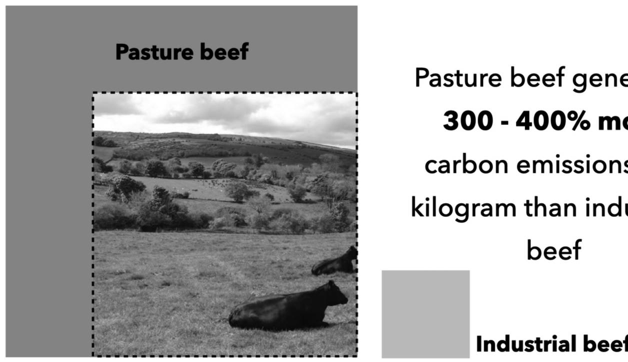
Between 1961 and 2016, pastureland expanded by an area almost the size of **Alaska**

ENVIRONMENTAL PROGRESS

Source: FAO, "Land Use"


Where **15%** of the Earth's land surface is protected,
just less than **8%** of the oceans are
15%
8%
ENVIRONMENTAL
PROGRESS
Source: "The State of World Fisheries and Aquaculture," FAO, 2016.


Pasture beef
Pasture beef requires **14 - 19x** more land per kilogram than industrial beef
Industrial beef
ENVIRONMENTAL
PROGRESS
Source: Durk Nijdam, Geertruida Rood, and Henk Westhoek, "The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes," *Food Policy* 37 (2012): 760–770, https://doi.org/10.1016/j.foodpol.2012.08.002.



Pasture beef generates **300 - 400% more** carbon emissions per kilogram than industrial beef

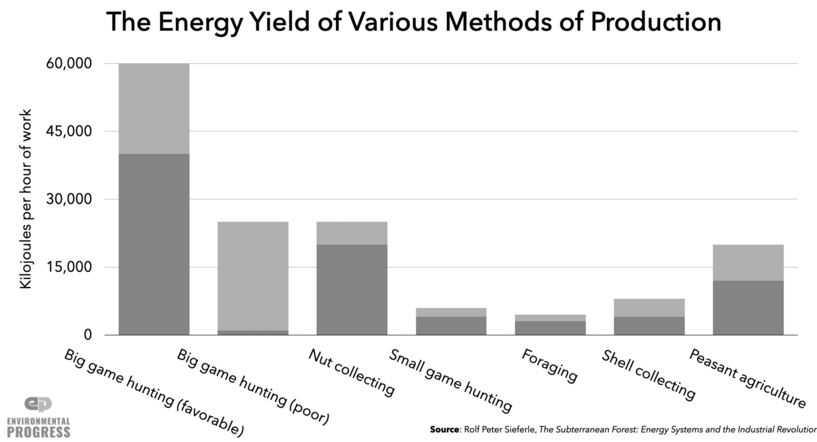
ENVIRONMENTAL PROGRESS

Source: Durk Nijdam, Geertruida Rood, and Henk Westhoek, "The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes," *Food Policy* 37 (2012): 760–770, https://doi.org/10.1016/j.foodpol.2012.08.002.

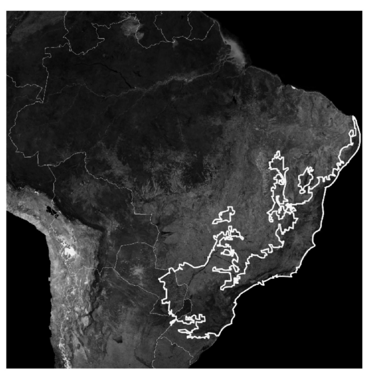
Since grass-fed cows gain weight more slowly and live longer, they produce more manure and methane

ENVIRONMENTAL PROGRESS

Source: C.D. Lupo, D. E. Clay, J. L. Benning, and J. J. Stone, "Life-Cycle Assessment of the Beef Cattle Production System for the Northern Great Plains, USA," *Journal of Environment Quality*, 42(5), 1386, doi:10.2134 /jeq2013.03.0101.



Source: Rolf Peter Sieferle, *The Subterranean Forest: Energy Systems and the Industrial Revolution*

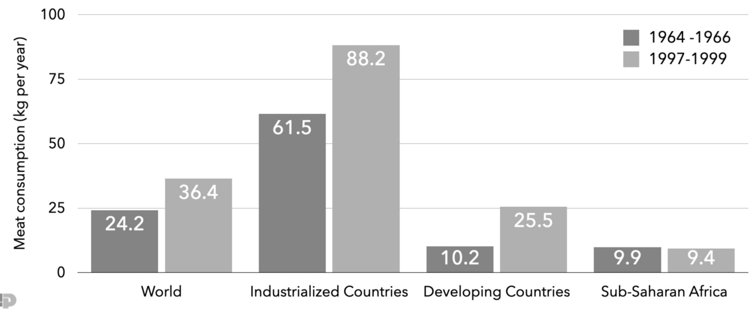


In Brazil, an area of land
twice the size of Portugal
could be restored to
rainforest without
impeding national
agricultural expansion

ENVIRONMENTAL PROGRESS

Source: Bernardo B. N. Strassburg, Agnieszka E. Lataweic, Luis G. Barioni et al., "When Enough Should Be Enough: Improving the Use of Current Agricul- tural Lands Could Meet Production Demands and Spare Natural Habitats in Brazil," *Global Environmental Change* 28 (September 2014): 84–97, https:// doi.org/10.1016/ j.gloenvcha.2014.06.001

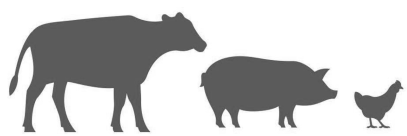
While people in developing countries consumed 2.5x the amount of meat per-capita in 1999 as 1964, people in the Congo and other Sub-Saharan African nations saw no such increase



ENVIRONMENTAL PROGRESS

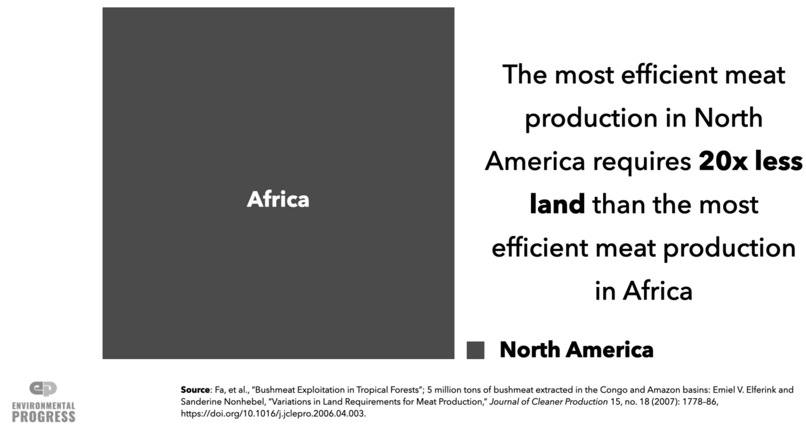
Source: World Health Organization, "Availability and changes in consumption of meat products"

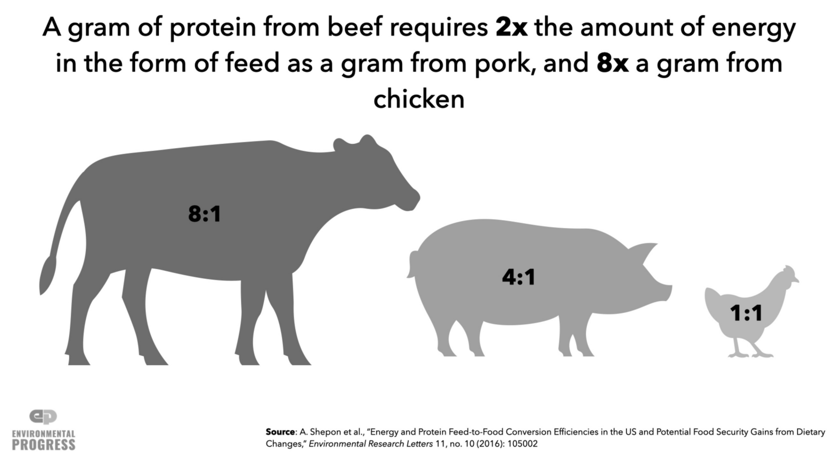
Replacing wild animal meat with modern meats like beef, pork, and chicken would require less than 1% of the total land used for farming globally (insert substitution effect)



ENVIRONMENTAL PROGRESS

Source: The world average yield for chicken is 14 m^2/kg, for pork 17 m^2/kg, and for beef 43 m^2/kg. Fa, et al., "Bushmeat Exploitation in Tropical Forests"; 5 million tons of bushmeat extracted in the Congo and Amazon basins: Emiel V. Elferink and Sanderine Nonhebel, "Variations in Land Requirements for Meat Production," *Journal of Cleaner Production* 15, no. 18 (2007): 1778–86, https://doi.org/10.1016/j.jclepro.2006.04.003.





The CHAIRMAN. Thank you. Thank you very much. Thank each of you very much.

And now, we are going to open it up for questions at this time, and Members will be recognized for questions in order of seniority, alternating between Majority and Minority Members. Each Member will be recognized for 5 minutes each, in order to allow us to get in as many questions as we can.

I want to start by just stressing the importance of we in agriculture—this hearing has been put together to address all of the impacts with climate change, but to make sure that we are addressing climate change directly as it impacts agriculture and our food security first.

And so, let me start with you, Mr. Brown. You were featured in the documentary, *Kiss the Ground,* and in that clip that we just saw, the narrator spoke of a simple solution for many of the climate changes we are experiencing, and that is what we are looking for today at this hearing: solutions. And what that announcer said was this, and I quote, "The solution is right under our feet."

Can you unpack that for us?

Mr. BROWN. I sure can. Thank you, Mr. Chairman.

The solution is under our feet. That solution is biology, and it is regenerative agriculture. The way this works is that living plants take in sunlight through photosynthesis. They bring in the carbon out of the atmosphere through photosynthesis. They produce all these compounds, and then they pump that into the soil.

Studies have shown, Dr. Teague in 2016 showed that we can sequester over ½ of the carbon emissions annually in the U.S. through regenerative agriculture, through using these six principles that I laid out. This is not rocket science. It is simply using time-tested ecological principles to heal our planet.

The CHAIRMAN. Now, let me ask you this, because I have been working very intimately with our farming interests, and there are two that come to mind. And I was wondering if this is an example of what you are talking about. One is with Bayer. Bayer has developed sequestration regeneration—and something called no-till farming, I believe. But at any rate, what they are doing is partnering with the farmers to get the solution that goes to your point, it is in the ground. It is there. Agriculture is agriculture for two reasons: the water coming from the heavens, and the carbon in the ground. Everything comes from that.

And so, I wanted your opinion on what Bayer is doing, and I found out yesterday that some of my friends in the peanut industry are doing something similar. So, my point is, is this the kind of thing that other interests in our farming sectors should be doing?

Mr. BROWN. Mr. Chairman, we all need to work together to further these practices of regenerative agriculture. No-till farming first came to the United States in 1962. We have only approximately 25 percent of the agricultural cropland today in no-till systems. No-till is a small piece of the puzzle, but we have to do much more than that. We have to keep the soil covered. We have to grow diverse cash crops, diverse cover crops, and then we have to integrate livestock onto those systems.

Yes, Bayer and other companies such as General Mills, are doing good things by partnering with farmers and ranchers. This needs to continue. It needs to be all of society coming together for the betterment of all.

The CHAIRMAN. Okay. I am going to end there, because I want to make sure we get our Members in, as many as we can.

I will yield to you, Ranking Member Thompson.

Mr. THOMPSON. Mr. Chairman, thank you. Thank you to all five witnesses. All five of you, just great testimony. It just reaffirms, very frankly, what you are talking about are the things that this Committee has been dedicated to.

I think at least 5 or 6 years ago, it was this Committee that had the first hearing on healthy soils in Washington. So, in terms of regenerative practices, it was just very reaffirming we have been doing the right things for a number of years with the Agriculture Committee.

Great to see my friend, Zippy Duvall.

Mr. Cantore, you probably don't remember, but you were in my district at the Weather Museum when you were honored in the Weather Hall of Fame in Punxsutawney, Pennsylvania. That is where we first met, and it is great to have you here with us today.

I am interested in working with solutions. The Biden Administration and the inside the Beltway think tanks are pushing a climate agenda, suggesting new and shiny programs. However, when I hear from the farmers about climate solutions—and that is what we should be focused on, is climate solutions. That should be the term that we use. They talk about the needs for research, more boots on the ground, access to precision agriculture, healthy soil practices, and the need for broadband connectivity to support this technology.

Now, this all sounds like assistance available within the farm bill programs that are there. Not to say that we can't improve upon them, but it is a great base for addressing really effective climate solutions, continuing those.

My question is simple. I will tee it up. I would love to get a response within the time I have from as many of you as possible. Is the solution as simple as doubling down on these proven programs? Why don't we start with Mr. Shellenberger?

Mr. SHELLENBERGER. Yes, thank you for the question.

Absolutely. I mean, we should continue to do what we have been doing. There has been a case made for expanded investment in research and development. Research and development works best when it is problem-focused, when it is trying to solve particular problems. We have terrific history through our agricultural extension programs of working with American farmers to improve yields.

So, yes, absolutely I think we should be continuing with what is working, rather than changing course into something really different, particularly you sometimes see proposals from the environmental community that would result in lower yields per unit of land, lower efficiencies. I think that would be a huge mistake. Anything that can get us to greater efficiencies and greater productivity is also going to be important for adapting to climate change.

Mr. THOMPSON. Thank you. Thank you, Mr. Shellenberger.

President Duvall, great to be with you yesterday, and good to see you virtually today.

Mr. DUVALL. It is good to see you, too. I appreciate the opportunity to be with you today.

The Committee has worked in the right direction. If you just look at how much we have improved productivity efficiencies, and even here on my farm here, I hear people talk about agriculture destroying the climate. You could look at my farm *versus* where my grandfather had it. I can show you evidence of gulleys in the forestland that is around my farm from bad conservation practices back then, and now over several, several decades, my dad's life and my life, we have improved it. It is all grassland. There are no gulleys anymore in the fields. We are sequestering carbon. We are making sure that we are putting animal manure with GPS. We are using comprehensive nutrient management plans. All those things were done through some of the programs at USDA. We are heading in the right direction. We just need partners to help us move forward.

I am concerned, if you look at the research dollars that we invest in our country *versus* the rest of the world, I am told that we are running behind on that. We need more research dollars so that we can have the new technologies and untie our hands. Give us a way to get the regulatory system streamlined so that these new products can get to the field faster, so that we can continue to be part of the solution to the problem.

Mr. THOMPSON. Thanks, Zippy.

Mr. Brown, congratulations on what you have been able to do on those 5,000 acres. I have also been on farms where I have seen the evidence of regenerative or healthy soil practices, and just right over the line, the comparison.

I have only got a few seconds left, but I will yield to you for any additional responses.

Mr. BROWN. Mr. Ranking Member, thank you, and yes, the agencies such as NRCS have done a good job, but we need to do much more in the way of education. We have to educate farmers and ranchers as to these time-tested ecological principles in order to move it forward.

It is an absolute travesty that right now, we have such a small amount of our landscape covered with cover crops. I fly extensively, and you fly anywhere, the amount of bare soil we see is absolutely appalling. There is no reason for that. We need to do more and work with these agencies to further education. Thank you.

Mr. THOMPSON. Thank you. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you.

I would like to take this opportunity to insert a statement from the National Association of State Departments of Agriculture, NASDA, for the record. NASDA's statement supports the expansion of Federal tools that incentivize climate smart practices.

[The statement is located on p. 326.]

The CHAIRMAN. And now, I would like to recognize Mr. Costa from California. You are recognized for 5 minutes. Is he not there? Mr. Costa, are you there? Are you on mute?

Mr. COSTA. I am unmuted now.

The CHAIRMAN. Wonderful.

Mr. COSTA. Can you hear me?

The CHAIRMAN. You are now recognized, Mr. Costa.

Mr. COSTA. Thank you. Thank you, Mr. Chairman. Congratulations on the first Committee hearing, and I look forward to working with you.

I think this is an excellent topic to begin, climate change and the agricultural economy in our country. America has led the way in so many areas, as many of our witnesses have just testified for.

I am reminded, as we discuss how we become even more productive and more creative, about a few facts. Some of us remember the old television series, *Dragnet,* and Sergeant Friday used to say, "Just the facts, ma'am." Right? Well, the facts are the following. Food is a national security issue, and less than five percent of America's population are directly involved in the production of food and fiber.

We have had an amazing change over the last 100 years. I am a third-generation farmer, but I don't farm the same way my parents did, nor my grandparents. And it continues to evolve with technology and innovation.

Another fact: 200 years ago, we had 1½ billion people on the plant. A few years ago, we just clicked over seven billion people on the planet in less than 200 years. Climate change has been occurring throughout the history of our planet. The real question is, how much are we contributing to it?

Well, I will tell you that in 200 years, we have gone from 1.5 to over seven billion people. We are putting a lot more stuff in the air, a lot more stuff in the water, and we are having an impact. As a matter of fact, in 2006, I went with the National Academies of Science—I don't know if you can see this—to the South Pole for a week. This is a little vial that calls itself the cleanest air on Earth, but it also shows using isotope measuring from 1955 to 2006 that the CO_2 emissions have increased by over 300 percent. Obviously, we are having an impact, and American agriculture can play an important role, as has been cited by the statistics that have already been put out there. Because it matters.

California, where I come from, where we have been farming for three generations in the San Joaquin Valley, is experiencing drought conditions again, on the heels of the worst drought that we had in the recorded history from 2012 to 2017. Our snow packs that we depend upon are becoming less plentiful, as well as the rainfall. Ninety-nine percent of California's agriculture, the number one agriculture state in the nation, is irrigated. We have an imbalance between overdrafting our groundwater.

But I firmly believe that with science and our productivity, we can address these issues. The ingenuity of America's farmers, ranchers, dairymen and -women have played a big part in increasing our production and the quality of our food. From healthy soils programs to state water efficiency enhancement programs, alternative manure management, and research and technical assistance that is occurring all around the country, not just in California.

And by the way, I am a big believer in not reinventing the wheel. Our ag universities across the country, whether it is Texas A&M, whether it is the University of Georgia, whether it is Purdue, whether it is UC Davis or Fresno State, where I come from. There is a lot of good stuff going on that we ought to combine in terms of research and development and innovation with public and private partnerships.

Let me just talk about sustainability and talk to you, Zippy, because you and I are both farmers, and you said it and I have said it. Farmers are stewards of the land. So, sustainability is a critical role.

Can you talk about—I think this infrastructure package and the efforts that the Administration wants to deal with climate change is an opportunity, and I think we should look at as an opportunity, not only with existing farm programs, but how we can provide incentives to do the right thing to increase our productiveness. You are leading a conservation program and a climate change effort. How do you think we can combine these efforts?

Mr. DUVALL. Well, I think that if you are talking about the leadership that we provided to create the Food and Agriculture Climate Alliance, we talk about those three principles that I mentioned in my testimony of making sure that they are supported—we support voluntary market incentive-based programs, like some that we have, and to find new ones through research. We want to advance the science-based outcomes——

The CHAIRMAN. Thank you.

Mr. DUVALL.—of it, and then, of course, all of us are very interested in the resilience in our rural communities and what we can do there.

But it all boils down to broadband, which is part of our infrastructure, and research and development.

Mr. COSTA. Mr. Chairman, I have run out of time, but I think it would be helpful if our witnesses, and Zippy, with your effort, if you can write to the Committee about the mission and development of your coalition, and share some of the policy principles that the coalition sees as a fundamental way in which we address climate change, and look at combining the efforts with this infrastructure package to plus up these incentive-based programs and farm programs that exist today, and new things we might look at.

Mr. DUVALL. Yes, sir, we can do that.

Mr. COSTA. Thank you.

The CHAIRMAN. Thanks to both of you there.

Now moving on, I will now recognize Mr. Austin Scott of Georgia. You are recognized for 5 minutes.

Mr. AUSTIN SCOTT of Georgia. Thank you to my good friend, Chairman Scott, and to Ranking Member Thompson.

I know that the title of the hearing is based on climate change, but when we talk about this, candidly, we are talking about environmental policy as a whole, and we are talking about habitat, we are talking about water. And the better we are at taking care of the land, the better the land will take care of us. I will tell you, I think we can and we should do a better job with the environment, and I look forward to being a part of that further discussion.

One of the things that I will tell you bothers me is that when I see forestlands being cut down and solar panels being put up, when clearly there is new technology today that will do a better job of providing carbon-free or extremely limited carbon emission electricity. I think that one of the things that we should look at is just the facts surrounding where the tax credits are going with regard to that aspect of environmental policy. I recognize that comes through a different committee, but again, I want us to be reminded that it is environmental policy as a whole that we have to focus on, and not just agriculture with regard to climate change.

The other thing I want to do is say a big thank you to Ms. Knox. When Hurricane Michael hit the State of Georgia, as you know, it was devastating to the 2nd and the 8th Districts. Had it not been for the University of Georgia and the other land-grant institutions, through their research and extension programs that provided the information to Chairman Scott and Chairman Bishop and myself, then we would have not been able to get the additional funds for the relief from Hurricane Michael for our producers. And so, a big thank you to Ms. Knox. I know you are doing a lot of great work down there on water conservation and other things in my hometown of Tipton, and where the National Environmentally Sound Production Agriculture Lab is. I would certainly invite all of my colleagues on the Agriculture Committee to make a trip down there to see all of the great work that is going on at NESPA.

Mr. Cantore, thank you so much for your coverage of Hurricane Michael, and what was happening to our farmers during that storm. The losses were astronomical, and it was your coverage that actually helped share our pain with the rest of America, and their sympathy and their prayers were much appreciated. I appreciate your coverage there.

With that said, Zippy, we have been friends a long time. We rewrote the WHIP program with Hurricane Michael. It didn't work as well as we had hoped it would. What suggestions do you have for how the Agriculture Committee can improve the WHIP program as we push forward?

Mr. DUVALL. Well, Congressman, we have been friends a long time, and I very much appreciate the friendship. Of course, every time we have a disaster, it looks like it is a scurry on the Hill to try to get the help out to the farmers. Unfortunately, even though the amount of money that was finally delivered to Georgia, it was 18 months, 2 years later, and a lot of our farmers had already suffered the deadly consequence of it and they lost their businesses and their farms, and weren't able to continue farming. So, we have to find some way to fast track, whether it be set aside special funding for it with certain restrictions around it, make sure it doesn't get misused. But it needs to be readily available when these disasters hit across our country.

Mr. AUSTIN SCOTT of Georgia. Mr. Duvall, I agree with you, and one of the concerns I have is that if money that is currently set aside for our ag producers, which candidly is a very small percentage of the budget, when it is the largest portion of the economy in most of the states. I don't want to see that money moved into environmental policy. And again, that is coming from someone who thinks that we can and should take better care of the environment. And so, the concept of moving the $30 billion to environmental policy bothers me. The concept of doing anything with the carbon bank without an increase in the CCC bothers me.

In my last few minutes, I want to say this. Mr. Brown, there is a lot of great work at Fort Valley State University with ruminants, and so, I hope you are benefitting from that. I do want you to know, respectfully, crop insurance is and it has to remain a risk management tool available for our farmers, and if a producer has a history of higher yields and lower losses, then they are rewarded with a higher average production history and increased amount of coverage at lower premiums. And so, if you have suggestions on how we improve it, I certainly am open to suggestions of it. But I will just tell you, production agriculture can't survive without some type of crop insurance program that rewards good farm practices. And so, that not only gets the environmental practices, but it gets the production practices as well. And so, I am open to suggestions on how to improve it. I thought we did a pretty good job in the 2018 Farm Bill to encourage people to adopt conservation measures, but I am not open to getting rid of the crop insurance program.

Mr. Chairman, my time has expired, I know, but I appreciate, again, everybody for their work on this, and again, Hurricane Michael taught all of us from Georgia and Florida big lessons on the value of insurance and the environment, and we can and we should do a better job.

With that, I yield back.

The CHAIRMAN. And I just want to recognize also those words that you said, and also take a moment to compliment you in helping provide the leadership for us after Michael. And you so eloquently stated that Georgia was slammed, and thank you, Austin, for pulling together. We went together, you, Mr. Sanford Bishop, and myself, got money down there. So, we want to thank you, and the young lady from the University of Georgia.

Now, I will recognize Mr. McGovern, the gentleman from Massachusetts, for 5 minutes. You may need to unmute. Oh, he is? Can we get one of our technicians? He's on? Good. All right. We will get working on it. Jim, they should get it cleared momentarily.

Mr. MCGOVERN. Can you hear me now?

The CHAIRMAN. Yes, I hear you a little.

Mr. MCGOVERN. Okay. All right.

The CHAIRMAN. I hear you.

Mr. MCGOVERN. All right.

The CHAIRMAN. Go ahead, Jim.

Mr. MCGOVERN. All right. First of all, let me just say thank you, Chairman Scott, for organizing this hearing. I think it is a long overdue conversation, and I want to take just a moment to underscore the sense of urgency that we should all be feeling.

We have an extremely narrow window to limit warming to 1.5 °C to avoid the most devastating impacts of climate change, full stop. That means we need to achieve net zero emissions across our entire economy, including agriculture, and it means we need to prepare our farmers for the impacts of even the best-case scenario of 1.5°. That level of warming will still be hugely consequential, and it is already happening.

Now, this might be news to some of my colleagues, but it is not news to farmers. Farmers are not the ones who got us into this mess, but now, they are on the frontlines of the climate crisis. We need to think big to help them build resilience into everything that they do, and we need to ensure that they have a seat at the table.

Now, Mr. Brown, I want to thank you for sharing your story of making ecological balance the heart of land stewardship. I think there are both economic and ecological benefits that can be achieved here, and I am reminded of the work that went into developing standards for organic producers, which was a collaborative process. Many organic producers live by the practice you mentioned, while adhering to strict program standards. When farmers transition to organic, they are taking a risk, but having standards means that they have a roadmap and a path to building consumer trust.

I want to make sure that we are providing real guidance and real support to farmers who are eager to follow your example. I think we need to have a roadmap that has integrity. So, could you please discuss what work lies ahead to develop standards for adopting regenerative techniques that will produce clarity to both farmers and consumers? Again, organic farming is good for the environment, and consumers have confidence in it because of the standards. I wonder if you could respond with your thoughts to that question.

Mr. BROWN. Thank you, Representative McGovern.

First, I need to just briefly jump back and address—there was a couple prior questions that were brought up that I did not get a chance to answer.

Representative Costa talked about the need to sustain what we are doing and to be sustainable. I am sorry, but I have spent a great deal of time in the Central Valley of California, and with all due respect, that is some of the most degraded land in the United States. Do any water infiltration test there, and you will see how degraded those soils are.

Representative Scott, I did not at all say we needed to end crop insurance. That is not what I said at all. I simply said that we need to make it outcome-based, and that outcome cannot be solely yield, because yield comes at a detriment to the environment. We also have to realize that in regenerative agricultures, we increase the amount of nutrient-dense food grown per acre. There is a misconception out there that regenerative practices mean less yield. That is not at all true. I produce now literally 30 times as much nutrient-dense food per acre than I did before I started these regenerative practices.

Now, Mr. McGovern, to answer your question. Yes, we do need standards. The business that I work for, Understanding Ag, we work with a lot of organic producers leading them down this path. Organic is good, but we can do better because we can minimize the amount of tillage that they are doing. We can also increase diversity, increase the use of cover crops, produce more nutrient-dense food, and then through Acts such as the PRIME Act, we will be able to add value to the goods that they are producing. Regenerative agriculture is a time-tested, proven pathway to heal not only our land in respect to climate change, but we can heal our communities, the profitability on our farms and ranches, water quality, water quantity issues, and many of the other things that we are currently facing as a challenge in society today.

Mr. MCGOVERN. Thank you. I appreciate your answer very much.

I think my time is up, but I just think it is important for all of us here to be focused on actually building a roadmap with standards, because otherwise, we are just talking the talk and we are not walking the walk. Again, I think the organic example is an example that we should follow.

But thank you very much. I yield back.

Mr. BROWN. And we do have that roadmap.

Mr. MCGOVERN. Thank you.

The CHAIRMAN. Thank you very much, Mr. McGovern.

And now, I recognize for 5 minutes Congressman Crawford from Arkansas.

Mr. CRAWFORD. Thank you, Mr. Chairman. I appreciate it.

Mr. Duvall, thanks for being here today. I wanted to visit with you a little bit about some of the things that you know about our district. We are the largest agriculture district in Arkansas, produce about ½ of the U.S. rice crop in my district. But, also a lot of production in other crops like cotton, soybeans, a big producer.

A lot of the climate dialogue related to agriculture is centered around carbon sequestration. I think it is important to recognize that the diversity of agriculture demands that there is not a one single solution approach that is appropriate for every crop or every cropping system, or every region. But there are some unique considerations to each of those areas and systems.

Rice farmers are some of the most sustainability-minded producers I think we have in the country, and they have employed considerable techniques to increase efficiency, reduce greenhouse gas emissions, and water use. And also, creating excellent wetland habitat, which are very biodiverse with numerous species of waterfowl, as you know. You have probably even harvested some of those yourself.

My question to you, though, Mr. Duvall, is that one of the great things about the farm bill conservation programs is that they are flexible enough to help any farmer that wants to address a natural resource concern that is important to their farm. Whether it is a rice farmer that wants to work on water management, or a rancher that wants to put up fencing, the program allows farmers to decide. And I worry about a carbon bank being accessible to everyone, and providing a level of flexibility. Do you share that concern?

Mr. DUVALL. I do share that concern, Congressman, and farmers are concerned that we start a carbon bank, and then some company in between the farmer and the people that are buying the carbon credits makes all the money. What we need is something that generates some additional income at the farm level so that we can continue to do conservation practices. We need partners, and of course, USDA is a great partner and has been for years and years and years, and we look forward to not just accelerating those programs to go from 30 to 40 percent of cover crop to, hopefully 100 percent one day, and kind of follow some of the principles that we heard Mr. Brown speak of.

But education is a key part, and he mentioned that, too. But we need partners, and the carbon credit bank and moving in that direction, we do have concerns in that area whether or not it will be available to everyone.

Mr. CRAWFORD. You mentioned partners, and I know you mentioned in your testimony that you are working with Food and Agriculture Climate Alliance, which has been very focused on cover crops and soil health, as you also mentioned, related to carbon sequestration. And as you know, and as I mentioned before, rice producers hold water in their fields in the off season that provides habitat for waterfowl. It also helps decompose rice straw from the previous growing season. So, in effect, ducks are our cover crop. It appears that the policies that FACA has identified to sequester carbon might only work for a couple of commodities. If the government provides an incentive that is coupled to one or two commodities, then we could see drastic shifts in plantings and markets. I am just asking if you can look into that and work with them and with us to make recommendations to make sure that we are able to avoid that, and we find a solution to work for all commodities.

Mr. DUVALL. I would agree with that, and we are very concerned that a lot of the practices that farmers have been doing for decades now have been sequestering carbon all that time won't get recognized if we move forward, too. The rice farmers, the pasture and cropland management we have already done, forestry, all those farmers have been sequestering carbon for years and years and years, and we need to recognize what they have done in the past, too.

Mr. CRAWFORD. I appreciate that. Thank you, Mr. Duvall, and Mr. Chairman, I will yield back.

The CHAIRMAN. Excuse me. I wasn't on.

Now, I recognize, for 5 minutes, Ms. Adams of North Carolina.

Ms. ADAMS. Thank you, Mr. Chairman, and to the Ranking Member as well for hosting today's hearing, and thank you to our witnesses for their testimony.

This is such an important topic. Climate change is a crisis, and we must treat it like one. It is already impacting our nation in deadly and destabilizing ways. And like this pandemic, its impacts are being felt disproportionately by the most vulnerable among us. Today's testimony has further enforced that the climate crisis is also threatening our farmers' ability to grow food in productive and environmentally sustainable ways, which could have detrimental impacts all the way up and down the food supply chain.

When talking about climate change and how it will impact the agriculture sector, I also want to make sure that we are strongly considering the role of our 1890 land-grant institutions and the role they can play. These institutions, such as North Carolina A&T State University, my alma mater, have incredible expertise in conducting agriculture research and providing extension services to farmers and ranchers, particularly socially disadvantaged producers. I was proud that our Committee included provisions within the American Rescue Plan Act that will support these institutions, their students, including resources for research and education and extension.

Professor Knox, I know that you are with the University of Georgia, but I assume that you work with research and extension professionals at other land-grant institutions. So, my question is, can you provide more detail on how you collaborate with other institutions, particularly with the professionals at 1890 institutions such as Fort Valley State University?

Ms. KNOX. Yes, Congresswoman Adams, I am happy to answer that. As you might not be too surprised to know, Fort Valley is the group that I work with the most, since I do a lot of my work with Georgia. We have had a number of research projects that have specifically included folks from Fort Valley as part of a consortium of researchers. Quite often those not only are in Georgia, but they also include other researchers from Florida and Alabama. And so, we draw not from just 1890s group, but also from other universities. But they serve a very crucial role in our research because they have an audience that we really need to reach. We need to take our scientific knowledge and make it useful to a variety of farmers, including a lot of the Black farmers and minority farmers that have very unique needs. A lot of them don't run really big farms. A lot of them are growing specific kinds of crops, and we need to be aware of those needs and really respond to them. And that is where the 1890s institutions really fall in, because they can help translate the science that is being done by the researchers to the farmers that are part of the community. And so, by doing that, they serve really a critical role.

Ms. ADAMS. Great, thank you, and you've answered part of my next question in terms of what role our institutions in supporting research and education and extension related to climate change, what is their role? And are there ways that we can further empower 1890 land-grants to support this ongoing work or to strengthen their collaboration with institutions like yours to expand opportunities?

Ms. KNOX. Yes, I think that there are always ways to include, say, multi-university consortiums to do more research, and I think there can be ways to say we really want to encourage the 1890s land-grant institutions to participate in that. And so, I know in the past some of the research groups I have been on have specifically asked for those kind of partnerships, and I would like to see that continue or maybe even expand so that we can really use that expertise from the 1890s universities.

Ms. ADAMS. Great, thank you.

Mr. Brown, you mentioned carbon markets and some of your priorities for the policy in your testimony. Currently, many private carbon market offerings have minimum acreage requirements, indicating that this solution will benefit large-scale operations at the expense of small, diversified operations, which I find concerning. The minimum acreage requirements could have serious implications for consolidation in the agriculture industry, making it even more difficult for middle- and small-scale farms to survive.

How important is it that all farmers be able to participate in carbon markets, and do you think that there are specific steps that Congress and USDA can advance to ensure that farmers of color and small, mid-size diversified and beginning farmers can participate in and be rewarded for implementing climate stewardship practices?

Mr. BROWN. Thank you, Representative Adams, and yes, that is certainly a major concern of mine as well.

It does not matter the size and scale of farms. They should be rewarded based on their practices and their outcomes. Small farms, in my opinion, have the ability to produce greater outcomes. They should be rewarded accordingly. I would urge that this Committee looks to ensure that these small farms have the ability to be rewarded for what they are actually doing, and that you make sure that any carbon market, the vast majority of the income that can be had from selling carbon credits goes back to the farmer themselves.

Ms. ADAMS. Thank you. I think I am out of time, so, Mr. Chairman, I will yield back.

The CHAIRMAN. Thank you so much. That was very informative. Thank you, Congresslady Adams.

And now, I will recognize, for 5 minutes, Congressman DesJarlais of Tennessee.

Mr. DESJARLAIS. Thank you, Mr. Chairman.

The CHAIRMAN. Five minutes.

Mr. DESJARLAIS. I thank all of our witnesses for appearing today. A special shoutout to Mr. Duvall from all the fine folks at Tennessee Farm Bureau. As you know, we have the largest farm bureau in the nation right in our district, and we are proud of the working relationship we have. So, I would like to get a question to you.

But my first question is going to go to Mr. Shellenberger. It is timely because tomorrow we will be voting on H.R. 803, Protecting American Wilderness Act, and western wildfires are burning almost year-round now due to poor forest management. I think we can prevent these disasters from breaking out in the first place by doing a better job. We have over 80 million acres of Forest Service land that is considered high risk for severe fires, and we have overgrown forests that are in desperate need of both management and hazardous fuel reductions.

Mr. Shellenberger, how do you view the current management of our nation's forests, and what should Forest Service and other land managers be doing better to encourage healthy forests?

Mr. SHELLENBERGER. Well, thank you very much for asking the question.

We saw a very dramatic instance last fall in California, which is where I am based, where we saw a high intensity fire that was burning through the crowns of forests that were badly managed. When that fire arrived at a well-managed forest, the fire dropped down to the ground and became a low intensity fire. What that shows is that while climate change may be influencing forest fires, it is neither a necessary nor sufficient cause of high intensity fires, and the good news is that with better forest management, whether it is through selective harvesting, prescribed burns, or other methods that we already know how to use, we can prevent those kinds of high intensity fires from impacting our forests in the future.

So, thank you for the question. Absolutely there is more we should be doing, and it needs to involve both the Federal Government and state governments, given that a significant amount of our forestlands are federally owned.

Mr. DESJARLAIS. Thank you. Contrary to popular belief, as a doctor and as Republicans, we do believe in science and when discussing climate policy, it is important to note that the U.S. leads the world in reducing carbon emissions, and within 10 years, nearly 90 percent of all emissions will come from outside the United States. But still in 2018, we on the Agriculture Committee put together one of the greenest farm bills ever, providing $6 billion a year to farmers, ranchers, and forest owners to implement soil health practices such as cover crops and no-till that can help draw down carbon and store it in the soil. These changes came after hundreds of hearings and listening sessions across the country where we heard directly from farmers.

So, before I get to Mr. Duvall with a question, I hope, Mr. Chairman, that you can commit to this Committee holding a number of listening sessions with farmers and ranchers before we pass any new climate legislation.

Mr. Duvall, can you talk about the importance of both having stakeholder involvement in the creation of any new programs, as well as any changes to current programs, and the need to ensure that these are voluntary and incentive-based programs for the farmers?

Mr. DUVALL. Well, the voluntary market-based incentive programs have been proven to work. Our farmers, if it is based on sound science and they know that it will improve their soils, improve their production to become more efficient, they will grab a hold of those new projects and move forward. Whether they are new or old ones, we need to make sure we continue to support them, and you are exactly right. You all supported them very well. We appreciate that. We just need to do something—Mr. Brown mentioned we need to do more education to the farmers of how they can use those programs. Our outreach as good as it should be, and it needs to be available to all sizes of farmers. We are all concerned that consolidation is going on. That is not what a general public wants. We want to be, there for the large farmer, but also make sure the small and middle-sized farmer is able to succeed and participate in all those programs.

To talk about having private investment, of course the private companies out there, especially the food companies are marketing their products in a certain environmentally sensitive way, and if they are going to do that, they should be able to put some of the money behind where their thoughts are and be able to help support some of these expensive things like manure digesters and other things that farmers are having to put on their land to be able to help move forward in controlling our climate.

Mr. DESJARLAIS. Thank you, Mr. Duvall.

As we all know and was mentioned, nobody cares more about the land and the Earth than our farmers and our agriculture community, so we are standing ready to make things as good as we can.

So, thank you all, and I yield back.

The CHAIRMAN. Thank you very much, Congressman DesJarlais. To answer your question, you can rest assured that this Chairman of this Agriculture Committee will make sure that our farmers are at the center of our movement out of whatever legislation, whatever appropriations—that is the whole purpose of this Committee is for us and agriculture to have the inside pole position when it comes to climate change. My good friend, Richard Petty, told me and gave me that great advice when I asked him how he won so many races. He told me, "Don't check the ones I have won. Look at the number of inside pole positions I have won." I didn't know what that meant at the time, but later I did.

Mr. DESJARLAIS. Thank you, Mr. Chairman.

The CHAIRMAN. Then I looked back in the mirror and I can see all the wrecks.

Our farmers will definitely—that is why we are having this hearing, to make sure our farmers, our agriculture industry, has the inside pole position on our whole response to climate change.

Now, I would like to recognize the distinguished lady from Virginia, my good friend, Ms. Spanberger.

Ms. SPANBERGER. Thank you.

The CHAIRMAN. Five minutes.

Ms. SPANBERGER. Thank you, Mr. Chairman, and thank you to our witnesses. I came to Congress with a background in national security, and I know that climate change presents a national security threat. It also presents a threat to our health, economy, and the future of our nation. But agriculture, the work and purview of this Committee, can be and is part of the solution in addressing climate change.

As you, sir, President Duvall, said in your testimony, U.S. farmers and ranchers have long been at the forefront of climate smart farming, and America's farmers and ranchers play a leading role in promoting soil health, conserving water, enhancing wildlife, efficiently using nutrients, and caring for their animals. I am so glad to see our Committee address climate change with the urgency that it requires, and I am glad that we have brought farmers to the table, though virtually only, today.

I am glad we brought farmers to the table in discussing the role of agriculture in combating climate change. At times, farmers have been left out of the national conversation on climate change. When as we have heard today, farmers, foresters, and ranchers can and in so many cases are a part of the solution. We have heard from President Duvall and our colleague, Mr. Costa, about how the practices they have employed on their own farms have changed from the practices their parents and grandparents used, and Mr. Brown has spoken today and widely about his choice to employ new methods to make his farm profitable and increase his soil carbon more than six-fold.

Back home in Virginia, I have heard similar stories from crop and livestock producers in my district about how farming and conservation practices they employ are benefitting the environment, building more sustainable operations, and benefitting their bottom line. As Chair of the Conservation and Forestry Subcommittee, I have listened to farmers, not just back home in my district, but here in this room before our Subcommittee. And as a result, I worked to introduce H.R. 7393, Growing Climate Solutions Act last Congress with our colleague, Representative Bacon of Nebraska, and this bill has been endorsed by national farmer organizations, as well as large environmental and conservation groups, while garnering the support of corporations like McDonald's, Bayer, and Microsoft. This legislation has built a broad coalition because it empowers farmers to voluntarily employ or continue employing climate-friendly conservation practices, and it would help farmers unlock new revenue streams.

Over the next month, I will be introducing a series of bills, including larger ones like (H.R. 2820) the Growing Climate Solutions Act, or simple, straightforward ones like H.R. 8057, Healthy Soil Resilient Farmers, and these bills would ensure that farmers are front and center in the conservation conversations that we are having, and that farmers have the tools to participate and benefit from voluntary programs as we all work together to tackle the climate crisis.

Now, I would like to direct my question to President Duvall with the time remaining.

Just yesterday, Mr. Duvall, you published a column in which you stressed the need to give farmers a voice at the table, particularly when it comes to changes in conservation programs. If the other Committee Members haven't read it, I recommend it to everyone.

So, Mr. Duvall, could you expand a bit more for Committee Members on how is it we can make sure that the voices of farmers are heard when it comes to addressing climate change, and how we can prevent some of the mistakes we may have made in the past? Thank you.

Mr. DUVALL. Well, Congresswoman, you have made the first step today in asking me to come here and sit on this panel, along with the other panelists that have done such a tremendous job and have my respect.

We need to be at the table during the discussions so that we can tell you how those policies that you are considering, how it is going to affect us on our land? How is it going to affect small, medium, and large farms? And as we do that, we can tell you what will work and what will not work. You also can help us make sure that the research dollars are there, find the new technology that needs it. Let's make sure that we don't tie our hands with the current technologies we have, because those technologies have allowed us to make the progress that we have made. And just like you said, as long as they are voluntary, they are market-based, and they are incentive-based, our farmers will latch on to it and do a good job with it.

So, I think you are making the right steps. Just please, let us keep our seat at the table and we will make sure that you have all the information from the countryside, from our farmers, to make sure that you can make wise decisions that make not only farming successful, but also makes our rural communities resilient.

Ms. SPANBERGER. Thank you very much, President Duvall, and to the other witnesses today, thank you so much for participating. Thank you for bringing your knowledge, and thank you for joining us. I hope that we will be able to welcome you here in person at some point in the future.

Mr. Chairman, thank you for this hearing. I yield back.

The CHAIRMAN. Thank you, Ms. Spanberger. I have to remember to put my light on there.

Now, I will recognize, for 5 minutes, Mrs. Hartzler from Missouri. Oh, she's not on? Then we will go to Mrs. Hayes of Connecticut. You are recognized for 5 minutes.

Mrs. HAYES. Thank you, Mr. Chairman, for holding this hearing, and thank you to all the witnesses who are here today. Can you hear me?

The CHAIRMAN. Go ahead, Mrs. Hayes. You are recognized for 5 minutes.

Mrs. HAYES. Okay. Climate change is an important threat to Connecticut. From June 2016 through May 2017, Connecticut experienced its longest drought since 2000. At one point, more than 70 percent of the state was considered in extreme or severe drought. Simultaneously, the average temperature in Connecticut is continually rising. Since 1970, Connecticut has warmed by 8°, compared with the national average increase of 2.5 °F. To compound these issues, more frequent extreme weather is already costing Connecticut huge amounts of money. Between 2017 and 2019, Connecticut experienced two severe storms and two winter storms. The damages led to losses of at least $1 billion. Small farmers in Connecticut are leading the charge in sustainable agricultural practices, but we cannot leave the health of the planet up to individual decisions.

As the Members of this Agriculture Committee, it is our responsibility to ensure that the industry is providing clear solutions to address climate issues.

My question today is for Mr. Brown. A report from the USDA recognized increased food insecurity as a risk posed by climate change. As a farmer who is practicing and teaching resiliency, can you explain how climate change could impact levels of food production, and ultimately increase global food insecurity if we do not act?

Mr. BROWN. Thank you.

The way for Congress and ranchers to not only mitigate climate change by taking more carbon out of the atmosphere and putting it into the soil is to make our soils more resilient.

In 2020, Burleigh County, North Dakota, where I ranch, was the second driest year ever recorded. Yet, even though that happened, we were still able to graze the same amount of livestock. We were still able to raise profitable cash crops because of the resiliency we had built into our soils, by taking massive amounts of carbon out of the atmosphere and putting it into our soils.

The other thing that many of us who are practicing regenerative agriculture are doing, is that we are diversifying our farms and ranches. So many of our farms and ranches today are not diversified. They only grow one or two different cash crops. They only grow or raise one species of livestock. We need to diversify that, and by so doing, that is going to allow society to have the food security we need.

Mrs. HAYES. Thank you. You are right. Clearly, it is essential that we preserve the resiliency of our agriculture sector if we have any hope of eliminating hunger in America, which we have seen literally in the last year grow to be blown to a much larger problem.

Mr. Duvall, we all know that heat stress will likely cause the overhead costs of dairy farms to go up, while driving their production down. Many small farmers in my district, dairy farmers, already turn limited profits under this current situation. Can you provide some steps that Congress and the USDA can take to help small dairy farms as they prepare for climate change?

Mr. DUVALL. Well, of course, I think we have taken some huge steps already through Congress to help in the farm bill fix some of the problems we had around the risk management tools that we had built in there for the dairy farmers, and there has also been some private products that have been offered to them.

But, we need to take a hard look at the Federal Milk Marketing Order system. We need to make sure that our farmers have an opportunity to speak to changes that are made in the Federal Milk Marketing Order system, and that each one of them have the opportunity to speak to that. So, we are, right now, continuing to do a study of our own, and we will be glad to share with you the results of that study as we finish it out on how we move forward and make it more profitable.

We continue to see small dairies go out of business and more consolidation in dairy getting bigger.

Now, this country—really, American agriculture was built on the back of small dairies all over this country when we were all real diversified, and it really is a shame to see these small dairies not survive anymore. We have to find a way that small, medium, and large dairies can survive in this environment, and to help them be financially stable enough to be able to take on the practices that, in some cases, are going to cost a lot of money to help us end climate change.

Mrs. HAYES. Thank you, Mr. Duvall. I truly appreciate you saying that, because in my district in my State of Connecticut, small dairy farmers are really the backbone of our farming and agricultural industry, so I really appreciate you saying that, and for coming to this hearing because we cannot continue to have these circular conversations debating if climate change is real or if it is happening or what the impact is. We have measurable data that tells us all this information, and now we have a responsibility to act.

Thank you, Mr. Chairman. With that, I yield back.

The CHAIRMAN. Well, thank you, and also thank you, Mrs. Hayes, for the excellent job you are doing as the Chairwoman of our Subcommittee on Nutrition, Oversight, and Department Operations.

And now, let me give an apology there. I got my paperwork mixed up and recognized two Democrats. Now, thank you for allowing me to represent and to recognize two Republicans. Thank you for your understanding.

Next, we will have Mr. LaMalfa from California.

Mr. LAMALFA. Thank you.

The CHAIRMAN. Five minutes, sir.

Mr. LAMALFA. Thank you, sir.

Mr. Duvall, real quickly I wanted to touch on the concept with the carbon banks and the USDA, maybe through CCC, being a possible authority of establishing carbon banking. Has AFBF looked into whether the USDA can do this on its own authority, or would the Farm Bureau be joined with us in opposing any attempt to have that just be done by Executive actions, as opposed to running it through a Congressional process so this can be vetted, and that there are not winners and losers on how the carbon banks would work? Has Farm Bureau looked at that? What do you believe the position should be on that?

Mr. DUVALL. Yes, I haven't asked my staff if we were looking into the legality of it. I will tell you that we are concerned that if it is developed and financed through the CCC that the levels of CCC borrowing authority is not nearly high enough. We support raising that level to $68 billion. We think because of the economy and the increases over the years that it should be at that level instead of $30 billion. I have spoken to Secretary Vilsack about that certain issue, and he committed to me that he would not pay for it off the back of our title I program or our conservation programs, so I was delighted to hear that.

But, we are interested in seeing, this is the place. Agriculture is the place. This is the Committee where we see the most cooperation between both sides of the aisle. You all always find a way to find ways to work together, and I hope that in this environment we can continue to do that, and I think I see that in the leadership of this Committee. And I would love to see the conversation through this Committee decide how that is going to be paid for and where it is going to come from. If we are going to put in modern day agriculture, we have to have modern day practices. It requires research dollars. It requires extension and education. It requires funding for new programs that we put out there if it has to do with climate. The funding has to follow those programs so that our farmers and ranchers can afford to do that.

Mr. LAMALFA. Yes, sir, I hear you.

Yes, I just don't want to see an authoritarian attitude come out of this, because it looks just a little bit ominous. What hasn't been talked about very much is an already difficult situation with ag profitability, and where are they going to find the profitability?

We have the concept of diversification. Well, certain climates, certain soil types, certain water availabilities just don't lend themselves to change crops, and I experienced that in northern California. We have some of the best crops grown in Central California if they have the water supply not taken from them. That is the only place that many of these crops are grown anywhere in the world—or in our country, at least. We would have to import is part of the problem.

Mr. Shellenberger, I appreciated your testimony and your way of talking about things in this conversation, as well as recognizing farmers are doing a pretty good job in this country in innovation and trying to keep up.

We are hearing a lot of talk about the crisis of climate change, and what is your interpretation of where we are at, especially with how what agriculture might be driving in or helping with in this crisis as it keeps being presented *ad nauseum,* in my view, around here. Please bring that in on forestry, because my area is a part of the area that is burning so much. I believe strongly that it is from an overload of fuel in our western forests.

Mr. SHELLENBERGER. Yes, thank you for the question.

I will make a couple of comments. I mean, I think the first is that I think it is a mistake to use climate as the single overriding measure of success with farming or anything else. I mean, we see that carbon emissions have been coming down in the same way that other air pollutants came down in the 1970s. It is actually quite extraordinary progress in the United States mostly due to the transition from coal to natural gas.

In the case of farming, increased efficiency and productivity should be the goals, because those result in what we call land sparing. It results in less land being used, less fertilizer, less runoff, less air pollution, less land farmed. I mean, there is less air pollution from farm machinery. So, I think it is a mistake to organize strictly around carbon. I think, in many ways, you want to organize more around land use efficiency or input efficiency.

On the question of emergency crisis, those aren't words that I think are very helpful. We saw some activists encourage panic. That is not something we should ever encourage, since panic means unthinking behavior. Climate change is a long-term process. It is not something that you solve with one piece of legislation or that one generation will solve. It is something that we are going to be managing for a long time.

And so, when it comes to forests, I would love to see more money spent on forest management. I think that is a much more higher priority, since we just have a lot of fuel built up in western forests that led to the severe fires that we saw last fall.

Mr. LaMalfa. All right, I appreciate that. The crisis really seems to be driven by a lack of forest management, and the overload we have per acre of forest fuels, and we don't seem to be able to get much cooperation. I appreciate that your points on grazing could be part of that tool in your comments, and grazing is always under attack in western states as part of that tool. Great points as well on the more you cause some of these effects, it takes more land to grow the same amount of crops, and with that, more water that we are in short supply in California as well.

So, Mr. Shellenberger, I would love to have you come up to my ranch in northern California some time and talk about this some more. Thank you.

Mr. Shellenberger. Thank you.

The Chairman. Thank you, and now I recognize Mr. Allen, for 5 minutes, from Georgia.

Mr. Allen. Thank you, Mr. Chairman, and I want to wish everyone a good afternoon. Welcome to our panelists. I am just delighted that we are having a hearing. For almost exactly a year, this Committee has, for all intents and purposes, been not operational. Since March 4, 2020, we have had one single full Committee hearing, and in my opinion, this is inexcusable, and I believe Chairman Scott and Ranking Member Thompson share that opinion with me. I am looking forward to returning to regular order quickly, and Chairman Scott, I appreciate again your insistence on getting this ball rolling very quickly.

We have a lot of important business and oversight to attend to. Particularly, we begin the preliminary first steps of writing a new farm bill. It is hard to believe that that is coming up so quickly.

Zippy, as you already pointed out, farmers are not the problem when it comes to greenhouse emissions, with the ag industry only producing about ten percent of U.S. greenhouse gas emissions. We are kind of barking up the wrong tree with this hearing. Farmers are the best environmentalists in the world because they depend on the land for their livelihood.

In the *Book of Genesis,* we are told that God gave us dominion over the Earth. All the challenges found in the ag industry come right out of *Genesis* 3:18. God created man and woman and he created them to tend the garden in which, again, God created.

If we want zero net carbon emissions, there are a lot of ways to do it. One is obviously plant three trillion trees would be a start. But what the two sides of the aisle disagree over is not really climate change. We all want to be good stewards of the environment. What we disagree over is the power that should be given to the government. Climate change at its worst can be and is used by various actors as a Trojan horse by which they gain the power to regulate and have total oversight over every industry and citizen in this country. There is room for both educated insight and common sense in this debate, but right now I feel that we have too many absurd policy proposals coming from the far-left alarmists.

One fact from the Earth Observatory at NASA on the actual tilt to the Earth suggests that the debate on how much this has caused is still ongoing. In fact, that piece of article says that as the actual tilt increases, the seasonal contrast increases so that winters are colder and summers are warmer in both hemispheres. Today, the

Earth's axis is tilted 23.5° from the plane of its orbit around the sun. But, this tilt changes. During a cycle that averages about 40,000 years—again, I think I heard someone say this is a long-term issue, the tilt of the axis varies between 22.1° and 24.5°. Because this tilt changes, the seasons as we know them can become exaggerated.

And Zippy, I will start off with you. I think you and I—of course, I don't believe anyone has claimed that they are in charge of that tilt. Zippy, I think you and I know who is in charge of the tilt and who created it. But my first question to you is what is the greatest environmental challenge that our agriculture industry faces?

Mr. DUVALL. What is the biggest environmental challenge?

Mr. ALLEN. Yes, sir.

Mr. DUVALL. Well, I can tell you what the biggest challenge is to agriculture. The biggest challenge to agriculture, biggest limiting factor of agriculture is labor. But that doesn't have anything to do with the climate.

Mr. ALLEN. Right.

Mr. DUVALL. I think the biggest limiting factor is our outreach and our communication. We need to make sure that we continue to tell farmers, because we do not have every piece of ground with cover crop on it. We do not use no-till on every piece of ground. But we need to continue to talk about what that does for us in the future, and we need to educate people and move them toward that. But it takes partners to do that. It takes money to do that, and of course, the programs that we have had have helped us, but we need to continue to move forward in that direction to put those practices on the ground.

Another one of the limiting factors is the amount of research dollars that is being spent on these issues. I keep hammering on that because it is important. Research has kept us on the cutting edge of agriculture. A lot of times American agriculture gets downplayed as the bad guy, where agriculture in the rest of the world represents 25 to 35 percent of the greenhouse gases, we only represent ten percent. We are the leaders. Everyone should be following what we are doing in our country, and we ought to be accelerating through research monies and new projects to put on the ground and encouraging people to do it. Partners, research, and moving forward.

Mr. ALLEN. Well, thanks Zippy, and I am out of time, and I yield back, Mr. Chairman.

The CHAIRMAN. Thank you very much, Congressman Allen.

And now, I recognize the gentleman from Illinois, Mr. Rush, for 5 minutes.

Mr. RUSH. I want to thank you, Mr. Chairman. Mr. Chairman, I was born on a farm, and as the son and grandson of two Georgia farmers, I am very excited about being on the Agriculture Committee, and I am excited about this hearing, and I want to commend both you and the Ranking Member for conducting this hearing.

My question to you, directed, rather, to Mr. Duvall.

Mr. Duvall, according to Feeding America, before the COVID–19 pandemic, more than 35 million people struggled with hunger in the U.S., including more than ten million children. The coronavirus pandemic has made this situation worse, and we know that climate change will only further exacerbate the problem. Innovations in food production can enable growers to produce higher yields with lower inputs and help crops sustain the environmental stressors, and that will likely get worse during the climate change. New technologies can also help address the lack of fresh fruits and vegetables and food deserts, while among other things, cutting down on food waste.

Mr. Duvall, how can we accelerate the development of new technologies to prepare for a changing environment, the growing problem of hunger? How can we assure that these technological breakthroughs are widely shared to benefit socially disadvantaged farmers and ranchers and urban communities who have historically been unable to access nutritious offerings?

Mr. DUVALL. Yes, sir, thank you for the question, and you are exactly right. The technologies that we have had at our fingertips have helped us improve our production by three-fold in the last decade.

So, what can you do to help us? We need to streamline the regulatory system. When these technologies come forward, let's streamline the process to be able to get them approved and get them out on the farms to help us do that. We can do things, put crops in the ground that use less water. We can grow vegetables that have more nutritional value. If all these technologies are streamlined and instead of it taking 5 to 10 years, cut it back to a year, year and a half and get it out on the farms so that we can grow the crops, be more efficient, and keep the price down, because the way we can produce in America, there is no reason for anyone in America to be hungry. Farmers don't want that. We want to do the best job we can. We want to keep the cost of food reasonable so everybody can have access to it. And we appreciate the work that Congress did with us and Feeding America through USDA to deliver. When the market changed after COVID hit, you helped us deliver food boxes to families and helped our farmers change the way they marketed their food. So, we are very appreciative of those programs. But streamlining regulatory agencies to where we can get those products out to the farm quicker.

Mr. RUSH. Thank you, Mr. Duvall, for that fine answer.

Mr. Cantore, in your testimony you mentioned how, and I quote, "Children are being diagnosed with increasing respiratory illnesses due to a more hostile atmosphere." We know that Black and Brown children already tend to have a higher risk of respiratory illnesses as a result of poor air quality. As environmental conditions continue to change, what impact do you anticipate that they will have on an already vulnerable population?

Mr. CANTORE. Thank you, Congressman Rush, for the question.

When you have these high air quality days, we have already have tools out there at our disposal to keep people inside as much as possible, but sometimes that isn't possible, and they have to go outside. Things like asthma are certainly becoming more prevalent with children and adults because there are so many pollutants that are just trapped in the air, and the longer we have these heatwaves—and they are popping up everywhere. Nobody is unprivy to this. You are going to have these pollutants just trapped and trapped in the air. Nothing is there to mix them off.

In addition to what we are watching with weather, air quality issues, even though it is not something we see coming down at us, it is just as important to watch. So, these are expected to increase in the future, sir.

Mr. RUSH. I want to thank you, Mr. Chairman, and I yield back the balance of my time.

The CHAIRMAN. Thank you, Mr. Rush.

And now, I recognize Mr. Kelly of Mississippi for 5 minutes.

Mr. KELLY. Thank you, Mr. Chairman. I ask for unanimous consent that I get at least 25 minutes to ask my questions, because there is so much in this, and I thank you for having this important hearing. I am joking about the 25 minutes.

But one of the things I want to talk about is I want to make sure that we are focusing on results, and not resources or on one solution. Many times, we ignore results because once we get invested in our solution or one way, we ignore new technology or new solutions. And so, when we are talking about zero emissions—I know Zippy Duvall talked about many farmers now have zero emissions or net zero emissions, and I think that is important. And going back to the cover crops and doing that to enrich the soil, you have rice as Mr. Crawford brought up, and I just got off a call with USA Rice, and talking about the cover crops literally being ducks to flood those areas.

But in my area, we have many different types of crops, and so I am not sure that they are the same cover and I want to make sure we do the right research to get those. Whether that be peanuts or cattle or sweet potatoes or poultry.

And so, Zippy, can you address any crops that may be a one cover crop is not a—one solution is not—does not fit all, or any specific crops which may have a different cover program to make sure our soils are preserved? Can you address that, Mr. Duvall?

Mr. DUVALL. So, of course, I think all of us know trees are the best way to sequester carbon. And then a diverse landscape of different crops in different regions would be the next best step. But there is tremendous work we do in the animal area. There are feed additives, and I was asked earlier what can we do to help it along? There are feed additives the FDA—they consider those as drugs. They need to be considered as feed so that we can get those additives approved and get them out on the farm to lower the greenhouse gases that are coming from our animals.

And, those are some of the suggestions I would make.

Mr. KELLY. Thank you very much, you know Mike McCormick at Mississippi Farm Bureau and you, Mr. Duvall, have been such great friends and great resources. I just hope before we do a one size solution fits all, that we talk to our Farm Bureaus or other organizations across our nation that represent all of our farmers, not just certain areas, because regions are different.

The other thing, Mr. Duvall, how effective with getting rural broadband to our farmers to have access and would that be helpful to them being able to have the technology and the information and education to farm better for our environment?

Mr. DUVALL. I talked a little bit earlier about broadband being part of that building on our infrastructure, and today, broadband is not a luxury. It is a necessity. Whether it be education, healthcare, and taking advantage of technologies that are coming down the pipe that farmers can use to be more efficient and more climate friendly. So, it is absolutely necessary that we get those maps right, the Federal dollars that you all are so kind to put out there to try to fill that gap between urban and rural America, that those dollars go to the correct places, because a lot of places those maps aren't right. I struggle here with it in my house, and I am only 70 miles from Atlanta. So, we have to do this.

If you think about electrification back in the 1930s and how important that was to all Americans, broadband is no different. It has the same importance today that electrification had back then, and we have to find a solution. We found a solution to that one. We can find a solution to this one.

Mr. KELLY. Thank you again, Mr. Duvall. I want to go back to Ms. Adams' point. I have many 1890 universities that I represent, HBCU, the many agricultural colleges, which includes Mississippi State University, which is not an 1890s college, but also an agriculture college. And I just think it is so important that we use research dollars to allow these universities to look at all these individual areas that I am talking about in crops and specific regions, because nobody is better situated to talk about specific regions.

I am running real close on time, and the final comment I will make is, number one, invest in research and our 1890s universities and other universities, agriculture universities, and the second is we really need to get our State Department engaged in foreign policy that deals with nations that are either too poor or either ignore the environmental consequences and climate consequences of their nation. We need to engage them and make them part of our farm policy, whether it be through trade or other initiatives with our foreign policy.

And with that, Mr. Chairman, I yield back.

The CHAIRMAN. Yes, thank you very much, Mr. Kelly, and thank you for emphasizing our 1890s and the fine work you did with me and the Committee. What a great bipartisan effort in getting that $80 million down to those schools. I always lift that up as one of our shining bipartisan moments.

And now, I would like to recognize the lady from Maine, Ms. Pingree, for 5 minutes.

Ms. PINGREE. Thank you very much, Mr. Chairman. Thank you so much for hosting this hearing and making it our first hearing. I think it really has been very interesting and informational, and I really appreciate that we have a lot more agreement than we often think that we do, and many of the topics that we have brought have shown our similar thoughts.

I won't get a chance to ask everyone a question, but I do want to thank all the presenters. You really have given us such a great cross section, weather professionals to the importance of the cooperative extension service, the farmers' perspective, and Zippy, I really appreciate—I would like to have a meeting with you. It was a long time ago because we can't have a meeting anymore, but the work you have done with the Food and Agriculture Climate Alliance is really a great way to bring all the commodity groups and the farmers thinking together. I think that has really advanced a lot of our thinking on this. So, thank you so much on that.

I have worked on this topic for a long time. I care deeply about it, and I encourage many of you to sign on to my piece of legislation, (H.R. 2803) the Agriculture Resilience Act. I think there are a lot of things we agree on that you all have been talking about on both sides of the aisle: research, soil health, viability for our farms, pasture-based livestock, food loss and waste, which is a big topic that our cooperative extension service mentioned. So, there really are a lot of ways that are farmer-driven that we can work on this.

I want to try my first question on Mr. Brown. Thank you so much for really representing the point of view of what it takes for a farmer to make this transition. I want you to know, I am long-time fan of yours here. I have your book. If you were in the same room, I would ask you to sign it and I would give it to one of my favorite farmers, because I really enjoyed reading it. And I also want to thank you for giving a shoutout to H.R. 2859, the PRIME Act. We are not talking about that today, but that really addresses the importance of having more infrastructure available to farmers and farmers who want to sell directly to consumers. There is a real dearth of slaughtering capability in our country, particularly for small and medium-sized farmers. So, I appreciate that you brought that up.

You have gotten such a good explanation here to people about the work that you have done. But I know for a lot of farmers, it is very hard to make this transition. You have invested a lot, farmers have in the way they do things. Maybe it is generational. So, making this shift is a big leap, and I know you do a lot with talking to farmers about how you made the transition. What do you think we need to do to help support farmers in those transitions through the programs that we have, or other things that we could be doing more of?

Mr. BROWN. Thank you. I would be happy to sign a copy of my book for you anytime.

The number one thing that is needed—and Mr. Duvall touched on this—is education. You don't know what you don't know. I owe a debt of gratitude to NRCS. There are many good people who work for that agency. They are moving in the right direction, but they need to be given the opportunity to educate farmers and ranchers. We need to really refocus conservation programs to maximize the adoption of these regenerative principles.

Everyone here agrees that these principles work. Some say—have said well, these principles—cover crops may not work in my area. Well, they missed the principle of context. You have to grow the species that work in your area. Farmers and ranchers are not going to know that intuitively. Okay? We have to use programs, use agencies like NRCS, the extension service, to educate farmers and ranchers. And I think it is important to note that by doing so, farmers and ranchers are able to significantly decrease their inputs. I can't say that enough. For instance, look at corn today. The average cost to produce a bushel of corn is near $5, yet I know many regenerative farmers who are doing it for less than $2 an acre because they are educated and have the information that it takes in order to cut those input costs.

So, thank you for the work you are doing. We certainly appreciate it.

Ms. PINGREE. Thank you. I don't have much time left, but let me give it to Zippy if he wants to talk at all about the food and agriculture work that you have been doing, and just how that has brought so many different commodity groups and farmers together to talk about these things?

Mr. DUVALL. If you look at the Food and Ag Climate Alliance, it is a historic alliance. Never before have these organizations that think differently come together and agreed on three principles and put forth 40 recommendations. We are very proud of that work. We hope that people on the Hill as yourself, Congresswoman, that you will use those recommendations to help go forward and set policies.

But it was not an easy feat, and none of us knew that we could make it happen. But when I sat down across the table from environmental advocates, people's eyebrows kind of went up. But we were able to do that because what we discovered is what we all want is thriving communities, successful farming, providing a great environment for our families, livestock, and the wildlife. We all want the same thing. We just have different ideas of how to get there. It is kind of like pitting conventional farming against organic farming. There is room in the marketplace for all of it, but we surely don't need to be throwing each other under the bus. We need to be working together to provide it for the people that want it, and provide a good environment for us all to live in.

Ms. PINGREE. Thank you. I have gone way over my time, but thanks for the work you do for farmers. And to all the witnesses, thanks so much.

Mr. DUVALL. Thank you.

The CHAIRMAN. Thank you, Ms. Pingree, and now, I recognize Mr. Bacon of Nebraska.

Mr. BACON. Thank you, Mr. Chairman.

The CHAIRMAN. Five minutes.

Mr. BACON. Thank you, Mr. Chairman, and it is such a joy to be part of the Agriculture Committee.

Agriculture plays such an important role in Nebraska. It is the primary industry. It is the backbone of our economy, and even in Omaha, in the district I represent, agribusiness is the core.

I just want to make a brief comment, and then I got two questions. I just want to start off by saying conservative climate solutions work. I mean, just look at the energy sector. Over recent years, we have become the largest energy producer in the world. We have become energy independent for the first time since the 1950s. Just think about that, 70 years ago roughly. We are exporting energy now. We are helping out our allies in the Baltics gain energy independence from Russia. We have done all of this while cutting emissions more than the next 12 countries combined. I think that is an incredible accomplishment. From 2005 to 2019, we reduced carbon emissions by 33 percent, and we did this not by punishing people. We did it by incentivizing behavior. We also did it by incentivizing technology and innovation, and that is what we should continue doing.

So, my first question goes to Mr. Duvall. We know farmers are already making many positive changes, and we are already seeing the results. So, my question is should we implement policies for our farmers and ranchers to help them make more money when they implement sustainable agriculture practices? In other words, should we be focusing on incentives more so than the punishments? Mr. Duvall?

Mr. DUVALL. The heavy hand of any one network, even sometimes when you think about our children, and when you make it market-based, voluntary, incentive programs and prove to our farmers that it has a science-base and it is going to provide that kind of outcome, they are going to take advantage of that program that you put out there. So, it is vitally important that we make voluntary, market incentive-based programs as we move forward. And we look forward to having that discussion about what that looks like, and making sure that it fits all size farmers. That is crucially important to us, because we want to make sure—a lot of people look at American farmers and say you represent the large farmers. We represent large, medium, and small. We are always there to have their back, and we look forward to working with you to find those solutions.

Mr. BACON. Well, we look forward to working with you, too, on this because this is the right way to go forward.

Conversely, I just want to get your input. What happens if we put a carbon tax on our farmers, such as fuel and energy? What kind of impact is that going to have on a farmer's top line and margins?

Mr. DUVALL. Inputs are one of the biggest expenses that we have, and when you start taxing that, the profits in agriculture are so razor-thin now, that is why people become bigger, because the margins are thinner and thinner, and you got to do more and more to be able to make a living out there. So, if you put a carbon tax on it, it is just going to make it more expensive, and it is going to be hard for people to make a living.

I want to go back and touch on one thing. We want to be energy independent. This country turned to American agriculture to be part of that solution. We built a whole infrastructure around renewable fuels, and we need not forget that farmers answered that call, that infrastructure is valuable to our rural communities, and it is valuable to our farmers to market their grain. I think that is the important thing we need to think about.

Mr. BACON. Well, thank you, Mr. Duvall. I totally agree.

Mr. Shellenberger, how do we best balance implementing climate solutions that don't raise the costs of food? For example, if we do a lot of different measures, it could make our beef, our pork, vegetables and fruits much more expensive, and in the end, that affects the poorest amongst us. Those who are most food-insecure will find themselves even more food-insecure. So, how do we balance this while we are protecting the most needy amongst us, in your view?

Mr. SHELLENBERGER. Well, thank you for the question.

I think there is a real serious misunderstanding, because there is this idea that if you make things more expensive, that that is better for the natural environment, and that is just not the historical pattern. We find that by making food production and energy production more efficient, it also becomes better for the environment. So, you just use less land when farming, that is also part of reducing costs. Similarly, you mentioned before that carbon emissions peaked and have been declining since 2008. Very significantly, that occurred not by making energy expensive, but by making energy more abundant and cheaper, particularly natural gas with the Shale revolution. So, I think that that should be the orientation. Anything that seeks to make energy more expensive is obviously regressive. I think Democrats and progressives and every other context would oppose those things, just as we have tended to oppose taxes on food. So, I think the orientation should be heavily towards efficiency and productivity.

Mr. BACON. Thank you.

Mr. SHELLENBERGER. When we are looking at solutions, if they start to make energy and food expensive, that would be a red flag, both for equity reasons, but also for environmental ones.

Mr. BACON. Okay. Thank you very much, and Mr. Chairman, I yield back.

The CHAIRMAN. Thank you. Thank you, Mr. Bacon, and now, I recognize the gentlelady from New Hampshire, my good friend, Ms. Kuster.

Ms. KUSTER. Thank you, Mr. Chairman, and thank you for your leadership and your decision to hold this landmark hearing.

I want to begin by noting the dedication and commitment of farmers and foresters in New Hampshire to reducing emissions and mitigating climate change on their land. they know, perhaps better than any sector of our economy, how climate change threatens their livelihoods, and we are seeing warning signs already.

The USDA Hubbard Brook Experimental Forest in my district has provided top notch analysis through their work studying New Hampshire's climate for the past half century. They found our average annual temperature has already risen a staggering 2.6°. Rainfall has increased, often in condensed periods of heavy storms. Flooding has become more common, and as the Co-Chair of the bipartisan Ski Task Force, I want to point out that we have 10 fewer days of snow on the ground. Climate change shortens our maple sugaring season, complicates the growing season for our farmers, and brings more invasive species to our forests, and that is just the tip of the iceberg.

Our farmers and foresters have enough uncertainty to deal with running their business. Climate change is exacerbating those challenges.

So, one such effort is President Biden's 30 by 30 Initiative, conserving 30 percent of our land and water by the year 2030. Our conservation heritage runs deep in the Granite State, and more needs to be done to ensure that private farmers and forestland will continue to serve this purpose as land prices rise.

So, my first question is for Zippy Duvall. I know the Farm Bureau is proud to note over 100 million acres of farmland are now in conservation programs with the Natural Resources Conservation Service, including 42 percent of agricultural land in New Hampshire. Could you speak about the importance of conservation from the Farm Bureau's perspective?

Mr. DUVALL. Yes, ma'am, and thank you for the question. Of course, those conservation programs putting land into conservation with USDA has been vitally important. We put the least valuable, less productive lands in that area. So, that is extremely important. But we also have a huge moral responsibility to recognize that as population grows, we have to feed them. We have to feed them. So, we are interested in continuing those programs that you speak of, but we also want to see working land programs that helps us be more productive there and do an even better job for the climate in those areas, and that is going to require research and development dollars, and extension and education, and broadband. It is just crucially important. But those programs are very important, and we are very proud to be part of that.

Ms. KUSTER. Great, thank you. I 100% agree with you on the broadband.

Ms. Knox, I appreciate hearing your initiatives. Your counterparts at the cooperative extension at the University of New Hampshire have been incredible partners to me and the farmers and foresters in my district. You mentioned the need for more research, as Zippy just did, to help foresters adapt to new climate conditions, as well as best practices for making working forests the most effective carbon sinks possible. From your perspective, how can Congress be most helpful in fostering this kind of research?

Ms. KNOX. I think that USDA already has a number of programs that are really geared towards improving research in forestry. We certainly need to see more attention paid to that, and we need to work with extension agents to identify not only the research that's there, but also how to talk to landowners about planting more land. You have to pick the right trees, you have to pick the right location, and so, it is not just a matter of the research on the trees themselves, but communicating how the landowners can use that. The same thing works with what Zippy said about technology. If you have information but you don't have a way to get that to the farmers, then you have really lost a critical step, and that is really where extension falls in, because they talk between—they are translators, essentially, between the scientists and the farmers. And it works both ways, because the scientists also need to hear from farmers, because they need to know what is important to the farmers.

Ms. KUSTER. And one last quick question. You talked about the overuse of fertilizers contributing to carbon emissions. Does your cooperative extension encourage farmers to adopt strategies like planting trees and perennial grass to reduce fertilizer usage and runoff?

Ms. KNOX. They provide a number of different solutions. Of course, in farming one solution does not fit everybody. But the extension agents use a variety of techniques to talk about what is the most responsible way to deal with the farm on a case-by-case basis. So, they are really boots on the ground to look at what is happening for individual farmers.

But yes, they do talk about that quite a bit.

Ms. KUSTER. Great. Well, thank you so much for being with us. My time is up, and I yield back.

The CHAIRMAN. Thank you, Ms. Kuster, and now, I recognize for 5 minutes Mr. Johnson from South Dakota.

Mr. JOHNSON. Thank you, Mr. Chairman. I appreciate that.

I have a couple of things. I have enjoyed the comments a number of my colleagues have made, like Mr. Bacon talking about America reducing its carbon footprint by 33 percent from 2005 to 2019 he said. That is incredible progress. And then I liked Mr. Scott, Mr. Crawford, and others talking about the role that American ag producers have had in that environmental stewardship, and I think it is fantastic. I am just thinking about the impact that the farm bill, this incredible piece of legislation that incentivizes and encourages good stewardship, has had on clean water. You think about the impact, 19.3 million acres where we have had increased soil habitat, we have had better soil health and habitat. There are a lot of success stories to be told here in agriculture. And of course, I was glad to hear Mr. Duvall talk about the role of technology. I don't want to be a home state braggart, but of course, I do want to recognize South Dakota State University and their first in the nation 4 year degree in precision agriculture, because I think that plays a role in good stewardship as well.

But Mr. Duvall, I want to dive in a little bit deeper into a conversation that you noted that you and Secretary Vilsack had. We have been talking about a carbon bank, and there are a lot of questions I have about a carbon bank. You mentioned that the Secretary committed that it would not, in any way, come at the expense of title I programs. Can you tell us a little bit more what that conversation was like?

Mr. DUVALL. Well, I think it was just out of rumors that I was hearing and it was referenced earlier—in an earlier question. So, I just point blank asked the Secretary. He was very—he didn't have to think about it at all. He said, "I understand how important the farm bill title I, all the commodity programs are in conservation," and he says, "I don't have any interest in shorting them anything by using monies from that area that would go into climate." Secretary Vilsack, did a great job in the past, going to do a great job in the future. We look forward to working with him, and I was real satisfied with his answers.

Mr. JOHNSON. And so, did you get the sense—and I know you are part of an alliance that has spoken in favor of a carbon bank. I mean, is the CCC the mechanism that would be used, either in your understanding or what Secretary Vilsack relayed, to make these investments in a carbon bank?

Mr. DUVALL. Our conversation did not go that far to talk about whether or not the CCC was to be used to do that. I will tell you the historic alliance that I spoke of, we are interested in having that carbon bank and looking forward to having that set up. And of course, the fear that we get from the countryside of our farmers is what does that really look like, and is it going to be valuable enough to actually make that commitment? How many regulations are going to be around it, and who is really going to make the money out of it? Is it going to be an additional revenue stream to me on my farm to help me be more assertive of doing more practices that are climate friendly, or is someone in the middle going to make all that money? Of course, we do trust USDA more than we would some outside person handling it.

Mr. JOHNSON. Well, and I am glad you mentioned that kind of—how does the money work thing, because hopefully you can educate me and some others about this. I mean, there are high transaction costs. I think a number of experts indicate that that could be a real concern with something like a carbon bank, and I think some estimates are that the highest recurring cost associated with carbon credits would account for 50 percent of the cost. Under that kind of analysis, only ten percent would actually get to the producer, and that doesn't seem like a very producer-focused mechanism in my mind. So, Mr. Duvall, give us some sense of what your understanding of those costs would be?

Mr. DUVALL. I think they still haven't been discovered yet, and I think that the biggest fear farmers have is they want to know before they buy into it or before they support that, and before we support it, we got to know what that carbon bank looks like, and we got to know what kind of return it is to our farmers. Because ten percent—I am like you. I am not sure that it is really a viable program. I don't think you will have a lot of people participate.

Mr. JOHNSON. Sure. It looks like I am down to very little time, but perhaps maybe the Chairman can give you an indulgence of 1 more minute to answer my question. I mean, I do have concerns about a carbon bank and what exactly the Federal Government's role would be in it.

I got to be honest with you, Zippy. I have loved working with you. Everybody in this Committee trusts you, and the Farm Bureau. You are good people. So, give me some sense of what analysis made you all comfortable getting on board with a carbon bank? I have questions on impact on land prices, impacts on market conditions, on private markets, on whether it should be performance-based or outcome-based. I mean, what got you to a point of comfort, because I am not there yet?

Mr. DUVALL. Well, I will admit to you, I am not totally comfortable yet, but I am ready to have the conversation what that looks like and how we develop that market. And someone really smarter than me is going to have to figure that out, and I am sure there are smart people out there. So, I am just as eager as you are to find out how this works, and what the—because everybody wants to claim it as an alternative revenue stream to farmers. I want to know what that revenue stream looks like, and I want to know what procedure that carbon tax or carbon market is going to return back to the farmer. There may be a time in the future when we as an organization may not support that, but we have to have a conversation about what that looks like. And when we get those answers that you are asking for, we will be glad to share them with you.

Mr. JOHNSON. Mr. Chairman, thank you for your indulgence. I would yield back the negative time I have.

The CHAIRMAN. You are quite welcome, but I must admit and assure you that Zippy is indeed a very smart man.

Thank you for that, and now Ms. Plaskett, you are now recognized for 5 minutes.

Ms. PLASKETT. Thank you so much. Thank you, Mr. Chairman.

As the Subcommittee Chair of the Biotechnology, Horticulture, and Research Committee, I appreciate the Committee's focus on climate change and its impact on our farmers and ranchers. This is a topic I care deeply about, and one that my constituents are already facing.

Early in the 116th Congress, the Biotechnology Subcommittee held a hearing on examining ways for farmers to increase resiliency and mitigate risks through research and extension. I am so glad we are continuing that discussion here today.

I would like to direct my questions at Ms. Knox. In your testimony, you touched on the frequency of extreme weather events and how climate change can influence those events. This is something that is painfully familiar to my constituents in the U.S. Virgin Islands who experienced two major back-to-back hurricanes in 2017, and have faced periods of drought in years since. Specifically, your testimony touched on flash droughts as an area of focus for your research. Can you elaborate more on this phenomenon and why these droughts are so powerful to farmers and ranchers?

Ms. KNOX. Yes, ma'am, thank you for your question.

Flash droughts is an area of huge concern right now in agriculture. Flash drought, if you don't know, is a drought that comes on very rapidly, and so because it is coming on rapidly, often with either high temperatures or a complete lack of rainfall, or maybe some of both, really accelerates stress on plants. And of course, plants need to have regular amounts of rainfall or irrigation water to survive. And so, when we have flash droughts, the plants can go from healthy and thriving to really stressed and sick plants in a very short time, sometimes even as much as a week. And so, our ability to identify those flash droughts is, of course, important because then it will tell the farmers they need to do something about it. But we also need to be able to plan for what can you do to help keep your plants alive during these times of flash drought. And so, you can use irrigation, you can grow different types of crops, you can do cover crops which keep more soil moisture available. But all of those are things that need to be looked at.

Flash droughts, one of the projects we are working on right now looks at soil moisture and measuring soil moisture, because that is an important piece of information that farmers need to have, and yet, there is not a lot of really inexpensive pieces of equipment that people can use to do that. So, some of the projects I am working on right now are to identify some of these less expensive ways to monitor soil moisture, and provide that information to the farmers in a way that they can use it to put on just the right amount of water. They don't need to overwater, but they need to put on enough water to keep the plants alive.

Ms. PLASKETT. Thank you.

What is the role of cooperative extension in helping our farmers and ranchers become more resilient, particularly for those who are small scale and limited resource producers?

Ms. KNOX. I think cooperative extension plays a really critical role because there is a lot of research that is out there, but it isn't necessarily getting to those small producers in a form that is useful to them. So, cooperative extension really serves as a way to translate some of that research into useful information. And I am a pragmatist, so I want to make sure that whatever information is provided is useful and is in the right format for those producers.

And so, every situation is different. You have to go out in the fields, perhaps. A lot of extension agents spend significant amounts of time walking the fields with their farmers, and so they really know the needs of those particular farmers. And it could be big farmers or small farmers. But they need to be able to talk in such a way that the information that is provided by the scientists is useful, and they need to listen to the farmers and tell the scientists what they should be working on, because the scientists can't really work in a vacuum either.

Ms. PLASKETT. Okay, thank you.

In the short time that I have left, can you say what additional research is needed to better understand how climate change will impact farmers and ranchers, and how USDA can help close those knowledge gaps?

And after your answer, I yield back. Thank you, Mr. Chairman.

Ms. KNOX. Thank you.

Some of the research that we don't really know very much about, we know that climate change is going to impact temperatures. We don't know really how well it is going to impact things like solar radiation or moisture balance in the soils, because those are secondary things, and they depend on a lot of other things that are not as easy to resolve, say, in climate models. For example, the cloud cover, which obviously controls the amount of sunlight. But sunlight is important to the growth of many crops, and if you have cloudy conditions, if you have a lot of rain or just cloudy conditions, then it is very difficult to plan how fast the crops are going to grow.

And so, looking at some of the secondary variables that are really important for agriculture, which include things like soil temperature and humidity, and things like degree days and how fast they accumulate, cloudy conditions, are all important.

Ms. PLASKETT. Thank you very much. I yield back, Mr. Chairman. Thank you for the time.

The CHAIRMAN. Of course. Thank you. Thank you very much.

Now, we have had a call of votes. This is an important hearing. We have a wonderful panel, and we have Members that want to make sure they are recognized for questions. So, my excellent staff and I have worked out a procedure that we are going to do where we will keep our hearing going as some of our Members go. And as you go, remember, please, as soon as you come back, to make sure you contact the staff and let us know that you are back in position.

Now, it has just been called, and let's see. Where is my—I had a list of—no, the—oh, here it is. Okay. These are the next five Democrats and Republicans who will be recognized, and the reason I am calling their names is hopefully they will be here and vote. Others who are further down can leave and then come back quickly.

So, Mr. Baird, you are next. That is followed by Mrs. Bustos, and then Mr. Hagedorn, and then Mr. Carbajal, and then Ms. Craig and Mr. Cloud. That is six—one, two, three, four, five, six people at 5 minutes gives us a good half hour here now, and these six can go and hopefully some of you all who are leaving now whose names have not been called, you can leave and hurry back within the next 30 or 40 minutes, and we can keep it going. I think that is our strategy.

Okay. Now, I assure you that everyone will be recognized. This is an extraordinarily important hearing, and we can work this out. So, those of you whose names I haven't called, please feel free to go. We are coordinating with the floor and they will allow you to vote as soon as you get there, so you can return. Thank you. Is that right? I see Anne here. Is—did I do all right, Anne? Okay. Anne says I did.

Now, we will recognize Mr. Baird.

Mr. BAIRD. Thank you, Mr. Chairman, and I really appreciate you and the Ranking Member having this very important hearing. It really gives a platform to highlight agriculture and its importance to providing practical solutions to this climate change. And so, it is extremely relevant, and I am so pleased to be a part of it.

My first comment really goes to Mr. Brown, and it is just a comment, because I think it leads to my question to Mr. Duvall next. But, it is exciting to see the soil samples that you held, Mr. Brown, and the changes you made in that 20 year period, and the relevance of capturing carbon in the soil. The black color and the interaction of that carbon, and its importance in helping improve productivity. So, anybody that knows anything about soil, those two soil samples you held up were just very informative. And so, it looks to me like with the one slide you had, you were able to move in a 20 year period, 1993 to 2013, from one percent or less than one percent carbon in the soil, and went to a level of seven percent. So, it is exciting to see that we have and farmers and ranchers have already been incorporating things that help carbon capture, and I think that is important.

So, now I need to get on to my question, and that really—you alluded to it before, Mr. Duvall, but it has to do with the regulatory concerns for livestock feed. The development—and livestock has been a part of my life, really all my life. I grew up in west central Indiana. I went to Perdue, so animals and a Ph.D. in monogastric nutrition all contributed to my concern about livestock. And so, you mentioned greenhouse gases and the emissions associated with livestock, and so on.

Feed additives have been shown to reduce methane levels produced by ruminants by as much as 30 percent. The addition of enzymes to chicken feed can also improve protein digestibility, which helps reduce nitrogen emissions from the manure. Probiotics help animal feed and improve the gut health of the animal. Not only do these additives increase the nutritional value of the feed and lower the cost of production for the farmers, but it ends up being a win/win situation because we can reduce greenhouse gas emissions.

As you mentioned earlier, many of these innovative products lack a suitable regulatory product category, and they end up being involved as animal drugs rather than being a feed additive. And so, I am pleased to see that the Food and Agriculture Climate Alliance, FACA, that the Farm Bureau has founded identified the need to expedite and reduce this regulatory burden in regard to FDA feed additive approvals.

So, having said that, I would like to give you the opportunity to comment on what you think we need to do to streamline those FDA approval processes, and if there are any incentives or rewards that we can use to help producers utilize this kind of technology? Mr. Duvall?

Mr. DUVALL. Congressman, I am a farmer and I am an animal agriculture farmer out there for 30 years, and also worked for my dad as a child for 20 other years before that. And now I have beef cattle, and this is my 34th year growing chickens. I will tell you that that environment is the first area that you can improve your farm more than anything. Animals eat grass, and grass sequesters carbon. So, it all works together and kind of plays off what Mr. Brown was saying.

The regulatory system, and I will admit to you, I don't know that I can give you the recommendations, but I will sure seek my staff on it to give you some recommendations about that in writing afterwards. But we know that it is very cumbersome. It takes too long. These companies go out and develop these additives that are food additives that helps us do this, and they have put tremendous dollars into creating them, and then they have to sit on the shelf at FDA and the things that we use to grow plants, to head off pests and disease, they sit on the shelf and they are just grilled to death for years and years and years. And by the time they get to the field, a new one is already on the shelf waiting to be approved the next time. We shouldn't be that way. We have people to feed. We have Americans that are hungry. We need to keep food affordable. We need to be as efficient as we can, and the only way we can do that is to streamline that system so that we can have those innovations and research reach the farm quicker.

Mr. BAIRD. Absolutely. Thank you for your comments.

Any other witness would care to comment about that?

The CHAIRMAN. Mr. Baird, your time is up.

Now we will recognize Mrs. Bustos for 5 minutes.

Mrs. BUSTOS. Thank you, Mr. Chairman.

My question is for Mr. Brown. In your testimony, you mentioned the benefits of sustainable practices and how they can help sequester carbon, increase water capacity and absorption, build resilience, and mitigate risk. These themes are consistent with the goals of something that I wrote out of my office called the Rural Green Partnership.[5] That is a framework of policies and principles that are geared toward getting rural America involved in the climate conversation, and making sure that we play a part in spurring economic growth in our part of the country.

So, as a Member of Congress who represents a district where ag is our main economic driver, and as Chair of one of the Subcommittees of this Committee, General Farm Commodities and Risk Management, these are all issues that are top-of-mind for me, because they are top-of-mind for the growers and producers that I am lucky enough to represent in northwestern and central Illinois.

So, over the past few weeks, we have been hosting a series of roundtables, and in every single one of them, our growers and our

[5] **Editor's note:** the statement referred to is located on p. 383 and is available at *https://bustos.house.gov/bustos-announces-rural-green-partnership-to-combat-climate-change-and-spur-economic-growth/*.

producers are talking about how they are engaging in sustainable best practice like cover cropping, no-till farming. But they don't feel that the Federal incentives match up with the work that they are putting in on the farm.

So, Mr. Brown, and then—I would like you to go first, and then maybe Mr. Duvall, if you have something to add. Here is my question for the two of you. Where do you see potential for increased Federal investment and incentives to help more farmers adopt these practices while also rewarding those who have already been active in this space? That is also something that we have gotten some questions on.

Again, Mr. Brown, if you can go first, please?

Mr. BROWN. Thank you. Thank you for the work you are doing.

Where it begins is, as I said before, in education. You don't know what you don't know. We need to educate farmers and ranchers as to these principles. We need to show them that by applying these principles, they can significantly not only mitigate climate change, but they can significantly lower their input costs and increase their profitability.

We seem to get hung up here on production and yield in pounds, and yes, we need to feed America, but what most don't realize is that production increases as we use these regenerative practices. Also, not only does production increase, but the nutrient density of our foods increases significantly. And I think that has been totally overlooked. We want to help the underserved? Let's increase the nutrient density. The only way we can increase nutrient density of foods is through healthy soils on land-based produced foods.

Take a look at the work that Dr. Stephan van Vliet is doing at Duke University Medical Center using a mass spectrometer to measure over 2,500 different phytonutrient compounds in food. He is doing work currently that is showing a significant difference between food grown in the current production model and food grown in the regenerative model. Farmers and ranchers need to learn about this, and then they need to be rewarded with an outcome-based for the principles that they produce—for the principles that they enact.

We cannot keep going down this model where the only incentive is based on yield in pounds. It does no good if we are feeding our society cardboard. Take a look at the facts. We are spending twice as much on healthcare as we are on food. Now, I am all in favor of lowering the cost of food from the standpoint that—but we have to do it in a way that brings profitability back to the farm and ranch. I agree totally with Mr. Duvall on that. We have to increase profitability to the farms and ranches. He talked about margins being razor thin. Well, I am sorry. One of the reasons I don't accept any government programs or subsidies is because I can't—I have decent margins because I have been able to lower my input costs due to the fact that I have enacted these principles.

It all goes back to education. Thank you for your question. Please, this Committee has the ability to make sure that we educate through NRCS, through extension, and through other means. Thank you.

Mrs. BUSTOS. Very good. Mr. Duvall, I am going to pass on you answering any more, because I have 8 seconds left.

And with that, Mr. Chairman, I yield back. Thank you so much. Thank you, Mr. Brown.

Ms. ADAMS [presiding.] And thank you. I want to recognize now the gentleman from Minnesota, Mr. Hagedorn.

Mr. HAGEDORN. Thank you, Madam Chair. I appreciate it. It is good to be at the hearing today, and Mr. Shellenberger, I appreciated your presentation and the way it demonstrated that farmers in America are already doing things to be sustainable, and to manage their land properly. And in many instances, of course, we lead the world in all that.

But I find it really difficult to have a hearing about the effects of so-called manmade climate change and what we need to do about it with agriculture, and not address the proposals that are out there that would change the energy sector in this country, and what that would do to sustainability of our farmers from generation to generation, and the profitability of our farmers and keeping the price of food affordable for the American people.

Now, President Duvall, let me ask you. I am going to list a few programs here, and I would like you to let me know if the Farm Bureau affirmatively supports any of these energy policies that are proposed by the Democratic party at this time in one way or another, whether it is the President or Congress.

So, obviously these are all like the Green New Deal. First of all, the cancellation of the Keystone Pipeline. I will read these out, and you just let me know if you support any of them.

Cancellation of the Keystone Pipeline. Imposing a carbon tax. Obama's Clean Power Plan. A ban on fracking. Rejoining the Paris Accord. Imposing livestock ban. Enacting a cap and trade system or mandating the phaseout of the combustion engine at a certain point, and the end of gasoline and ethanol use as we know it today. Does the Farm Bureau support any of that?

Mr. DUVALL. No, sir, we do not support any of those.

Mr. HAGEDORN. And that is my point. If you are worried about farmers and sustainability, these are the types of policies that are going to dramatically drive up the cost of energy for agriculture, agribusinesses and make it darn near impossible for most of our providers to stay in business, and to produce affordable food and an array of products for our people. I mean, depending on the commodity prices and the cost of fuel, 30 to 40 percent of the cost of producing a bushel of corn can be energy.

So, all these policies are very highly inflationary, and they are going to hurt our farmers.

Now, Mr. Shellenberger, in a recent *60 Minutes* interview,[6] billionaire Bill Gates suggested that established nations like the United States should transition to eating fake, synthetic plant-based beef. And he even went on to say that government should force regulation of fake meat to force consumers to comply if they didn't like the taste, effectively.

Now, based upon your presentation, does Bill Gates or this type of recommendation, is that, based upon any accurate understanding of the U.S. beef industry?

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[6] **Editor's note:** the interview referred to, *Bill Gates: How the world can avoid a climate disaster,* is retained in Committee file and is available at *https://www.cbsnews.com/news/bill-gates-climate-change-disaster-60-minutes-2021-02-14/*.

Mr. SHELLENBERGER. Well, I can't be—I didn't see the *60 Minutes* interview, so I can't specifically comment on it, other than to just observe that it would be impossible for any government to mandate particular diets.

Just about four percent of the population is vegetarian, and most vegetarians eat some form of meat during the year. My view is that we should continue to innovate for alternatives to meat production, but certainly not mandate it. And as I mentioned, the meat industry has done a very good job at reducing their impact on land, particularly the transition from pasture beef towards more conventional concentrated beef production has been astounding.

So, yes, I mean, I support the innovation. I don't think we are going to mandate that.

Mr. HAGEDORN. Well, let me reclaim my time.

There is plenty of opportunity for the Federal Government and Democrats in Congress to mandate. They are going to mandate all these things that have to do with energy and what kind of cars we can drive, or what kind of energy is produced. There is no reason to think that they couldn't come forward and try to mandate that we could no longer have livestock production in our country the way we have it, and that we would need to move towards plant-based diets.

So, I would say that the biggest threat to production agriculture's future in the United States isn't so-called manmade climate change. The biggest threat to production agriculture's future in the United States is the Green New Deal and these extreme climate change agenda policies of the Majority party. And raising the cost of energy is something that should be addressed by this Committee. We should have a hearing on it because when you dramatically raise the cost of energy, you are going to undercut the profitability of farmers and you are going to take generational farmers and run them out of business, and we are going to disrupt this incredible system of agriculture that we have in our country.

With that, I yield back.

Ms. ADAMS. Thank you very much.

I want to recognize the gentleman from California, Mr. Carbajal. You are recognized for 5 minutes.

Mr. CARBAJAL. Thank you. Thank you very much, Madam Chair.

I represent one of the most beautiful places on Earth, the Central Coast of California. It features some of the most diverse habitats in North America, and it is also home to a robust and diverse range of agriculture products—or production, I should say.

Over the past decade, California has become more prone to weather extremes, and the Central Coast is no exception. Our community has felt the climate change crisis in a multitude of ways: more severe droughts, increasing frequency of heatwaves, and record setting wildfires.

Producers in my district are utilizing funding from Environmental Quality Incentives Program, EQIP, and the Conservation Stewardship Program, CSP. While I am glad to see farm operations in my district using important conservation practices, I have also heard that access to these programs can be improved.

Mr. Duvall, can you discuss the role of USDA conservation programs in addressing climate change, and helping farmers build resiliency? Can you speak to the demand for USDA's conservation programs?

Mr. DUVALL. Well, thank you, sir, for the question. I will tell you that those conservation programs are widely used, and I will tell you there are a lot more people that apply for them than actually receive them, because they run out of funds. There are not enough funds there to complete every project that a farmer will put forward. So, I think a lot of it is limited by the amount of funds that the Secretary has put in those areas. But they are widely used and they are widely popular.

Mr. CARBAJAL. Thank you.

Agriculture employers are constantly challenged by unpredictable weather, and they now have an ever-increasing need to protect farmworkers from extreme weather concerns.

Ms. Knox and Mr. Cantore, can you talk to me about the effects climate change has on farmworkers? What health risks may they experience while working in extreme weather conditions, including poor air quality due to smoke?

Ms. KNOX. Well, let me start off by saying that there are several different ways that farmworkers are affected by it. One is by the likelihood of increased heat stress. Farmers working outside, especially as temperatures go up, are more prone to have heat-related diseases, and so people who hired them have to make sure that they are providing appropriate health-related cooling areas or whatever, or modifying hours to make sure that the heat stress is not building up on them.

But as you point out, the air quality, especially in the western United States, is a very huge concern for people that are working outside. We have seen that with the vineyards and some of the vineyards that have really been hit by the fires out West, and how that smoke has really carried a long ways.

But I will stop so I can let Mr. Cantore answer that as well.

Mr. CANTORE. I mean, when you take a look at the fire situation just last year, over 4 million acres burned. The pictures that we saw out of San Francisco looked like some kind of movie set, but that was real, and those people had to breathe that air for days, workers alike.

So, if we get into a situation where these droughts worsen, and we get into these mega droughts that go year after year after year, and you increase 4 million acres two to six times, it is not only San Francisco and the vineyards that are going to be dealing with poor air quality. It could be the whole state. As a matter of fact, it is not just the whole state. A lot of that air, that poor air quality is carried east into other states, across the Rockies, to the Plains, into the Southeast. Heck, down here in Atlanta. You probably have seen the smoky skies, and it is not from the African dust but the smoke from the wildfires in the West. So, everybody suffers from this, and that is, to me, one of the worst things in terms of air quality.

Mr. CARBAJAL. Thank you both for your answers.

I happen to have agriculture as the number one industry in my district, and at the same time, I come from a family of farmworkers. So, I happen to see it from both perspectives, and I really do appreciate your answers.

With that, I yield back, Madam Chair.

Ms. ADAMS. Thank you. I want to recognize the gentleman from Texas, Mr. Cloud. You have 5 minutes, sir.

Mr. CLOUD. Thank you very much. I appreciate the opportunity to have this conversation. It is extremely important that we do have a discussion on how to steward our nation's resources.

Mr. Brown, I have to say, not to invite myself over, but I do hope that one day I can visit what you are doing there. It seems like you are doing some great work. You mentioned that your regenerative farming practices are able to produce more per acre while also increasing profit and being more effective. Is that what I understood?

Mr. BROWN. That is correct, and we are doing it in Texas also.

Mr. CLOUD. Okay. Well, that is even closer, so maybe I will have to stop by.

So, there is a built-in incentive already to move this way, am I correct?

Mr. BROWN. That is correct. I didn't get any incentives. I did it all on my own. I did, though, early on take advantage of EQIP and CSP contracts through NRCS. That was an important part of me starting down this path, but as soon as I was financially able to do it on my own, I would rather see that money go for other underserved or people who are starting out.

Mr. CLOUD. So, there is some initial cost getting started, and once you got started, it is self-sustaining, I guess is what you are saying, right?

Mr. BROWN. That is correct.

Mr. CLOUD. And you were able—I mean, this was just motivation in your heart to do, right? This was voluntary?

Mr. BROWN. Okay. No, my story was I started no-tilling actually in 1993. That I started on my own because it made good sense in my semi-brittle environment. Then what happened, the years 1995 through 1998, I lost 3 years of crops to hail, and 1 more year to drought. Financially I was going broke, and I had to figure a way how can I make my soils, my resource productive without all the expensive inputs? And that sent me on an education and learning process, at times learning from land-grant institutions, at times learning from other producers, learning from ARS. ARS was very important in my learning. And I picked up bits and pieces and learned these principles, and learned that they can truly work anywhere in the world where there is land-based agriculture.

Mr. CLOUD. Thank you very much.

I would like to say that the road to $30 trillion of debt is paved with good intentions. Of course, we do have a role to play here in the Federal Government, and there are important investments we need to make.

Mr. Duvall, I am not sure you are the best one to answer this. Do you have an estimate on how much it would cost to establish and operate a carbon bank?

Mr. DUVALL. No, sir, I am not qualified to answer that question.

Mr. CLOUD. Or anyone else? I don't know if anyone else does. No? Okay.

I mean, currently we have some volunteer carbon banks in place, and right now, the highest cost, my understanding, in operating them is the cost of verification. Basically, a severe bureaucratic burden. Only ten percent of it goes to the farmer, and so, in pragmatic terms, I don't know of many programs where the government has done things more efficiently, so I do have some concerns in that. Because pragmatically, and this would be typical of many Federal Government programs, is basically we would be taking $10 of investment out of another industry that also needs to make gains, transferring it through the Federal Government to the ag industry. Eight dollars of that would be lost in the bureaucracy somewhere, and only $1 would go to the farmer. And while that would be some small benefit to the farmer, a lot of the overall cost of what we could accomplish basically would be lost in a Federal bureaucracy.

So, it seems to me that we have to be very careful about overreaching here. I think, as has been stated, communication, education on the best practice is extremely important. And I would say not mandating the best practices, I wonder if Mr. Brown would have been able to make the advancements he made if we locked in the best practices of 20 years ago as a mandate, would allow that to happen as an environment that allows for innovation. And to that point, I would like to just say, Mr. Shellenberger, I really appreciated your balanced testimony and information-based evaluation of the state we are in as a nation. Too often we see the road left to the advancements that we still need to make, and sometimes those get demonized and we don't take the time to remember how much progress we have made. Could you just summarize and recap the United States, among other nations, the innovations we have made toward effective and sustainable farming?

Mr. SHELLENBERGER. Yes, I mean, gosh. There are so many of them, right? We are a huge innovator. I mean, all of the technologies in your iPhone, in those GPS-driven tractors——

Ms. ADAMS. The gentleman's time is up. The gentleman's time is up. Thank you.

I would like to recognize the gentleman from California. Mr. Harder, you are recognized for 5 minutes.

Mr. HARDER. Wonderful. Thank you so much. Thank you so much to Chairman Scott and Chair Adams, and thank you for hosting this hearing on this important topic. Thank you so much to the witnesses for contributing your testimonies.

I think that in our valley, we have really seen—the California Central Valley, we see farmers on the forefront of climate change, especially in our district. We have seen farmers face wildfires, face droughts, face floods, and I know how much the changing climate can impact them. It is not just affecting some polar bear in the Arctic somewhere else. It is affecting the everyday lives of every farmer and grower throughout our community. And I think folks really want to be part of the solution. I took a lot of time with our Farm Bureau, discussing updating farm equipment, by using low dust harvesters on almond orchards. And frankly, there is a lot of interest. But folks on the ground often express some of the financial challenges in purchasing or updating their equipment or technology, or needing staffing assistance to keep growing their climate updates. One of my constituents shared that for her almond orchard, it would cost about $200,000 for a low-dust harvester, and an additional $70,000 for a low emission tractor. And so, with my work in business and startups, that was my background before coming to Congress, I understand how these decisions are made. And I understand that they really need to make financial sense if ag operators are going to move them forward.

So, we have worked a lot with ag groups and environmental groups to introduce H.R. 7482, the Future of Agricultural Resiliency And Modernization Act, which I think is one of the only bills that is actually endorsed by our local Farm Bureaus, as well as by a number of environmental groups all around ensuring that we can make sure that we are moving towards more agricultural resilient practices. It basically creates a Federal partnership for farmers to access financing, which would provide grants that support climate-friendly projects. It also creates a pilot program for pyrolysis, which essentially helps convert tree nut byproducts into climate-friendly biocarbon, a really important effort especially in California's Central Valley.

So, my question is actually for you, Mr. Duvall. As the President of the American Farm Bureau with such a wide-ranging network of members across our district, what have you heard are the financial needs of farmers in this space, and how can Congress or the Federal Government support farmers when making those financial decisions towards more climate resiliency? Thank you.

Mr. DUVALL. Well, thank you for the question, Congressman, and you are exactly right. Other than trying to figure out how some of these programs are going to work, and what regulations come along with it and the burden that comes with it, is the cost. You are exactly right. What is it going to cost me to put this practice on the ground? What new equipment am I going to have to buy? And then, you are exactly right. My membership goes from small, medium, large, different size organizations. A large organization might can afford that $200,000 piece of equipment, but a small operator can't and it makes it just not feasible for him to do that.

If we have practices or we have policies put in effect, we have to make sure that there are monies that follow that practice or that policy, monies that are going to help farmers and assist them in order to put those practices on the ground.

And whether it is all Federal Government or whether it is private or public together, and how all that fits together, someone else would have to figure that out. But you are exactly right. It is very expensive for some of those new projects to get put on the ground, and the new policies that are going to be put into effect. There needs to be money to follow it. If Americans and the rest of the world want agriculture to be the answer to this problem, then we got to have partners to be able to meet those obligations that we are going to have to meet to be successful and do it.

Mr. HARDER. Well said, Mr. Duvall. Thank you for that.

We look forward to working with you. We have some strong partners with our local Farm Bureau, and I think there is a lot of interest. That is the good news. I mean, I think folks want to be able to adopt 21st century technology, 21st century practices. They just want to know how to pay for it, and I totally get that. I mean, it has to make business sense, and the question is, as legislators, how can we help them have it make business sense? And I think we are looking forward to working with you on some ideas for that.

Thank you so much for your time, and I yield back the remainder, Ms. Adams. Thank you.

Ms. ADAMS. Thank you.

I want to recognize the gentleman from Kansas, Mr. Mann, you have 5 minutes.

Mr. MANN. Thank you for the time.

Thank you, Chairman Scott, for your remarks about ensuring that agriculture is in the pole position in these discussions, and that we highlight the climate solutions that are produced by agriculture while our producers feed, fuel, and clothe not only the country, but really the world.

I proudly grew up on a farm in Quinter, Kansas, population 800. I was the fifth generation to live in my house. My folks and my brother still run our farming operation. We raise corn, milo, wheat, had a feed yard, spent thousands of hours on a tractor combine, doctoring sick calves, really a privilege to get to grow up there. And I think it is important in these discussions that we all remember that agriculture also is the lifeblood to keeping a lot of our basic values alive that we hold dear in this country. Those values being faith, family, looking out for our neighbors, working hard. The values that are central to us as Americans are supported by agriculture, which makes these discussions all the more important.

I proudly represent the big 1st District of Kansas, one of the biggest ag producing districts in the country. We are number one in the country on beef production. We are number one in the country on wheat production, number one on sorghum production, number three on corn production. We also have biofuels, food processors, dairies. It is a privilege and honor to get to represent these groups.

My question also is for Mr. Duvall. So, I don't know if you remember this, Mr. Duvall. I was our Lieutenant Governor of Kansas, and you and I were in southwest Kansas in Garden City, and checked out some water technology farms and spent the day together. I really enjoyed that day. It would have been almost 2½, 3 years ago.

One of my big takeaways—and my question will be for you, Mr. Duvall, like I said, is—and I think one thing we got to continue to highlight is we all should be encouraged to hear about the strides that American farmers and ranchers have made in addressing and mitigating carbon, especially with the reduction of agriculture's share of greenhouse gas emissions from 24 percent in 2010 all the way down to ten percent here in 2019. So, in 9 years we have gone from 24 percent down to ten percent. Remarkable. And I guess my question for you, Mr. Duvall, is can you explain how that reduction was made by farmers and ranchers in the U.S. in your mind, even as they continue to provide a safe, reliable, and affordable food supply? It is an amazing accomplishment and we need to keep highlighting it. I am just curious to know your perspective. Many of your members were part of that, and how do we go about accomplishing that?

Mr. DUVALL. Sure, and there is not one answer that answers that question, because we have talked about all of them here, the opportunity to participate in the programs through the USDA that are partnerships and incentive-based. Our farmers have latched on to that.

Technology that has come from the research from—whether it be the plant and how we can not have to disturb the soil to get rid of weeds, but we can control them with other products, and we can do it with GPS and in precision plant farming. So, we have just come a long way in the techniques that we use, and we can do that because of the technology. We could go so much further if we go back and talk about streamlining the approval of these new technologies coming, increase the research. And we can even do more to not just lower our emissions, but to help take in—take care of some of the problems of the emissions from other areas of other industries.

So, there is not one answer that answers that question. Our farmers are resilient, and they are technical savvy, and they will take advantage of every opportunity, and we have to have broadband to make sure that we can take care—utilize the new technology that is coming in the future, because precision agriculture is here, and our farmers aren't wearing overalls anymore. They are carrying computers and iPads around with them to get the job done, and broadband is important.

And your part of the state and that travel—that visit was wonderful. I absolutely fell in love with that part of our country.

Mr. MANN. Well, glad to have you, and you really touched on my next question, and that is, in my view, rural broadband has got to be a part of this discussion, because to really continue to improve on carbon, we have to have precision agriculture and rural broadband is the technological underpinning of that. So, I could not agree with you more, Mr. Duvall.

Thank you for all of our panelists today. I really appreciate your time. And with that, I yield back.

Ms. ADAMS. Thank you. I want to recognize now the gentlelady from the State of Washington, Ms. Schrier. You are recognized for 5 minutes.

Ms. SCHRIER. Well, thank you, Madam Chair.

Some of the biggest concerns that I hear from farmers in my district in Washington State have to do with concerns about declining snowpack year over year, and therefore, less reliable water resources for irrigation that will only worsen over time because of our changing climate. And that is why researchers out of Washington State University's Tree Fruit Research and Extension Center in Wenatchee, Washington are exploring ways to sustainably secure and more efficiently use water. And their goal is, of course, to help farmers and growers produce food, given scarce and unpredictable water resources. And they have actually discovered that grape growers can achieve better yields with less water. So, with the changing climate, we do need both resilience and adaptation.

Now, I want to focus on regenerative farming, which has been discussed so thoroughly today, and mostly how the Federal Government can support farmers. So, as discussed, regenerative agriculture refers to a constellation of practices like crop rotation, cover crops, and no- and low-till farming that improves soil health, sequesters carbon, reduce the need for fertilizer and water inputs, improve yields, and also help mitigate and adapt to climate change.

Now, these practices help farmers and are also key elements in addressing climate change. So, farmers are driving, as we have heard today, so much of the innovation and leading the efforts to expand these practices, and after up front investments, these are win/wins for farmers, as we heard from Mr. Brown.

But there are big front-end expenses, like drill seeding machines, and the payoff often doesn't happen until about 6 years later. And I am really excited by the Biden Administration's commitment to climate solutions, including these agricultural solutions. So, what I would like to ask is how the USDA programs can help scale up? For example, the USDA's EQIP Program provides financial and technical on the ground assistance for conservation and regenerative agriculture.

And so, I guess my question first is to President Duvall. Could you say how else can the Federal Government help, and how could we ensure lasting help that could get farmers all the way through those 6 years?

Mr. DUVALL. Well, of course you are exactly right. It takes a tremendous investment to move in the direction. Even Mr. Brown admitted that he took advantage of some of those programs, and then earlier, I made the statement—and I know it is true—that there are farmers that want to participate, but there are not enough funds there to do it. And you are exactly right. That no-till machine, it costs a lot of money, and if you are not a medium- or large-sized farmer, you may not be able to afford that.

Ms. SCHRIER. I even asked farmers if they could share. Like if you could have one for the entire town, and you can't do that. They all plant at the same time.

Mr. DUVALL. Well, soil and water conservation district here owns one, and you can rent it from them. There is sharing going on, and that is a program that is very well-used here in my community.

There are ways to do this, we just have to explore how to do it. But there are more people wanting to be involved in it. They are interested in doing it. They just want to—they don't want anybody to force it on them. Because every farm is different, and I think Mr. Brown made the point that his techniques work anywhere in the world. I don't disagree with that, but there are a lot of differences in soils and regions and weather patterns and everything else. Some work good, some work better, and we just have to—we can't have one thing that fits all.

Ms. SCHRIER. Absolutely. Thank you.

I want to ask a little bit about carbon credits, but I don't know that I have time for that. Can I ask just maybe in 30 seconds, maybe Mr. Brown, can you tell me a little bit about biochar and whether that is being implemented? Whether that is something that can even be scaled?

Mr. BROWN. Thank you. Biochar is certainly a tool that can be used in the right context. Again, it comes back to carbon. So, in your situation, obviously in Washington State, you have sources of that carbon available where biochar could be made. I would use that as a tool starting out. I would look at the Johnson-Su bioreactor of adding biology, and then also a hidden gem you have is the Bread Lab there in Washington State. The work that Dr. Steven Jones is doing is just unbelievable with granule grains.

Ms. SCHRIER. Oh, fantastic. I have one more thing. I am running out of time, which is just that I agree with everybody today that we need to have farmers at the table, and that is why I have invited Robert Bonnie, USDA's Deputy Chief of Staff for Policy and Senior Advisor on Climate to my district in order to sit down at a roundtable with my farmers to talk about climate policy, the good, the bad, and the ugly, and our farmers need to be at the table.

I would like to submit that letter for the record.

[The letter referred to is located on p. 387.]

Ms. ADAMS. So ordered.

Ms. SCHRIER. Thank you. I yield back.

Ms. ADAMS. Thank you.

I want to recognize the gentlelady from Illinois, Representative Miller, you are recognized for 5 minutes. Representative Miller? Okay. All right, the gentlelady is not—I don't see her. Okay.

I want to recognize now the gentleman from Alabama, Mr. Moore. You are recognized for 5 minutes, sir.

All right. The gentlelady from Florida, Mrs. Cammack, you are recognized for 5 minutes. The gentlelady—is Mrs. Cammack here, gentlelady from—okay.

The gentlelady from Minnesota, Mrs. Fischbach, you are recognized for 5 minutes.

The gentleman from New York, Mr. Jacobs, you are recognized for 5 minutes, sir.

The gentleman from Iowa, Mr. Feenstra, you are recognized for 5 minutes. Mr. Feenstra?

The gentleman from—is that Iowa? No, the gentleman from North Carolina, Mr. Rouzer. You are recognized for 5 minutes, sir.

The gentleman from Ohio, Mr. Balderson. You are recognized for 5 minutes. Okay.

Let me go to the gentleman from California, Mr. Panetta. Mr. Panetta, you are recognized. Go ahead, sir.

Mr. PANETTA. Thank you, Madam Chair. Am I good to go?

Ms. ADAMS. You can go ahead, yes.

Mr. PANETTA. There you go. Thank you. I appreciate that. I am fortunate to have sat down in my seat.

Thanks to all the witnesses for being here. I appreciate your preparation and your contribution. I know it has been a long hearing, and I appreciate your patience with this. So, I appreciate your preparation, and of course, your participation in a very, very important hearing. And obviously, thanks to the Chairman for holding it, as well as the Ranking Member, "GT".

Look, I think if there is anybody concerned—at least in my experience with my producers on the Central Coast of California, if there is anybody concerned with fresh air, healthy soils, and clean water, it is our producers. And I think that has been made evident today with the similar sentiments that have been expressed, not only from our witnesses, but from the Members on both sides of the aisle.

I believe in my conversations and my work with my ag producers, they value and understand the concept that maybe some of you have or have not heard about. It is called *usufruct*. And basically, it is the temporary right to use the land, *usus,* to produce fruit, *fructus,* usufruct. And what that means is that they—I believe our producers understand that they are here. They use the land, but they also have to preserve it for our future, because they know it is not theirs. It is a temporary right. And that is important, because I believe that when it comes to dealing with the climate crisis, I can tell you, our producers understand that and our producers, therefore, as we have heard throughout this hearing, need to be at the table.

And I also want to give a shoutout and acknowledge our new USDA Secretary Vilsack for his vision to ensure that our farmers are at the table. And I believe it is our obligation to ensure that our producers, especially mine on the Central Coast, many, many specialty crops, are at the table. And as many of you have heard me say—and it is the first full—well, second hearing in which we are having at this Agriculture Committee, I can say people know that I come from the Salad Bowl of the World, and therefore, we have a number of specialty crops. And so, obviously those types of producers have been progressive when it comes to maintaining and preserving the earth that they use to produce their fruits and vegetables.

And so, I want to just focus on Mr. Brown right now. Obviously, when it comes to specialty crops—I know you are from North Dakota. My wife is from North Dakota up in Rugby. There are not many specialty crops up there, but when it comes to specialty crops, what type of smart agricultural efforts are there when it comes to their concern for climate crisis?

Mr. BROWN. The same principles apply, whether we are doing specialty crops, lettuce, salads, vegetables, fruits. We are working extensively in California working with your growers—I am sure some of them are—and the technologies they are using are these technologies to use these principles in order to lower their input costs. And they can do that. There was a previous comment that it takes 6 years to recoup the costs. That is not true at all. We are seeing significant savings by year 2, certainly by year 3. So, the same principles apply.

Mr. PANETTA. Okay. Let me pivot to Ms. Knox. Would you agree?

Ms. KNOX. Yes, I think there are a lot of immediate benefits. I mean, it doesn't take a long time to see benefits to the soil. It doesn't see—a long time to see other benefits to specialty crops. Here in Georgia, we are seeing people try new crops. We are growing satsuma mandarin oranges, and we are growing olives. You don't really think of Georgia as being a place to grow olives, but we do have a chance to expand into new areas that could be new markets, and to take advantage of that.

But growing them regeneratively is definitely going to help the producers in the long run, because it will reduce the number of inputs.

Mr. PANETTA. Thank you.

And speaking of Georgia, let me say hello to my friend, President Duvall. Obviously—let me first acknowledge the fact that he understands that the number one issue of agriculture right now is labor, and how important that is. However, we do have to deal with this climate crisis as well.

And so, President Duvall, tell me how the American Farm Bureau has reached out to our specialty crop producers to ensure that they are at the table as well when it comes to coming up with a solution, or the many solutions that we have to come up with for dealing with the climate crisis in the field of agriculture production?

Mr. DUVALL. Congressman, ever since I have been at the American Farm Bureau, I have encouraged inclusiveness. That means all kinds of agriculture, all genders, all races to come to the table, because you know, it is our job and our mission to be able to provide one united voice of the American farmer. How can we do that without all of them being there? So, we have been pretty successful and——

Ms. ADAMS. The gentleman is out of time.

Mr. DUVALL. Look, we are not here just to represent big agriculture, but we need you to come to the table and give us your ideas, and that is what we are trying to do.

Ms. ADAMS. Thank you.

Mr. PANETTA. I look forward to being at the table with you, President Duvall.

Thank you, Madam Chair. I yield back.

Ms. ADAMS. Thank you. Are there any Republicans that I can't see that need to be recognized? Okay, then we will move on to the gentlelady from Iowa, Mrs. Axne. You are recognized for 5 minutes.

Mrs. AXNE. Thank you, Madam Chair, and thank you to Chairman Scott just for holding this hearing that is so important. It is such a pressing issue, and I really appreciate our witnesses being here today to share your expertise. I very much appreciate the testimony given and the discussions around how much our environment has been affected by climate change, and how substantial that cost has been.

Jim, you noted in your testimony the increasing number of climate events that result in costs exceeding $1 billion, and what a shocking number: 22 events last year. But unfortunately, as you mentioned, those events have become all too common for folks back in my home State of Iowa. We are the ones who had the derecho sweep across our state, and when Iowans don't know what a storm should be called, it is definitely something out of the ordinary. And of course, we saw millions of farmland acres destroyed, left hundreds of thousands of Iowans without power. And then just a year prior to that in southwest Iowa in my district, we saw devastating flooding along the Missouri River, which destroyed homes and farmland up and down the river. And honestly, we simply cannot afford to accept that these events are the norm, and we have to take action on this climate crisis to reduce our carbon emissions and build up resiliency so that our farmers can be successful.

So, my first question is to you, Mr. Brown. Thank you so much for sharing with the Committee the successes that you and others have experienced as a result of sound soil health practices. I was reading your written testimony, and I was taken by the story of Mr. Adam Grady from North Carolina. Two weeks after waters receded from Hurricane Florence, Mr. Grady was already seeding his fields. Like Mr. Grady, farmers in Iowa are facing increasing challenges combating excess moisture each year as a result of more frequent wet springs.

Mr. Brown, can you just take a moment to describe how the soil health practices can help farmers adapt to floods and the changing climate more broadly?

Mr. BROWN. Well, thank you. That is an excellent question. I am going to hold up this jar to signify this is actually soybean seed in a jar, but think of it as soil aggregates. So, soil aggregate is just like one of these seeds. It is a little pad of sand, silt, and clay bound together. Water: your infiltration rates of water depend on those soil aggregates. A soil aggregate will only last about 4 weeks, and then new ones need to be built. In order to build new ones, you have to have soil biology. You have to have mycorrhizal fungi.

We were holding a soil health academy there in southeastern Iowa, and they were bragging about the very rich soils of eastern Iowa. Unfortunately, they had ½″ of rain and that water could not infiltrate.

You mentioned the flooding problems we are seeing along the Missouri and Mississippi Rivers, here in North Dakota, the Red River. Year after year we combat that. What we need to do to alleviate that is build soil aggregates. We can help alleviate our flooding, alleviate those costs that occur year after year, as you said, to society if we focus on the resiliency of our soils. We are not doing that anymore. I travel extensively, all 50 states, and I have taken soil test after soil test after soil test that shows that we no longer have the ability to infiltrate water.

In 2009, we had a major rainfall event on my ranch. We had 12.6″ of rain in 6 hours. The next day, I could go out in my fields and drive across them with the tractor and not leave a rut. It is all about biology and building back resiliency through soil health.

In Iowa, they can certainly do that with the wonderful resources you have there.

Mrs. AXNE. Well, I appreciate that, and it is inspiring to hear this, and thank you.

As your work as a farmer and educator takes you around the country, as you mentioned, what do you think are some of the biggest reasons that you hear from farmers that prevent them from adopting these soil health practices, and what technical and financial resources do you think are needed for us to encourage to scale up adoption of these practices?

Mr. BROWN. That is a wonderful question, one I get asked daily.

The number one reason is fear. For farmers and ranchers it is fear of the unknown. Again, it goes back to education. The second is the current farm program. The current farm program, I am sorry, but it is not conducive to adopting these practices. We make small steps through NRCS and that, but then the production model is wrong. We are on a path through Risk Management Agency where the crops seeded revenue insurance determines 95 percent of what farmers and ranchers plant. Because they have to obtain operating money, operating notes from the bank in order to stay in production that year, that bank is going to tell them you have to take part in this program, and then you have to plant those crops that will allow you the greatest return through risk management.

Don't get me wrong; we need crop insurance——

Ms. ADAMS. The gentleman is out of time.

Mr. BROWN.—we need risk management, but it has to be changed. Thank you.

Ms. ADAMS. Now, I want to recognize the gentlelady from Florida, Mrs. Cammack. You are recognized for 5 minutes, ma'am.

Mrs. CAMMACK. Thank you so much, and good afternoon. I would like to thank the witnesses for hanging in there on this long hearing today and appearing before the Committee. I would also like to start by asking everyone who has had a meal today to please thank a farmer.

While we have this important discussion about the environment, climate, and U.S. agriculture, it is important to remember that the realities already facing our farmers are pretty grim. Growers in my home State of Florida and those throughout the country continue to face a number of challenges to remain competitive in the face of rising foreign imports. These imports are not grown under the same high environmental standards adhered to by U.S. producers including standards for air, water, solid and hazardous waste, and not to mention the labor standards. This conversation about what more farmers need to do in order to protect our environment becomes a bit trivial, in my opinion, when our farmers are forced to add to food waste because they can't compete with cheaper imports, as I just saw last week in south Florida when our producers had to disk up crops simply because they could not compete with cheap imports. The disparities when it comes to labor, regulatory, and environmental standards have left our producers at a tremendous and devastating disadvantage.

So, I would like to start out with Mr. Duvall. Thank you for being here with us. For the record, if you can, and in one word, from what you have seen, which country produces on a large scale the highest quality agricultural products with the lowest environmental impact?

Mr. DUVALL. The United States of America.

Mrs. CAMMACK. I love that answer. And as a follow-up to that, Mr. Duvall, and in the same format, in terms of inequitable competition, which country poses the largest threat to American agriculture?

Mr. DUVALL. In your area, Mexico.

Mrs. CAMMACK. Thank you.

Mr. DUVALL. Over-dumping product into your state.

Mrs. CAMMACK. Absolutely, thank you.

Ms. Knox, you mentioned in your testimony that the environmental impact that the clearing of land has on the release of carbon dioxide into the atmosphere. I want to ask, do you agree that it is more environmentally conscious to support our local producers here in the United States, rather than foreign producers held to looser regulation?

Ms. KNOX. I think supporting local farmers is always an important thing to do. It minimizes the cost of transportation to help support the local economy, and so, I—and they really farm more responsibly in a lot of ways, because we are more strict about our regulations. And so, I really support local farmers because of that.

Mrs. CAMMACK. Excellent. Thank you, Ms. Knox, and I have to say go Gators, just because—well, you know why.

Now, Mr. Brown, as you know, many American farmers are ready and willing to participate in carbon sequestration and implement regenerative agriculture. I have seen a clear desire to embrace these practices in my home State of Florida; however, I have also seen farmers frustrated by the prohibitive costs associated with implementation. In my district alone, we have producers that are forced to spend anywhere up to the tune of $300,000 just to participate in a carbon sequestration program. In your opinion, how can we make carbon sequestration and other green infrastructure investments more affordable for America's producers?

Mr. BROWN. Well, they should not be participating in that program if it is costing that. It is about much more than carbon. Farmers and ranchers need to be paid for all ecosystem services. We are talking about carbon, but it is much more than that. It is clean air, clean water. It is taking nutrients out of the watersheds, holding them on the farm where they belong.

The way to do that is using the USDA programs to incentivize best use practices, and to educate those farmers and ranchers.

Mrs. CAMMACK. Thank you.

Mr. Shellenberger, you have done a tremendous amount of research and work developing your book, *Apocalypse Never.* Since I have about 40 seconds left on the clock, I would like to give you my remaining 30 seconds to give an elevator pitch as to why people should read your book, and what the biggest takeaway is.

Mr. SHELLENBERGER. Thanks for asking.

I mean, the argument of the book is that climate change is real, but it is not our biggest environmental problem. Our biggest environmental problems stem from the inefficient use of land, particularly in poor countries, and if I had more time, I would have described all the work that I think American farmers can do to extend the innovative, efficient, and productive kinds of agriculture that we have developed here to poor and developing countries, because that is really what matters in terms of protecting natural ecosystems and lifting everybody out of poverty, which are goals that I think we all share.

Mrs. CAMMACK. Thank you so much, and Mr. Cantore, I am sure I will see you in Florida later this year.

And with that, I yield back.

Ms. ADAMS. Thank you.

The gentleman from Florida, Mr. Lawson, you are recognized for 5 minutes, sir.

Mr. LAWSON. Thank you, Madam Chair, and I will try to go real quickly.

My question is going to be for Mr. Duvall. My district in north Florida is home to so much of the state's timber industry and working forests. Hurricane Michael in 2018 really pummeled our area's agriculture, delivering $1.2 billion in damages to timber. So, I am interested in policy that could incentivize reforestation and timber production, which could especially help producers in catastrophic events such as hurricanes.

Can you talk about the merit of intensifying sustainable practices on these lands, and their contribution to our overall goal of mitigating climate change?

Mr. DUVALL. Yes, the forests around our country contribute huge help to solving the problems of climate change, and we all know that trees are the biggest sequestrator of any forage that is out there, any plant that is out there. So, you are exactly right. To incentivize people to be more in agriculture in a forestry area, we have to make it profitable again. The only way to make a living on forestry is to have tens of thousands of acres and not all the farmers have that. Very few have that, and the management tools that they use, our state forestry units are kind of confined with the resources. There is not enough money there to help people go out and—technicians to go out and help them put those practices on the ground, whether it be state or Federal. But I think that would be a huge help if USDA could help assist that.

You come to your part of the country, my part of the country, we don't have forest fires because we manage our timber. We burn off that fuel. We make sure that that fuel is not there to harm all the homes that are around it. The management in forestry is vitally important, not just to being productive and not burning, but it is also important to sequestering carbon.

Mr. LAWSON. Okay, thank you very much.

Ms. Knox, from tomatoes, citrus, specialty crops are critical in the Florida economy. Our land-grant institutions are doing great research to address these to our crops. I am concerned that climate change will only make the battle more difficult. Can you please go into a bit more detail regarding potential impact that climate change would have on, especially, specialty crops?

Ms. KNOX. I think climate change will affect them in a variety of ways. I think as temperatures go up, there may be some specialty crops that are not going to grow well in Florida, and they will look for new varieties that may be able to keep better. I think they are going to also worry a little bit about water availability, although as I understand it now, a lot of the specialty crops in Florida are already under irrigation, so there would be a question of will there still be water available? But I think that is probably not as important.

I think one of the other issues is as the growing season increases—of course, part of Florida has a year-round growing season, but other parts still do see frost. We are going to see increases in the number of pests, and those pests aren't only coming locally, but they are also being blown in from other places, and we don't really know yet what the weather patterns are going to do as far as the wind shifting over time. And so, that is certainly something that could also be more than it shows. We get more of these pests and diseases that are blowing in and certainly affecting some of the specialty crops.

Mr. LAWSON. Thank you, Ms. Knox. That was really great to know.

And with that, Madam Chair, I yield back.

Ms. ADAMS. Thank you.

The Committee will recess subject to the call of the Chair.

[Recess.]

The CHAIRMAN [presiding.] Thank you. Our Committee will come back to order. We are getting around to the finishing line. I can't thank everybody enough for hanging in there with us. It lets you know how serious everybody is about this very serious issue we are facing on climate change. Thank you for tolerating our interruptions, particularly our panelists who have been with us here since 12. Great. I really, really appreciate you.

Now, we are going to finish up with our hearing. We have, I believe, Mrs. Fischbach from Minnesota. You are now recognized for 5 minutes.

Mrs. FISCHBACH. Yes, sir.

Thank you so much, and I hope everyone can hear me.

First of all, thank you, Mr. Chairman, and I would especially like to thank all of the panelists for hanging in there with us. It has been an interesting day of running back and forth and all kinds of other things happening here, but thank you so much for hanging out with us.

Mr. Chairman, there is no doubt that our changing weather patters presents challenges for farmers and ag producers, but while addressing those challenges, we must do so in a way that respects the industry and recognizes their achievements protecting our environment. Adding more regulations or pushing lopsided partisan measures is not the answer. Instead, we should incentivize farmers to adopt what many of them already do through innovation and ingenuity. The soils they cultivate better protect against erosion and nutrients lost. The equipment they use is far more efficient than just a few years ago, and farmers are utilizing technology to minimize inputs and further reducing their footprint.

There is a challenge that must be met without partisan agenda. All of us agree that we each have a role in protecting our environment and farmers are some of the best stewards of our lands and resources. The farmers and producers I know want to be partners in this work, but nothing meaningful will happen by enacting punitive measures that malign their hard work, and it will happen by affording them the respect they deserve.

That being said, Mr. Duvall, I firmly believe that any climate proposal that doesn't include biofuels in part of its calculus is not a serious proposal. This homegrown American energy source is a vital part of my district's economy, and many others of this Committee. Can you speak a little bit to the benefits of this product in reducing our emissions, and where it does fit in the climate-related proposals?

Mr. DUVALL. You are talking about renewable energies?

Mrs. FISCHBACH. Yes, biofuels in particular, I am sorry.

Mr. DUVALL. Yes, ma'am. I mentioned earlier to another question that we need to make sure that we recognize that this country went and asked agriculture to be a part of our energy independence solution, and we are a piece of that pie. And the infrastructure around that is so important. About 30 percent—I stand corrected if I am wrong—but I think about 30 percent of the corn and 30 percent of the soybeans goes to biofuels, and now we are generating enough that we can even export it. It has been a tremendous lift to your part of the world and the Midwest, and it has not only helped the farmers, it has helped rural communities and kept them vibrant. And anything we do to hurt that industry is going to be devastating to that part of our country. So, we would not support anything that would hurt that infrastructure and the biofuel.

Mrs. FISCHBACH. And Mr. Duvall, I appreciate that.

Mr. Shellenberger, we just touched a little bit on some of the issues of broadband, and I am just wondering if you can comment on how that increased broadband connectivity plays a role in the discussion, and how it relates to the precision agriculture technology?

Mr. SHELLENBERGER. Yes, great question. I totally agree that it is essential what we have been seeing with the revolution in precision agriculture is the application of GPS and high-processing computers to be able to take efficiencies and productivity to the next level. So, yes, I think it is obviously in the public interest to support that expansion and it seems like a no-brainer from my point of view.

Mrs. FISCHBACH. Well, and I will just comment on our last Committee hearing, I was dialing in remote from home and I had some connectivity issues, so it made quite the point that day.

But I will yield back the remainder of my time. Thank you, Mr. Chairman.

The CHAIRMAN. Now, Mr. Randy Feenstra from Iowa, 5 minutes.

Mr. FEENSTRA. Thank you, Mr. Chairman, Chairman Scott and Ranking Member Thompson.

First, I want to thank each of the witnesses for their testimony today. It is very important that we discuss how farmers, ranchers, and the agricultural industry have already been leading the world in reducing the environmental footprint and additional opportunities that exist for their continued leadership.

I would like to quickly note that in Mr. Cantore's testimony, he made mention of the devastating derecho storm that impacted Iowa last year. While I believe this Committee must work to understand how we can help the agriculture industry to mitigate and be resilient against disasters, we must also ensure that we provide timely relief for producers devastated by damage. And this is something that I have been actively working on.

With that, this question would be for Mr. Shellenberger. So, getting back to climate change, Iowa's agriculture community has been a leader in addressing climate change. I believe that biofuel production, just like Ms. Fischbach noted, and Iowa in the 4th District should be a leading—be made a leading role in the efforts to reduce carbon emissions. It is also important to recognize the potential of biofuels to further reduce the carbon intensity with the potential to be net carbon negative. Let me say that again. Biofuels can make things net carbon negative, unlike electric vehicles, especially if the Federal Government helps companies to implement innovative technologies.

Green Plains Incorporated just announced last week that three of their bio-refineries, including the plant in Superior, Iowa, have entered into a carbon capture and sequestration project. In short, the project will transport CO_2 from Iowa to North Dakota for the deposit in their geological storage. This will allow these bio-refineries to reduce their carbon intensity by as much as 50 percent, comparable or lower than the other low carbon fuels available on the market today. Green Plains Incorporated cited that section 45Q tax credits as being important to allow the company to invest in these innovative technologies.

So, Mr. Shellenberger, I think this aligns with your testimony's theme of encouraging technological innovations as an answer to climate change, instead of burdensome regulations. Could you discuss other incentives like the section 45Q credit that you believe would be helpful to drive innovation in the agriculture industry to reduce carbon emissions?

Mr. SHELLENBERGER. Sure. Yes, I mean, I think all of those investments are important, both for carbon sequestration and for biofuels. I think in the past, we have over-subsidized the production of biofuels when I think more targeted R&D was merited, so I haven't looked at the specific projects you mentioned, but clearly, this kind of cooperation to solve specific problems I think is the way to go. There are some calls that have been made for kind of generic increases of innovation that I don't think make as much sense. But I think we have seen, obviously, with the coronavirus vaccine and the Shale gas revolution, nuclear power, genetically modified seed technologies that when we have a specific objective that we are trying to achieve, that the public- and private-sector can come up with some really remarkable innovations. So, I think that those are all great directions to be going in.

Mr. FEENSTRA. Thank you, Mr. Shellenberger.

So, if you could—just a little more—would it be more beneficial—I mean, you think of biofuels and if you could make something net carbon negative, wouldn't that be the paramount structure of what we all desire?

Mr. SHELLENBERGER. It would. I think the challenge with biofuels, as you know, we have had a challenge in terms of counting the carbon sequestration and emissions in the past. There has been a pretty significant debate about whether clearing land for biofuels actually results in a net loss or a net gain of carbon emissions. So, I just think it is an area that we need to proceed with some amount of caution, because I do think we have seen biofuels scaled up in the past that have not really panned out in terms of their benefit. So, I think we need to take a close look at which of the biofuels we are using, and how we are doing those calculations.

Mr. FEENSTRA. Sure. Thank you.

But wouldn't that be the same for electric vehicles? I think that exactly what you just said would be noted for electric vehicles also. Would that be a fair statement?

Mr. SHELLENBERGER. Absolutely, and there is a very active debate within the energy analysis community about whether electric vehicles are going to be the right solution, or whether it would be hydrogen-powered fuel cell vehicles. There are good arguments on both sides. I am personally agnostic about it. I think they have to be decided on a case-by-case basis. There are reasons to think that hydrogen is the way we will be going in the long-term, but again, I just think it is a little bit too early to say.

Mr. FEENSTRA. Well, thank you for your comments, Dr. Shellenberger. I greatly appreciate them. I am still a believer that the combustion engine can do great things, as long as we can provide a negative carbon footprint.

Anyway, thank you. I yield back my time.

The CHAIRMAN. Well, thank you so much, and let me just say how grateful and just how thankful we all are on this Committee for the outpouring of help and knowledge and information, accurate, that will help us that you five experts have given to us today. We thank you for the time that you have put in. This has been a long and thorough hearing.

But let me just tell you the great good that you all have done too this day, because as I said in the outset, our whole thrust forward to deal with climate change must be anchored in agriculture. That is the major and critical thing we have established today. And that is what is important.

So, to you, Mr. Jim Cantore—and I think I got your name right—the senior meteorologist—and I hope I got that one pronounced—of The Weather Channel, thank you. Thank you so very much.

Ms. Pamela Knox, Director of the University of Georgia's Weather Network, thank you for your piercing insights that you gave to our Committee.

And to Zippy Duvall, my good friend and fellow Georgian, President of the American Farm Bureau Federation, thank you. You brought such great insight directly from the perspective of our farmers. They are the ones that we want to make sure our climate change is based upon making sure our farmers are not only at a seat at this table for climate change, but at the head of the table. Our farmers.

Mr. Gabe Brown of Brown's Ranch, the Brown's family ranch from Bismarck, North Dakota, thank you so much. You brought such great wisdom and information of which many of us were only dimly aware on this Committee. Thank you for that.

And also, I mentioned Mr. Gabe Brown from Bismarck, North Dakota. And Mr. Michael Shellenberger, President of Environmental Progress. The five of you have done a wondrous benefit, not only for this Committee, but for the nation. We have received information that literally thousands of people across this country were tuned in to this hearing, and that is what is important.

So, from the bottom of my heart and the bottom of the heart of our Agriculture Committee here, we just want to say thank you, and God bless you.

Now, I turn it over to you, Ranking Member, for your closing remarks.

Mr. THOMPSON. Well, thank you, Mr. Chairman. Thank you to our witnesses. They did just a tremendous job. And I have to say, an impressive turnout by our Members on both sides of the aisle participating in this. I know we went long, but that is because it shows the passion and the interest of the Members. Thank you, Mr. Chairman. I thought it was an efficiently run hearing. You got that much interest, and I think we are going to have long hearings because of the commitment of the Members that we have on the Agriculture Committee.

United States agriculture is the most productive and the most successful at mitigating greenhouse gases than anywhere else in the world. Our goal must be a healthy environment and a healthy economy. You cannot compromise one over the other. Anything that we do needs to be both good for the environment and for the economy. And that, quite frankly, means the economics of our farm and ranch families, money in their savings accounts and their checking accounts as well. Agriculture has the solutions. U.S. agriculture has the science, and U.S. agriculture has the proven outcomes when it comes to this topic of climate. Our focus should be climate solutions that are based on science, innovation, technology, and voluntary led conservation. That defines American agriculture.

So, thank you, Mr. Chairman, and I yield back.

The CHAIRMAN. Well, thank you, and before I adjourn, of course, none of this would have happened had it not been for our great staff, Ranking Member, and I am speaking on your side and mine. They worked night and day to pull this hearing together, and I tell you, I want to say just a big thank you to our great staff here in the Agriculture Committee for the great work that they have done.

Mr. THOMPSON. I certainly agree. They make us look pretty good.

The CHAIRMAN. I think so.

So, with that, then this hearing comes to an end, and thank you all very much for your participation.

Thank you.

[Whereupon, at 5:31 p.m., the Committee was adjourned.]

[Material submitted for inclusion in the record follows:]

SUBMITTED ARTICLES BY HON. DAVID SCOTT, A REPRESENTATIVE IN CONGRESS FROM GEORGIA

ARTICLE 1

ehp Environmental Health Perspectives

[*https://ehp.niehs.nih.gov/doi/10.1289/EHP41*]

ENVIRONMENTAL HEALTH PERSPECTIVES

Estimated Effects of Future Atmospheric CO_2 Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region

[Is companion of *Estimated Deficiencies Resulting from Reduced Protein Content of Staple Foods: Taking the Cream out of the Crop?* (*https://ehp.niehs.nih.gov/doi/10.1289/EHP2472*)]

DANIELLE E. MEDEK,[1, 2] JOEL SCHWARTZ,[1] and SAMUEL S. MYERS [1, 3]

Abstract

Background: Crops grown under elevated atmospheric CO_2 concentrations (eCO_2) contain less protein. Crops particularly affected include rice and wheat, which are primary sources of dietary protein for many countries.

Objectives: We aimed to estimate global and country-specific risks of protein deficiency attributable to anthropogenic CO_2 emissions by 2050.

Methods: To model per capita protein intake in countries around the world under eCO_2, we first established the effect size of eCO_2 on the protein concentration of edible portions of crops by performing a meta-analysis of published literature. We then estimated per-country protein intake under current and anticipated future eCO_2 using global food balance sheets (FBS).

We modeled protein intake distributions within countries using Gini coefficients, and we estimated those at risk of deficiency from estimated average protein requirements (EAR) weighted by population age structure.

Results: Under eCO_2, rice, wheat, barley, and potato protein contents decreased by 7.6%, 7.8%, 14.1%, and 6.4%, respectively. Consequently, 18 countries may lose >5% of their dietary protein, including India (5.3%). By 2050, assuming today's diets and levels of income inequality, an additional 1.6% or 148.4 million of the world's population may be placed at risk of protein deficiency because of eCO_2. In India, an additional 53 million people may become at risk.

Conclusions: Anthropogenic CO_2 emissions threaten the adequacy of protein intake worldwide. Elevated atmospheric CO_2 may widen the disparity in protein intake within countries, with plant-based diets being the most vulnerable. *https://doi.org/10.1289/EHP41*.

Introduction

Globally, 76% of the population derives most of their daily protein from plants (FAO 2014a). With projected population growth to 9.5 billion by 2050 (UN 2013), alongside dietary and demographic changes, future nutritional demands may overwhelm global crop production (Alexandratos 1999). Compounding the strain on food supply, plant nutrient content changes under elevated atmospheric carbon dioxide concentrations (eCO_2) (Myers, *et al.,* 2014).

Under the CO_2 concentrations predicted in the next 50 y, crops with C_3 photosynthesis, such as rice and wheat, may experience up to 15% decreases in grain protein content (Myers, *et al.,* 2014). The effects of eCO_2 are less on C_4 crops, such as maize

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Supplemental Material is available online (*https://doi.org/10.1289/EHP41*).

The authors declare they have no actual or potential competing financial interests.

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and sorghum, and on nitrogen-fixing plants, such as legumes (Myers, *et al.,* 2014). Thus, the impacts of eCO_2 on dietary protein intake will depend on which staples a country consumes, their dependence on the staple for protein, and their current risk of protein deficiency.

Protein deficiency usually co-occurs with energy and micronutrient deficiencies (Millward and Jackson 2004). Insufficient protein intake limits growth, tissue repair, and turnover (Gropper and Smith 2008). Few controlled studies investigate protein deficiency syndromes in otherwise energy and nutrient sufficient diets. In renal disease, isocaloric protein reduction decreased lean body mass and lymphocyte count (Ihle, *et al.,* 1989; Klahr, *et al.,* 1994). In elderly women, these diets reduced cell mass and protein synthesis while impairing muscle function and immune status (Castaneda, *et al.,* 1995). Low protein intake contributes to wasting, stunting, intrauterine growth restriction, and low birth weight (Black, *et al.,* 2008). Together with protein-energy malnutrition syndromes, this causes an estimated 90.9 million disability-adjusted life years (DALYs) and two million deaths annually (Black, *et al.,* 2008).

Previous meta-analyses conducted on the effects of eCO_2 on plant nutrient contents (Taub, *et al.,* 2008; Loladze 2014) have not assessed eCO_2 impacts on edible protein from a global dietary context, nor did they consider distributional effects within countries. We aimed to estimate eCO_2 impacts on global protein intake, and on the proportion of the population by country at risk of protein deficiency. We aimed to expand on the meta-analysis by Myers, *et al.* (2014), including all available studies reporting eCO_2 impacts on the edible portions of crop plants, including lesser-studied foods and studies in (sub)tropical locations. Then, using published food balance sheets (FBS) and measures of economic inequality within countries, we aimed to estimate dietary protein intake under current and future atmospheric CO_2. We thereby tested the sensitivity of global protein intake and inequality of intake to rising atmospheric CO_2, identifying key regions to target with nutritional interventions.

Methods

Systematic Review and Raw Data

We conducted ISI Web of Knowledge (*https://pcs.webofknowledge.com/*) literature searches in July–September 2014 and in January 2016 for the effects of eCO_2 on the protein content of all plants listed in the FAO FBS. This study supplements the meta-analysis of common European/U.S. staples conducted by Myers, *et al.* (2014). Because estimates of plant protein are commonly derived by multiplying measured plant nitrogen (N) by a conversion factor, we considered published changes in N and protein to be equivalent (Taub, *et al.,* 2008). For the full search string and exclusions, see “Part 1” and “Part 2” in the Supplemental Material. A total of 119 citations were used. For references, see “Part 3” in the Supplemental Material.

We included raw data from free-air CO_2 enrichment (FACE) and open-top chamber studies, with data from European wheat, barley, and potato Changing Climate and Potential Impacts on Potato Yield and Quality (CHIP) and the European Stress Physiology and Climate Experiment (ESPACE) studies (A. Fangmeier, unpublished data, 1994–1999) and Australian wheat and pea Australian Grains Free Air CO_2 Enrichment (AGFACE), Japanese rice, American soy, corn, and sorghum Soybean Free Air Concentration Enrichment (SoyFACE) and Arizona FACE (data from Myers, *et al.,* 2014). Raw data included free-to-air carbon dioxide elevation (FACE) and open-top chamber studies, 41 cultivars, nitrogen fertilizer, watering, and time of sowing treatments over multiple years.

Response ratios (RRs) and standard errors (SEs) for protein response to CO_2 were calculated from each study’s reported error terms. When studies indicated merely significant at $p<0.05$ or not significant, the SE was calculated from p-values of 0.049 and 0.1, respectively.

Metaregression

Metaregression was performed individually for each commodity where data were available from four or more experiments and for commodity groups listed in the FAO FBS (*Table 1*). We used the statistical package Metafor (version 1.9–4 Wolfgang Viechtbauer) in R (version 3.0.3; R Development Core Team). For each commodity or group, the difference between ambient (aCO_2) and eCO_2 treatments was tested as a modifier. We used multivariate linear (mixed-effects) models (the function rma.mv) with outcomes being percent decrease in protein, and modifiers being the difference between aCO_2 and eCO_2 in parts per million. Models included variance and were weighted by replicate facilities (*e.g.,* number of FACE rings or growth cabinets) with random effects being year within site, and each cultivar (and unless tested as a modifier, each watering and nitrogen fertilizer treatment) was treated as a separate experiment. We performed Q tests to assess heterogeneity.

Table 1. Percent change in protein content by commodity class.

Commodity (*n*)	Estimate [mean (95% CI)]
C_3 grains (257)	−8.14 (−12.17, −4.1)
Wheat (166)	−7.78 (−13.24, −2.32)
Rice (66)	−7.61 (−11.53, −3.69)
Barley (21)	−14.05 (−20.7, −7.39)
C_4 grains (12)	2.07 (−3.2, 7.35)
Maize (8)	3.08 (−5.19, 11.35)
Sorghum (4)	0.26 (−6.31, 6.84)
Root vegetable (15)	−3.42 (−8.61, 1.78)
Potato (9)	−6.38 (−10.33, −2.42)
Pulses, legumes (26)	−3.51 (−8.05, 1.04)
Peas (15)	−1.69 (−3.56, 0.18)
Beans (7)	−4.58 (−12.37, 3.2)
Chickpea (4)	−13.47 (−21.36, −5.58)
Oil crops (54)	−0.78 (−5.03, 3.47)
Soy (44)	−0.49 (−2.92, 1.95)
Rapeseed/mustard seed (5)	0.92 (−8.9, 10.74)
C_3 Vegetables (32)	−17.29 (−30.78, −3.8)
Fruit (5)	−22.9 (−54.04, 8.24)

Note: C_3, crops with C_3 photosynthesis; C_4, crops with C_4 photosynthesis; CI, confidence interval; *n,* number of experiments, where each treatment/cultivar/experiment was treated as a separate experiment, yet experiments at the same location for the same crop were grouped together.

Meta-Analysis

Because there was no reliable dose-dependent decrease in protein content with degree of CO_2 elevation, we used meta-analysis to derive average response ratios comparing plants grown in aCO_2 with plants grown in eCO_2, where eCO_2 was in the range of 500–700 ppm. We used the rma.mv function as for metaregression, but without the modifier term. Both meta-analysis and metaregression tested fixed effects of pot- *versus* field-grown plants and a qualitative measure of nitrogen fertilizer treatment, categorized as low, adequate, or high, based on descriptions in each study's experimental design. Neither modifier changed the magnitude of the CO_2 response, and neither was used in subsequent analyses.

We minimized publication bias by including unpublished data. Furthermore, we tested sensitivity to publication bias. For each commodity, we incrementally added experiments with no effect of eCO_2 on protein content (RR 1, variance 0.5) until confidence intervals for RR crossed 1. Some commodities, including rice, were sensitive to null results, but wheat was insensitive to null results (see Table S3).

Food Balance Sheets

The FAO FBS estimate per capita availability of each food-based commodity (including energy and protein contents). We averaged data over 2009–2013 FAO FBS. We assumed that protein availability equals protein intake, corrected for digestibility (FAO 2014a). Per convention, we assumed that plant-based protein was 80% digestible and that animal-based protein was 95% digestible (Millward and Jackson 2004).

The "Vegetables, other" and "Cereals, other" categories were large contributors to protein intake in some countries, and contained both C_3 and C_4 plants, and for vegetables, nitrogen fixers. We produced weighted estimates of the contributions of each these categories, using re-calculated 2009 FBS from the FAOstat classic platform (described fully by Smith, *et al.,* 2015). We converted from total grams to grams protein, using food composition tables (Abdel-Aal, *et al.,* 1997; USDA 2011; FAO 2012; Ballogou, *et al.,* 2013; New Zealand Ministry of Health 2014). We assumed that the "Cereals, other, not elsewhere specified" category within the "Cereals, other" category was derived from C_4 grains in sub-Saharan Africa, but from C_3 grains elsewhere.

To estimate the effect of eCO_2 on protein intake in each country, we assumed constant mass-based consumption of each commodity over time, with declining protein content predicted by our meta-analyses. We used commodity-based averages when available, and otherwise applied the averages from the commodity group to each commodity (*Table 1*). We found no studies on eCO_2 response of tree nuts, thus conservatively assumed no change in their protein content. Likewise, we assumed no eCO_2 effect on animal protein.

Plant-Based Diets

Within a population, the lowest protein consumers also frequently consume the least meat (*see* World Food Programme household surveys; *e.g.,* Santacroce 2008). For an extreme scenario, we reran the models, removing all animal-sourced foods (including eggs and dairy) from the diet, assuming no other changes in dietary fractional composition.

Intake Distribution

We assumed a lognormal distribution of protein intake within countries (FAO 2014b), a cumulative distribution function, with the mean,

$$\mu = \ln\bar{x} - \frac{\sigma^2}{2}$$

and the standard deviation,

$$\sigma = \sqrt{\ln(1 + CV^2)}$$

where $\bar{x}$ is the national mean protein intake, as estimated above, and CV is its coefficient of variation. Because protein intake is likely to be related to household income, we estimated the CV of protein intake ($CV_{protein}$) from the Gini coefficient of national household income inequality. The national Gini coefficient for household income describes a Lorenz curve plotting the cumulative percentages of total income against the cumulative number of households from poorest to richest. Using linear regression, we compared per-household $CV_{protein}$ from household surveys across 36 countries (FAO 2014a) with contemporaneous national Gini coefficients (Arneberg and Pedersen 2001; Garcia, *et al.,* 2001; Kim and Kim 2007; OECD 2009; Liberati 2013; USAID 2012; CIA 2014; Solt 2014; World Bank 2014). The FAO uses Gini coefficients, gross domestic product (GDP), and food prices to estimate CV for caloric intake (FAO 2015). We then estimated the national $CV_{protein}$ from the country's Gini coefficient in the year closest to 2011. Owing to high uncertainty among future economic projections, we assumed each country's future $CV_{protein}$ would remain constant.

Estimated Average Requirements

We calculated a weighted estimated average requirement (EAR) (grams per day) for absorbed protein from the published EAR for adults (0.66g/kg/d) and for children by age and sex, using current and mid-range 2050 demographic projections (IOM 2005; UN 2013). For adults, the minimum safe protein intake in grams per day is based on the minimum healthy body weight calculated from the lowest 5th percentile of body mass index (BMI), this being 18.5 kg/m^2 (WHO 1995). We calculated average height from national surveys (OECD 2009; Hatton and Bray 2010; USAID 2012). Where male height was unavailable, it was calculated as 1.08 female $\times$ height, based on the median male-to-female height ratio across all countries. For child weight, the ideal body mass was the 50th percentile by age from growth tables (WHO 2006). We adjusted EAR to include the increased protein requirements of pregnant and lactating women (IOM 2005) with demographics estimated from projected birth rates, 2009 stillbirth rates and infant mortality, and breastfeeding prevalence and duration (McDowell, *et al.,* 2008; AIHW 2011; CDC 2011; UN 2013; USAID 2012; Liu, *et al.,* 2013).

Risk of Protein Deficiency

From each country's 2050 population, we calculated the proportion and the number of people whose intake fell below the EAR under current and eCO_2 scenarios, with the difference between these populations being our measure of impact.

We used Monte Carlo methods to propagate error from the SE of the meta-analysis results, and for modeled $CV_{protein}$, through the model, using 10,000 random draws from normal distributions of mean national protein intakes, and again for error around linear regression of CVprotein on Gini coefficient. From these two parameters, we calculated the means ($\boldsymbol{\mu}$) and standard deviations ($\boldsymbol{\sigma}$) of 10,000 lognormal distributions. These were used to estimate the probability for each country of protein intake being below the calculated EAR.

We summarize data based on regional classifications from the reporting regions of the Global Burden of Disease Study 2010 (Lim, *et al.,* 2012), but we present India and the greater China region separately because of their large population sizes.

At each stage of analysis, where country-specific data were unavailable, data were derived from regional estimates, which were in turn derived from weighted means by population size of each available country represented within the region (*see Table S4* for regions).

Protein-Energy Ratio

Assuming all calories lost from declines in food protein contents were replaced as carbohydrates (as supported by the stoichiometry of Loladze 2014), we calculated the ratio of protein to total energy in current diets and projected diets under eCO_2. Because commodity-based digestibility of energy is less easily estimated, digestibility was not included in these estimates.

Results

Our analysis was based on 99 high-CO_2 experiments and 48 crops, and it included 54 field experiments. Of the 64 experimental sites, 37 were elsewhere than Europe or North America (*see Table S1*).

In maize, peas, and mustard seed, we found a linear dose response when the RR of protein content was compared with the degree of CO_2 elevation above ambient (*see Tables S1* and *S2*). Metaregression for other crops was not significant, partly because of insufficient statistical power. Maize protein content under eCO_2 was not significantly below that under aCO_2 when considered overall from meta-analyses or when predicted for an atmospheric CO_2 increase of 150 ppm from metaregression. Metaregression predicted a decrease in pea protein content of 4.1% (1.6–6.7%) with an atmospheric CO_2 increase of 150 ppm, and overall, meta-analyses showed no significant declines in pea protein. National changes in dietary protein content were on average 0.04% less when modeled for a 150 ppm increase in atmospheric CO_2 based on metaregression results compared with meta-analyses. This difference was small enough to warrant the use of meta-analyses rather than metaregression. Comparisons between field and pot-based experiments, and between nitrogen fertilizer treatments were largely nonsignificant ($p>0.05$; see Table S2).

Meta-analyses confirmed lower protein content of C_3 grains (including barley, 14.1% lower), tubers (including potato, 6.4% lower), fruit (23.0% lower), and vegetables (17.3% lower) under eCO_2, with no significant change in the protein content of C_4 grains, nitrogen-fixing pulses, or oil crops (*Table 1*).

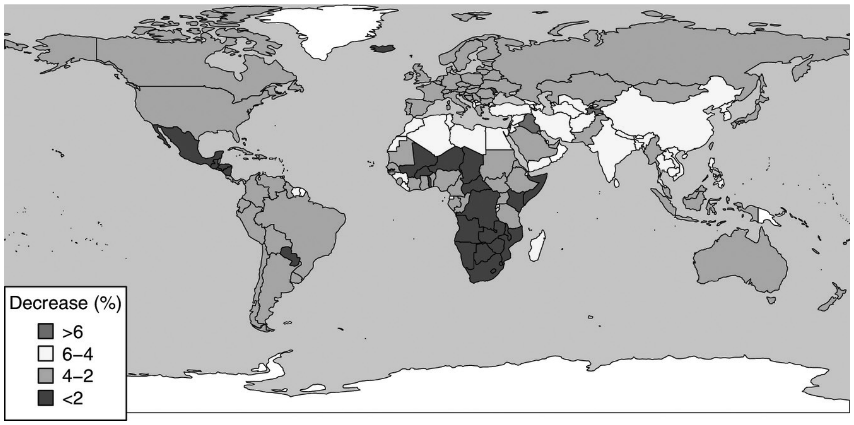
When these effect sizes were translated to FBS-standardized commodity intakes, the mean protein intake decreased under eCO_2 by >5% in 18 countries, including India, Bangladesh, Turkey, Egypt, Iran, and Iraq. Particularly large declines are expected through the Middle East and India, where a 5.3% decrease in dietary protein is predicted (*Table 2, Figure 1*).

Table 2. Change in dietary protein.

Region	Mean change in protein intake (%)	Mean change in protein intake (%), plant-based diet	Difference in protein-energy ratio (aCO_2 minus eCO_2, %)
CALACA	−1.99 (−3.61, −0.36)	−4.03 (−6.64, −1.42)	−0.20 (−0.37, −0.04)
CANAME	−5.04 (−7.29, −2.79)	−7.87 (−10.88, −4.85)	−0.52 (−0.75, −0.29)
CEEAEU	−3.43 (−4.90, −1.97)	−8.19 (−10.6, −5.77)	−0.39 (−0.55, −0.22)
CHINAR	−4.91 (−6.06, −3.75)	−8.86 (−10.4, −7.32)	−0.57 (−0.71, −0.44)
ESEASP	−4.01 (−5.51, −2.52)	−6.78 (−8.96, −4.59)	−0.36 (−0.50, −0.23)
HIGHIN	−2.67 (−3.65, −1.68)	−7.95 (−9.91, −5.98)	−0.32 (−0.43, −0.20)
India	−5.34 (−7.02, −3.66)	−7.04 (−9.02, −5.05)	−0.47 (−0.61, −0.32)
SOASIA	−4.69 (−6.44, −2.94)	−7.11 (−9.40, −4.82)	−0.43 (−0.59, −0.27)
SOTRLA	−2.40 (−3.46, −1.34)	−6.18 (−8.14, −4.22)	−0.27 (−0.38, −0.15)
SUSAAF	−2.03 (−4.05, −0.01)	−2.71 (−5.13, −0.30)	−0.18 (−0.36, 0.00)
World	−3.93 (−5.15, −2.70)	−7.14 (−8.91, −5.37)	−0.41 (−0.53, −0.28)

Note: Figures represent population-weighted averages (and 95% confidence intervals) globally and for each region (2050 populations). Protein-energy ratio is the percentage of dietary energy (calories) that is derived from protein. CALACA, Central and Andean Latin America and the Caribbean; CANAME, Central Asia, North Africa and the Middle East; CEEAEU, Central and Eastern Europe; CHINAR, Greater China; ESEASP, East and Southeast Asia and the Pacific excluding China; HIGHIN, high income countries; SOASIA, South Asia excluding India; SOTRLA, Southern and Tropical Latin America; SUSAAF, sub-Saharan Africa. See Table S4 for country grouping.

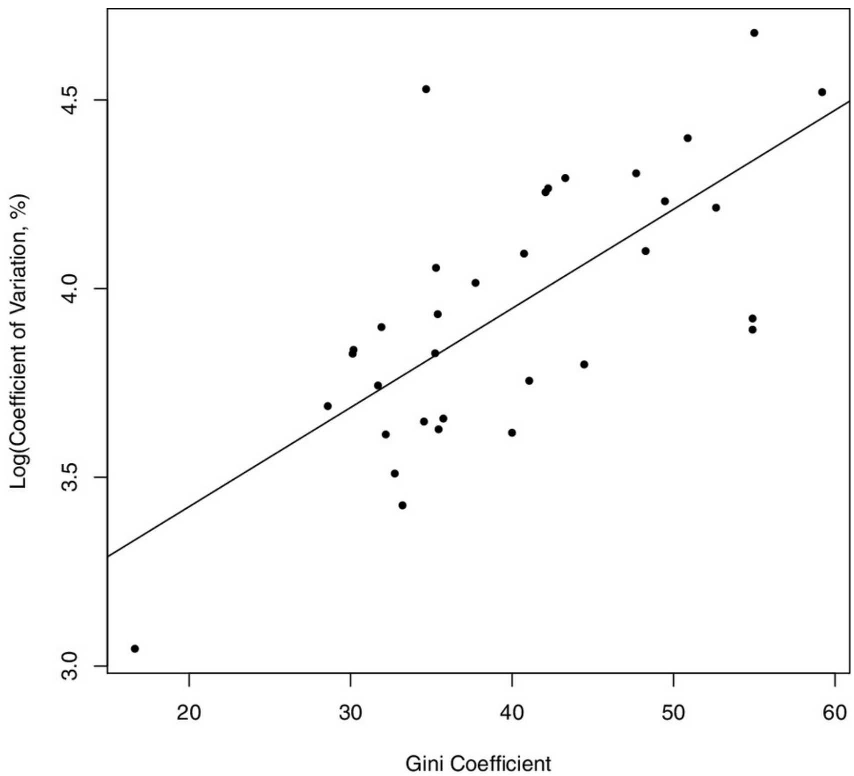
Figure 1



Per-country change in dietary protein intake under elevated carbon dioxide [eCO_2 (%)]. Baseline intake is based on Food and Agriculture Organisation of the United Nations Food Balance Sheets (FAO FBS) estimates, and changes are calculated from decreases in protein content in the edible portions of crops when grown under eCO_2. Data were plotted using the Rworldmap package in R (version 3.2.4; R Development Core Team).

Globally, >7% decreases in protein intake are predicted for plant-based diets under eCO_2, with countries dependent on C_3 staples particularly affected (*Table 2*), including Central Asia, North Africa and the Middle East (7.9%), Central and Eastern Europe (8.2%), and China (8.9%).A significant positive linear relationship existed between the natural log of $CV_{protein}$ and income-based Gini coefficients (slope 0.026, $p<0.0001$; *Figure 2*). Income inequality explained half of within-country variation in protein intake ($r^2=0.49$).

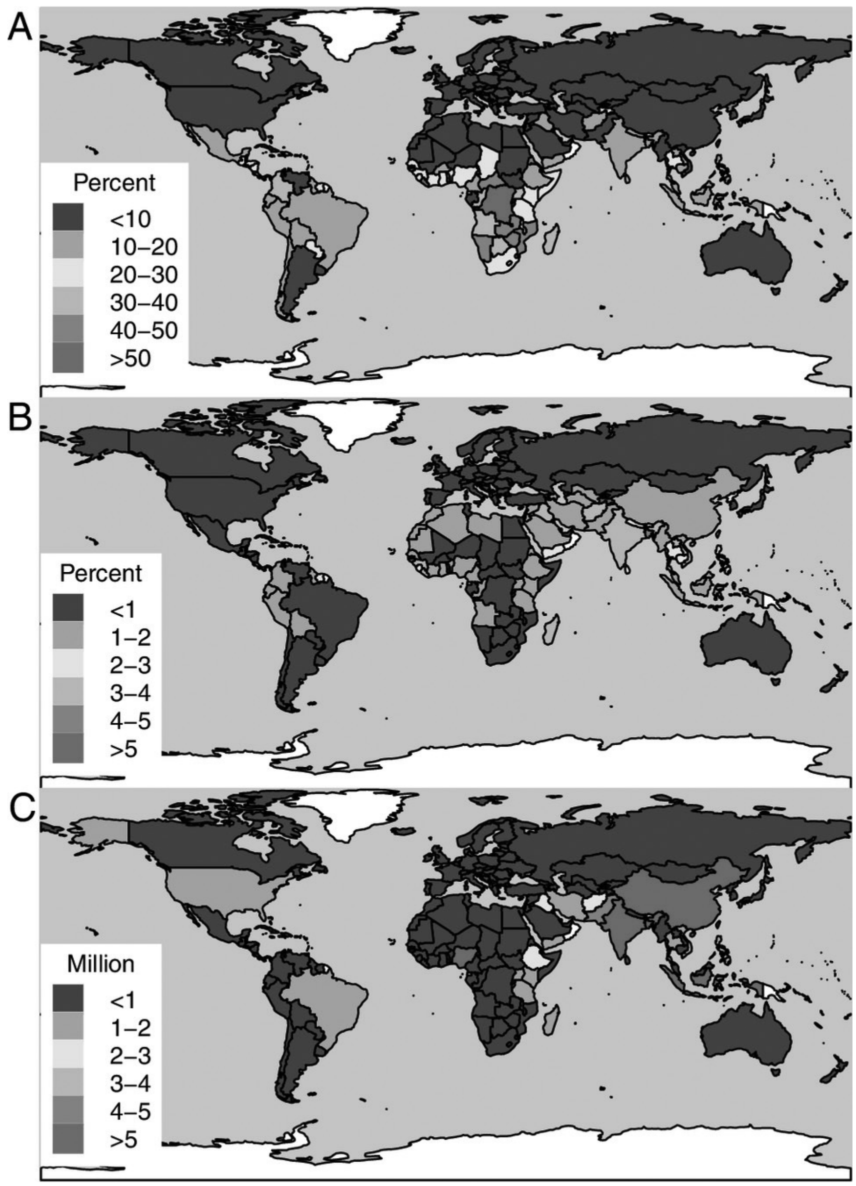
Figure 2



Coefficient of variation in protein intake derived from household surveys plotted against the income-based Gini coefficient for the year closest to the year household surveys were conducted (slope 0.026, $p<0.0001$).

Estimates indicated a 12.2% current risk of protein deficiency globally. With constant atmospheric CO_2 concentrations, we predict that globally, 15.1% or 1.4 billion people will be at risk of protein deficiency by 2050 because of demographic changes. This estimate includes 613.6 million people at risk in sub-Saharan Africa, 276.4 million in India, 131.7 million in Eastern and Southeast Asia and the Pacific, 84.4 million in Central Latin America and the Caribbean, and 77.8 million elsewhere in South Asia (*Figure 3, Table 3*).

Figure 3



Risk of protein deficiency as defined by protein intake below estimated average protein requirements (EAR). Estimates of (A) current percentage of the population at risk of deficiency, (B) percent of the population newly at risk of deficiency under elevated carbon dioxide (eCO_2), and (C) millions of people estimated to be newly at risk of deficiency under eCO_2, based on 2050 population projections. Data were plotted using the Rworldmap package in R (version 3.2.4; R Development Core Team).

Table 3. Populations at risk of protein deficiency under aCO_2 and eCO_2 (population-weighted averages and 95% confidence intervals)

Region	EAR, 2050 (g/d)	At risk of protein deficiency, aCO_2 (%)	Difference in protein-energy ratio (aCO_2 minus eCO_2, %)	At risk of deficiency in 2050, aCO_2 (%)At risk of deficiency in 2050, aCO_2 (millions)	Additionally at risk with eCO_2: 2050 (%)	Additionally at risk with eCO_2: 2050 (millions)
CALACA	30.49	17.05 (11.64, 24.65)	18.4 (12.84, 25.64)	84.37 (58.90, 117.61)	0.86 (0.57, 1.19)	3.94 (2.64, 5.46)
CANAME	31.46	6.22 (4.00, 9.32)	7.32 (4.88, 10.46)	57.2 (38.09, 81.71)	1.53 (1.14, 1.94)	11.97 (8.93, 15.12)
CEEAEU	33.44	3.58 (1.40, 9.84)	3.52 (1.37, 9.79)	9.64 (3.74, 26.77)	0.56 (0.27, 0.95)	1.52 (0.73, 2.61)
CHINAR	31.68	5.25 (0.16, 21.01)	5.38 (0.16, 21.31)	74.96 (2.27, 297)	1.14 (0.11, 2.04)	15.94 (1.47, 28.45)
ESEASP	29.47	15.35 (9.59, 22.78)	15.79 (9.68, 23.56)	131.67 (80.71, 196.44)	1.92 (1.40, 2.43)	15.99 (11.68, 20.28)
HIGHIN	33.05	2.62 (1.01, 6.86)	2.6 (0.99, 7.36)	28.39 (10.83, 80.47)	0.31 (0.16, 0.53)	3.41 (1.75, 5.78)
India	30.06	16.27 (3.73, 32.49)	17.06 (4.46, 33.36)	276.42 (72.32, 540.41)	3.30 (1.93, 4.55)	53.41 (31.22, 73.71)
SOASIA	30.41	13.23 (6.15, 21.98)	13.74 (6.91, 22.59)	77.76 (39.10, 127.88)	2.80 (1.88, 3.74)	15.86 (10.64, 21.20)
SOTRLA	31.35	11.46 (2.80, 27.14)	12.03 (3.25, 27.40)	38.14 (10.30, 86.87)	0.68 (0.26, 1.07)	2.17 (0.81, 3.39)
SUSAAF	30.53	27.12 (23.07, 31.46)	28.89 (24.73, 33.44)	613.56 (525.07, 710.24)	1.16 (0.73, 1.59)	24.64 (15.44, 33.83)
World	30.99	12.18 (9.07, 16.32)	15.06 (12.11, 18.71)	1424.59 (1145.89, 1770.20)	1.57 (1.26, 1.86)	148.37 (119.06, 176.09)

Note: Calculations use 2011 populations and 2050 population projections. aCO_2, ambient atmospheric carbon dioxide; CALACA, Central and Andean Latin America and the Caribbean; CANAME, Central Asia, North Africa and the Middle East; CEEAEU, Central and Eastern Europe; CHINAR, Greater China; EAR, estimated average protein requirement based on 2050 demographic projections; eCO_2 elevated atmospheric carbon dioxide; ESEASP, East and Southeast Asia and the Pacific excluding China; HIGHIN, high income countries; SOASIA, South Asia excluding India; SOTRLA, Southern and Tropical Latin America; SUSAAF, sub-Saharan Africa. See *Table S4* for country grouping.

With predicted atmospheric CO_2 concentrations >500ppm by 2050, we estimate an additional 1.57% of the world's population (148.4 million) will be at risk of protein deficiency, compared with 2050 aCO_2 scenarios. In particular, an additional 53.4 million people in India, 15.9 million elsewhere in South Asia and 24.6 million in sub-Saharan Africa are estimated to become newly at risk (*Table 3, Figure 3*). An additional 15.9 million people in the China region and 12.0 million in Central Asia, North Africa, and the Middle East are expected to become at risk with eCO_2. The greatest increases in percent at risk of protein deficiency are expected in Tajikistan, Bangladesh, Burundi, Liberia, Occupied Palestinian Territory, Iraq, and Afghanistan (*Figure 3B*).

Globally, we predict the protein-energy ratio (protein caloric contribution as a percent of total calories) to decrease under eCO_2 by 0.41%; in individual countries and regions, we predict this ratio to decrease by 0.6% in 17 counties including China, Iran, Iraq, Morocco, and Turkey. We expect decreases in China of 0.57% (*Table 2*).

Discussion

Our study highlights the potential impact of eCO_2 on dietary protein intake globally. Wheat and rice, among the most sensitive crops to eCO_2, are primary protein sources for 71% of the world's population (FAO 2014a). By 2050, 148.4 million people worldwide may become at risk of protein deficiency from rising CO_2. In India, expected to be the world's most populous country (UN 2013), and a country that is highly dependent on rice, 53.4 million people may be newly at risk of protein deficiency. Additionally, the protein deficiency in roughly 1.4 billion people globally (predicted under aCO_2 in 2050) is anticipated to become more severe under eCO_2 scenarios. Although estimates of current protein intake and income inequality highlight the current risk of deficiency in sub-Saharan Africa and South America, their dependence on less-sensitive C_4 crops make these diets less sensitive to eCO_2.

Importantly, we incorporated into the risk assessment different distributions of protein intake in countries based on income inequality from the association of income-based Gini coefficients with variability in protein intake from national dietary surveys. We find it equally plausible that $CV_{protein}$ would decrease or increase by 2050. We therefore provide the most conservative estimate of future protein intake distributions, namely that $CV_{protein}$ within countries will remain unchanged. We also assume unchanged duration and prevalence of breastfeeding, and unchanged adult height.

Although our calculations assume no change in the shape of the intake distribution, we anticipate a worsening of inequality in protein intake within populations because a larger decrease in protein content is observed in plant-based than in omnivore diets under eCO_2 (*Table 2*). Some changes in meat quality are anticipated owing to increased fat content under lower-protein diets (Blome, *et al.,* 2003), but this is likely to be negligible compared with the effects on plant-based protein sources. Those who consume the least protein have diets more dependent on plant protein, and these people are more vulnerable to eCO_2 effects on plant protein. This is likely to extend the lower tail of the intake distribution, increasing the severity and prevalence of protein inadequacy. Our estimates are worst-case scenarios where no substitution of animal-sourced protein sources for other high-protein foods is allowed. In particular, the predicted large decreases in protein content of plant-based diets in high income countries may be overestimates, where plant-based diets are likely to be supplemented with other protein sources.

The countries that we estimated to be currently most at risk of protein deficiency are also those with the greatest estimated prevalence of undernourishment (FAO 2014b), increasing confidence in our estimates; however, energy balance and nitrogen balance interact (Garza, *et al.,* 1976). For simplicity, we modeled overall protein intake and risk of deficiency based on the EAR, which assumes adequate energy intake. Published EARs are defined for zero protein balance, which is a conservative estimate of protein requirements (IOM 2005). Older, sedentary people and those suffering from or recovering from illness are likely to be at greater risk of deficiency in any population (Ghosh 2013). We have not accounted for current or future patterns of illness in our estimates of EAR. Furthermore, we have not considered changes in protein quality; however, several studies have shown that essential amino acids tend to be relatively preserved at the expense of nonessential amino acids under eCO_2, and degradability may decrease (Högy, *et al,.* 2009; Wroblewitz, *et al.,* 2013). Bioavailability may change, for example, if meal composition and thus digestibility changes. Furthermore, levels of secondary metabolites, including toxins, tend to increase under elevated CO_2 (Cavagnaro, *et al.,* 2011), which could decrease protein bioavailability.

In addition to increasing the risk of protein deficiency, there may be other nutritional consequences of changing the stoichiometry of carbohydrate-to-protein ratios in staple food crops. For example, replacing dietary carbohydrate with protein has been shown in interventional trials and observational studies to 15-y duration, and in diverse countries including Japan, China, the United States, and Chile, to improve cardiovascular disease risk through lowering blood pressure and changing lipid profiles (Hu, *et al.,* 1999; Obarzanek, *et al.,* 1996; Appel, *et al.,* 2005; Altorf-van der Kuil, *et al.,* 2010; Rebholz, *et al.,* 2012). Improvements are often greatest with plant—rather than animal-sourced protein (Altorf-van der Kuil, *et al.,* 2010). These experiments underscore the need for additional investigation into whether replacing plant-sourced protein with plant-sourced carbohydrate could exacerbate the already concerning pandemic of metabolic disease driving increased cardiovascular morbidity and mortality globally.

It is unclear how trends in dietary quality will be counterbalanced by the effects of population growth and climate change. That is why, for our analysis, we assume no future change to food composition of diets or to per capita food intake and no dietary substitution to compensate for deficits. Agricultural production will need to roughly double to match increasing demand by 2050 (Alexandratos 1999). Climate change may pose the greatest challenge to this need. Climate change-induced reductions in crop yield are expected to be greatest in lower-latitude regions, including developing countries and those dependent on C_4 crops (Rosenzweig, *et al.,* 2014). Resulting economic changes may shape future diets, and changes to water, soils, and weather in these areas may affect crops in ways that may overwhelm, or exacerbate, the effects of eCO_2. For example, decreases in yield under drought and warming temperatures may counteract the effects of rising CO_2 on protein concentrations (Kimball, *et al.,* 2001). Only 37 of 99 study sites in our meta-analysis were in countries outside of Europe and North America, and only just over half of the studies were performed in the field, with only 10% involving watering experiments (see *Table S1*). Most experiments were undertaken over 1 y only, and effects on crop nutrient content may not match those under the next 50 y of gradual atmospheric CO_2 increase. The consistent decreases in protein contents across C_3 crop cultivars, including 47 wheat cultivars and 27 rice cultivars, reassure us that our results are generalizable to other cultivars. Nevertheless, to better predict the dietary impacts of eCO_2, we need more long-term field-based eCO_2 experiments involving plants and cultivars grown under the climates and farming practices applicable to the developing world.

We also assumed that global population growth and future demographic trends will match UN projections, which include declining fertility rates, and migration from developing to developed countries (UN 2013). However, the greatest population growth is projected to occur in areas most vulnerable to climate change (Watts, *et al.,* 2015). Climate, economic, and demographic changes will likely interact, producing a global population distribution that we are not yet able to fully comprehend. In the absence of conclusive projections of future food production, we believe it is the most conservative, albeit perhaps optimistic, assumption that per capita food intake will remain constant despite sharp increases in global demand.

In predicting the nutritional consequences of eCO_2, other nutrients must be considered. Zinc and iron concentrations are greatly decreased in C_3 plants grown under eCO_2 (Myers, *et al.,* 2014). Zinc is a cofactor for protein synthesis, and protein inadequacy decreases uptake and availability of other nutrients (Gropper and Smith

2008). A recent analysis predicts strong increases in the risk of global zinc deficiency with eCO_2 (Myers, *et al.,* 2015). Identifying the countries most vulnerable to future malnutrition requires a targeted synthesis of crop research on climate and CO_2 responses. This information can then be applied to global climate and atmospheric models.

To our knowledge, this is the first global comparison of dietary protein that estimates a country-specific CV. Like energy consumption, the variability of protein consumption in a population relates to the Gini coefficient (Raubenheimer, *et al.,* 2015). Our use of this metric would be expected to produce more accurate estimates than the previously used 25% CV (Ghosh 2013). The WHO continues to refine its models of energy intake variability based on gross domestic product (GDP), Gini, and food prices, using skew log rather than lognormal distributions. As this methodology becomes available, future work could incorporate these considerations to produce better estimates of protein consumption.

Because added fertilizer did not predictably mitigate the effects of CO_2 on crop protein, and with the production and application of fertilizer being a principal contributor to agricultural greenhouse gas emissions (Vermeulen, *et al.,* 2012), we cannot simply add more fertilizer to reduce the protein deficit. As populations increase, and with livestock production being resource-intensive (Vermeulen, *et al.,* 2012), eating more meat is not a practical solution. Cultivars could be selected or bred based on their nutritional content under eCO_2. In addition to efforts to mitigate CO_2 emissions, nutritious and resilient crops should be promoted, for example legumes, which will withstand the effects of eCO_2 on protein content. Because eCO_2 may have the greatest effect on the protein intake of those with the poorest diets, more equitable food distribution, and poverty reduction measures should be a focus for minimizing risk of deficiency.

Conclusions

Anthropogenic CO_2 emissions, via their impact on the protein content of C_3 staples, may threaten the adequacy of protein intake for many populations. Although quantifying protein deficiency is notoriously difficult, we have estimated current and future risk of protein deficiency by country and region, suggesting enduring challenges for sub-Saharan Africa and growing challenges for South Asia, including India. For nutritionally sensitive agriculture, the high CO_2 effects on crop nutrient contents must be incorporated into future food security policies.

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ARTICLE 2

Association for Fire Ecology

[*https://fireecology.springeropen.com/articles/10.1186/s42408-019-0062-8*]

FIRE ECOLOGY

Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA

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Abstract

Background: Wildfires in the Pacific Northwest (Washington, Oregon, Idaho, and western Montana, USA) have been immense in recent years, capturing the attention of resource managers, fire scientists, and the general public. This paper synthesizes understanding of the potential effects of changing climate and fire regimes on Pacific Northwest forests, including effects on disturbance and stress interactions, forest structure and composition, and post-fire ecological processes. We frame this information in a risk assessment context, and conclude with management implications and future research needs.

Results: Large and severe fires in the Pacific Northwest are associated with warm and dry conditions, and such conditions will likely occur with increasing frequency in a warming climate. According to projections based on historical records, current trends, and simulation modeling, protracted warmer and drier conditions will drive lower fuel moisture and longer fire seasons in the future, likely increasing the frequency and extent of fires compared to the twentieth century. Interactions between fire and other disturbances, such as drought and insect outbreaks, are likely to be the primary drivers of ecosystem change in a warming climate. Reburns are also likely to occur more frequently with warming and drought, with potential effects on tree regeneration and species composition. Hotter, drier sites may be particularly at risk for regeneration failures.

Conclusion: Resource managers will likely be unable to affect the total area burned by fire, as this trend is driven strongly by climate. However, fuel treatments, when implemented in a spatially strategic manner, can help to decrease fire intensity and severity and improve forest resilience to fire, insects, and drought. Where fuel treatments are less effective (wetter, high-elevation, and coastal forests), managers may consider implementing fuel breaks around high-value resources. When and where post-fire planting is an option, planting different genetic stock than has been used in the past may increase seedling survival. Planting seedlings on cooler, wetter microsites may also help to increase survival. In the driest topographic locations, managers may need to consider where they will try to forestall change and where they will allow conversions to vegetation other than what is currently dominant.

Keywords: adaptation, climate change, disturbance regimes, drought, fire regime, Pacific Northwest, regeneration, vegetation.

Resumen

Antecedentes: Los incendios de vegetación en el Noroeste del pacífico (Washington, Oregon, Idaho, y el oeste de Montana, EEUU), han sido inmensos en años recientes, capturando la atención de los gestores de recursos, de científicos dedicados a los incendios, y del público en general. Este trabajo sintetiza el conocimiento de los efectos potenciales del cambio climático y de los regímenes de fuego en bosques del noroeste del Pacífico, incluyendo los efectos sobre las interacciones entre disturbios y distintos estreses, la estructura y composición de los bosques, y los procesos ecológicos posteriores. Encuadramos esta información en el contexto de la determinación del riesgo, y concluimos con implicancias en el manejo y la necesidad de futuras investigaciones.

Resultados: Los incendios grandes y severos en el Noroeste del Pacífico están asociados con condiciones calurosas y secas, y tales condiciones muy probablemente ocurran con el incremento en la frecuencia del calentamiento global. De acuerdo a proyecciones basadas en registros históricos, tendencias actuales y modelos de simulación, condiciones prolongadas de aumento de temperaturas y sequías conducirán a menores niveles de humedad, incrementando probablemente la frecuencia y extensión de fuegos en el futuro, en comparación con lo ocurrido durante el siglo XX. Las interacciones entre el fuego y otros disturbios, son probablemente los principales conductores de cambios en los ecosistemas en el marco del calentamiento global. Los incendios recurrentes podrían ocurrir más frecuentemente con aumentos de temperatura y sequías, con efectos potenciales en la regeneración de especies forestales y en la composición de especies. Los sitios más cálidos y secos, pueden estar particularmente en riesgo por fallas en la regeneración.

Conclusiones: Los gestores de recursos no podrían tener ningún efecto sobre el área quemada, ya que esta tendencia está fuertemente influenciada por el clima. Sin embargo, el tratamiento de combustibles, cuando está implementado de una manera

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espacialmente estratégica, puede ayudar a reducir la intensidad y severidad de los incendios, y mejorar la resiliencia de los bosques al fuego, insectos, y sequías. En lugares en los que el tratamiento de combustibles es menos efectivo (áreas más húmedas, elevadas, y bosques costeros) los gestores deberían considerar implementar barreras de combustible alrededor de valores a proteger. Cuando y donde la plantación post fuego sea una opción, plántulas provenientes de diferentes stocks genéticos de aquellos que han sido usados en el pasado pueden incrementar su supervivencia. La plantación de plántulas en micrositios más húmedos y fríos podría ayudar también a incrementar la supervivencia de plántulas. En ubicaciones topograáficas más secas, los gestores deberían considerar evitar cambios y donde estos sean posibles, permitir conversiones a tipos de vegetación diferentes a las actualmente dominantes.

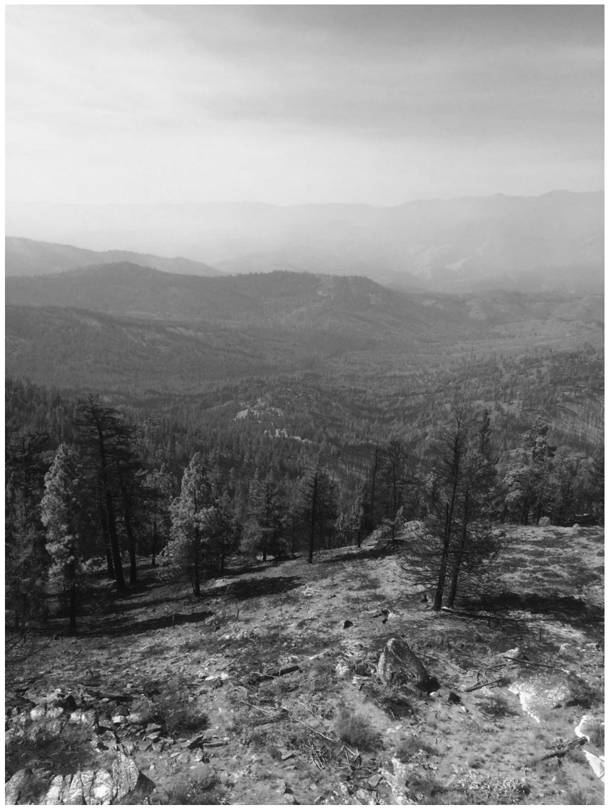
Abbreviations

ENSO: El Niño-Southern Oscillation
MPB: Mountain Pine Beetle
PDO: Pacific Decadal Oscillation

Introduction

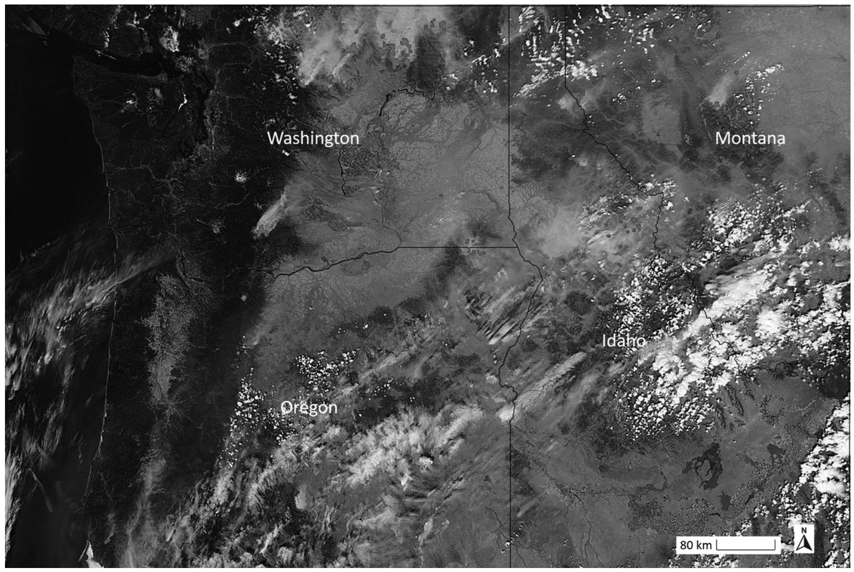
Large fires are becoming a near-annual occurrence in many regions globally as fire regimes are changing with warming temperatures and shifting precipitation patterns. The U.S. Pacific Northwest (states of Washington, Oregon, Idaho, and western Montana, USA; hereafter the Northwest) is no exception. In 2014, the largest wildfire in recorded history for Washington State occurred, the 103 640 ha Carlton Complex Fire (*Fig. 1*). In 2015, an extreme drought year with very low snowpack across the Northwest (Marlier, *et al.,* 2017), 688 000 ha burned in Oregon and Washington (*Fig. 2*), with over 3.6 million ha burned in the western United States. Several fires in 2015 occurred in conifer forests on the west (*i.e.,* wet) side of the Cascade Range, including a rare fire event in coastal temperate rainforest on the Olympic Peninsula. In some locations, short-interval reburns have occurred. For example, one location on Mount Adams in southwestern Washington burned three times between 2008 and 2015 (*Fig. 3*). Similarly, during the summer of 2017 in southwestern Oregon, the 77 000 ha Chetco Bar Fire burned over 40 000 ha of the 2002 Biscuit Fire, including a portion of the Biscuit Fire that had burned over part of the 1987 Silver Fire. At over 200 000 ha, the Biscuit Fire was the largest fire in the recorded history of Oregon.

Fig. 1



Large wildfires, such as the 2014 Carlton Complex Fire in Washington, USA (103 640 ha), have occurred throughout western North America during the past several decades. These disturbances have a significant effect on landscape pattern and forest structure and will likely become more common in a warmer climate, especially in forests with heavy fuel loadings. Photo credit: Morris Johnson.

Fig. 2



Fires burning across the Pacific Northwest, USA, on 25 August 2015. This natural-color satellite image was collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite. Actively burning areas, detected by MODIS's thermal bands, are outlined in red. National Aeronautics and Space Administration image courtesy of Jeff Schmaltz, MODIS Rapid Response Team.

Fig. 3a

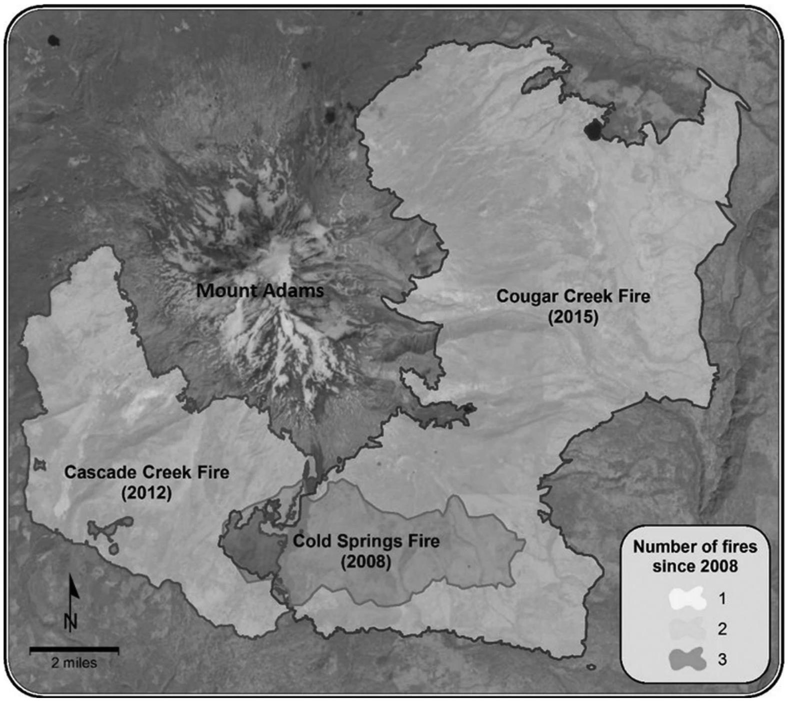


Fig. 3b

(**a**) Large fires around Mount Adams in Gifford Pinchot National Forest in southwestern Washington, USA, between 2001 and 2015 (area in orange burned twice, and area in red burned three times); and (**b**) area in Gifford

Pinchot National Forest that has burned three times since 2008 (2008 Cold Springs fire, 2012 Cascade Creek fire, and 2015 Cougar Creek fire). Map credit: Robert Norheim; photo credit: Darryl Lloyd.

Over the twentieth century in the Northwest, years with relatively warm and dry conditions have generally corresponded with larger fires and greater area burned (Trouet, *et al.,* 2006; Westerling, *et al.,* 2006; Littell, *et al.,* 2009; Littell, *et al.,* 2010; Abatzoglou and Kolden 2013; Cansler and McKenzie 2014; Dennison, *et al.,* 2014; Stavros, *et al.,* 2014; Westerling 2016; Kitzberger, *et al.,* 2017; Reilly, *et al.,* 2017; Holden, *et al.,* 2018). Decreasing fuel moisture and increasing duration of warm, dry weather creates large areas of dry fuels that are more likely to ignite and carry fire over a longer period of time (Littell, *et al.,* 2009).

A warming climate will have profound effects on fire frequency, extent, and possibly severity in the Northwest. Increased temperatures are projected to lengthen fire and growing seasons, increase evaporative demand, decrease soil and fuel moisture, increase likelihood of large fires, and increase area burned by wildfire (McKenzie, *et al.,* 2004; Littell, *et al.,* 2010; Stavros, *et al.,* 2014; Westerling 2016). Decreased summer precipitation is also projected to increase area burned (Holden, *et al.,* 2018).

Interactions between fire and other disturbance agents (*e.g.,* drought, insect outbreaks) will likely catalyze ecosystem changes in a warming climate. Increased tree stress and interacting effects of drought may also contribute to increasing wildfire severity (damage to vegetation and soils) and area burned (McKenzie, *et al.,* 2009; Stavros, *et al.,* 2014; Littell, *et al.,* 2016; Reilly, *et al.,* 2017).

Climatic changes and associated stressors can interact with altered vegetation conditions (*e.g.,* those resulting from historical management practices) to affect fire frequency, extent, and severity, as well as forest conditions in the future (Keeley and Syphard 2016). Human influence through domestic livestock grazing, road construction, conversion of land to agriculture, and urbanization has resulted in (direct or indirect) exclusion of fires in dry forests (Hessburg, *et al.,* 2005). Many larger, fire-resistant trees have been removed by selective logging. These activities, along with active fire suppression, have resulted in increased forest density and fuel build-up in forests historically characterized by frequent, low-severity and mixed-severity fires (Hessburg, *et al.,* 2005). Although landscape pattern and fuel limitations were key factors that limited fire size and severity historically, these limitations have been largely removed from many contemporary landscapes, thus increasing the potential for large high-severity fires, particularly in a warming climate.

Facing such changes, land managers need information on the magnitude and likelihood of altered fire regimes and forest conditions in a warming climate to help guide long-term sustainable resource management. Many published studies have explored the potential effects of climate change on forest fire in the Northwest, including paleoecological, modeling, and local- to regional-scale empirical studies. However, to our knowledge, there is no single resource that synthesizes these varied studies for the Northwest region. A synthesis of this information can help managers better understand the potential effects of climate change on ecosystem processes, assess risks, and implement actions to reduce the negative effects of climate change and transition systems to new conditions.

In this synthesis, we draw from relevant published literature to discuss potential effects of changing climate on fire frequency, extent, and severity in Northwest forests. Sources of information include: (1) long-term (centuries to millennia) paleoecological studies of climate, fire, and species distribution; (2) medium-term (decades to centuries) fire history studies; (3) near-term (years to decades) studies on trends in vegetation and fire associated with recent climatic variability and change; (4) forward-looking studies using simulation models to project future fire and vegetation change; and (5) recent syntheses focused on potential climate change effects.

We used regionally specific information where possible, including information from adjacent regions with forests of similar structure and function when relevant. Following an overview of climate projections, we (1) identified risks related to wildfire as affected by climate change in three broad ecosystem types; (2) explored the magnitude and likelihood of those risks; and (3) concluded with a discussion of uncertainties about future climate and fire, potential future research, and implications for resource management.

Overview of climate projections

Warming temperatures and changing precipitation patterns will affect amount, timing, and type of precipitation; snowmelt timing and rate (Luce, *et al.,* 2012; Luce, *et al.,* 2013; Safeeq, *et al.,* 2013); streamflow magnitude (Hidalgo, *et al.,* 2009; Mantua, *et al.,* 2010); and soil moisture content (McKenzie and Littell 2017). Compared to the historical period from 1976 to 2005, 32 global climate models project increases in mean annual temperature for the middle and end of the twenty-first century in the Northwest. These projected increases range from 2.0 to 2.6 °C for mid-century (2036 to 2065) and 2.8 to 4.7 °C for the end of the century (2071 to 2100), depending on future greenhouse gas emissions (specifically representative concentration pathway 4.5 or 8.5; Vose, *et al.,* 2017). Warming is expected to occur during all seasons, although most models project the largest temperature increases in summer (Mote, *et al.,* 2014). All models suggest a future increase in heat extremes (Vose, *et al.,* 2017).

Changes in precipitation are less certain than those for temperature. Global climate model projections for annual average precipitation range from −4.7 to +13.5%, averaging about +3% among models (Mote, *et al.,* 2014). A majority of models project decreases in summer precipitation, but projections for precipitation vary for other seasons. However, models agree that extreme precipitation events (*i.e.,* number of days with precipitation >2.5 cm) will likely increase, and that the length of time between precipitation events will increase (Mote, *et al.,* 2014; Easterling, *et al.,* 2017).

Risk assessment

A risk-based approach to climate change vulnerability assessments provides a common framework to evaluate potential climate change effects and identify a structured way to choose among adaptation actions or actions to mitigate climate change risks (EPA 2014). Risk assessment is linked with risk management by (1) identifying risks—that is, how climate change may prevent an agency or other entity from reaching its goals; (2) analyzing the potential magnitude of consequences and likelihood for each risk; (3) selecting a set of risk-reducing actions to implement; and (4) prioritizing those actions that address risks with the highest likelihood and magnitude of consequences (EPA 2014).

Here, we summarized potential risks that are relevant for natural resource management associated with climate-fire interactions, including: wildfire frequency, extent, and severity; reburns; stress interactions; and regeneration for (1) moist coniferous forest (low to mid elevation), (2) dry coniferous forest and woodland (low to mid elevation), and (3) subalpine coniferous forest and woodland (high elevation). The likelihood and magnitude of consequences, and confidence in inferences are described for each risk. Although the information provided here does not constitute risk management, as described in the previous paragraph, this information can be used to inform more site- and resource-specific risk assessments and risk management.

The risks identified here were inferred from the authors' review of the published literature described below, as well as experience with developing climate change vulnerability assessments in the study region over the past decade (Halofsky, *et al.,* 2011a, b; Raymond, *et al.,* 2014; Halofsky and Peterson 2017a, b; Halofsky, *et al.,* 2019; Hudec, *et al.,* 2019). These assessments encompassed all ecosystems and species addressed in this synthesis, and included extensive discussion of the effects of wildfire and other disturbances. Climate change effects and adaptation options in the assessments were greatly informed by input from resource managers as well as by scientific information. Thus, many fire-related vulnerabilities identified in the assessments are relevant to the risk assessment discussed here.

Risk in moist coniferous forests

Most climate-fire risks in moist coniferous forests are relatively low (*Table 1*). These forests occur west of the Cascade Range in Oregon and Washington and are frequently dominated by Douglas-fir (*Pseudotstuga menziesii* [Mirb.] Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). Moist coniferous forests are characterized by an infrequent, stand-replacing (*i.e.,* high-severity) fire regime (Agee 1993). Although fire frequency and severity may increase with climate change, the frequency of fire in these moist ecosystems will likely remain relatively low.

Table 1

Risk assessment for the effects of fire-climate interactions in moist coniferous forest, low to mid elevation (Olympics, west-side Cascades, northern Idaho, west-side Rocky Mountains, USA), for the mid to late twenty-first century. Likelihood and confidence are rated low, moderate, and high. Low likelihood represents consequences that are unlikely (approximately 0 to 33% probability), moderate likelihood represents consequences that are about as likely as not (approximately 33 to 66% probability), high likelihood represents consequences that are likely to very likely (approximately 66 to 100% probability). Low confidence is characterized by low scientific agreement and limited evidence, whereas high confidence is characterized by high scientific agreement and robust evidence, with moderate confidence falling between those two extremes

Fire-climate interaction	Magnitude of consequences	Likelihood of consequences	Confidence
Wildfire frequency	Small increase	Low	High
Wildfire extent	Small increase	Low	Moderate
Wildfire severity	No change to small increase	Low	Moderate
Reburns	No change to small increase	Low	Moderate
Stress interactions	Small increase	Low to moderate	Moderate
Regeneration	No change to small decrease	Low	Low

Risk in dry coniferous forests

Climate-fire risks in dry coniferous forests and woodlands are high for increased fire frequency, extent, and severity (*Table 2*). Dry coniferous forests and woodlands occur at lower elevations in southwestern Oregon, east of the Cascade Range in Oregon and Washington, and at lower elevations in the Rocky Mountains in Idaho and Montana. Fire regimes in these forests and woodlands range from moderate frequency and mixed severity to frequent and low severity. Ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) is a characteristic species, along with Douglas-fir, grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), and white fir (*Abies concolor* [Gordon & Glend.] Lindl. ex Hildebr.). These forests and woodlands are also at risk from interacting disturbances and hydrologic change (moderate to high likelihood and magnitude of consequences), and post-fire regeneration failures are likely to occur on some sites.

Table 2

Risk assessment for the effects of fire-climate interactions in dry coniferous forest and woodlands, low to mid elevation (east-side Cascades, southern Idaho, drier areas of Rocky Mountains, USA), for the mid to late twenty-first century. Likelihood and confidence are rated low, moderate, and high. Low likelihood represents consequences that are unlikely (approximately 0 to 33% probability), moderate likelihood represents consequences that are about as likely as not (approximately 33 to 66% probability), high likelihood represents consequences that are likely to very likely (approximately 66 to 100% probability). Low confidence is characterized by low scientific agreement and limited evidence, whereas high confidence is characterized by high scientific agreement and robust evidence, with moderate confidence falling between those two extremes

Fire-climate interaction	Magnitude of consequences	Likelihood of consequences	Confidence
Wildfire frequency	Large increase	High	High
Wildfire extent	Large increase	High	High
Wildfire severity	Large increase in areas with elevated fuel loading	High	High
Reburns	Moderate increase	Moderate	Moderate
Stress interactions	Large increase	High	High
Regeneration	Low to high decrease, depending on site	Moderate	Moderate

Risk in high-elevation forests

Climate-fire risks in high-elevation forests are moderate, with a primary factor being increased fire frequency and extent in lower-elevation forests spreading to higher-elevation systems (*Table 3*). Regeneration could be challenging in locations where seed availability is low due to very large fires. High-elevation forests occur in mountainous areas across the Northwest. They are characterized by species such as subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), mountain hemlock (*Tsuga mertensiana* [Bong.] Carrière), and lodgepole pine (*Pinus contorta* var. *contorta* Engelm. ex S. Watson). High-elevation forests are characterized by infrequent, stand-replacement fire regimes (Agee 1993). Risks of stress interactions are also moderate, because drought and insect outbreaks will likely affect high-elevation forests with increasing frequency.

Table 3

Risk assessment for the effects of fire-climate interactions in subalpine coniferous forest and woodland, high elevation (including aspen; all U.S. Pacific Northwest mountain ranges), for the mid to late twenty-first century. Likelihood and confidence are rated low, moderate, and high. Low likelihood represents consequences that are unlikely (approximately 0 to 33% probability), moderate likelihood represents consequences that are about as likely as not (approximately 33 to 66% probability), high likelihood represents consequences that are likely to very likely (approximately 66 to 100% probability). Low confidence is characterized by low scientific agreement and limited evidence, whereas high confidence is characterized by high scientific agreement and robust evidence, with moderate confidence falling between those two extremes

Fire-climate interaction	Magnitude of consequences	Likelihood of consequences	Confidence
Wildfire frequency	Moderate increase	Moderate	High
Wildfire extent	Moderate increase	Moderate	Moderate
Wildfire severity	No change to small increase	Low	Moderate
Reburns	No change to small increase	Low	Moderate
Stress interactions	Small increase	Moderate	Moderate
Regeneration	Variable, depending on fire size	Moderate	Moderate

Historical and contemporary fire-climate relationships

Paleoclimate and fire data

Wildfire-derived charcoal deposited in lake sediments can be used to identify individual fire events and to estimate fire frequency over hundreds to thousands of years (Itter, *et al.,* 2017). In combination with sediment pollen records, charcoal records help to determine how vegetation and fire frequency and severity shifted with climatic variability in the past (Gavin, *et al.,* 2007). Existing paleoecological reconstructions of the Northwest are based mostly on pollen and charcoal records from lakes in forested areas west of the Cascade Range, with few studies in the dry interior of the region (Kerns, *et al.,* 2017).

The early Holocene (*circa* 10 500 to 5,000 years BP) was the warmest post-glacial period in the Northwest (Whitlock 1992). During the early Holocene, summers were warmer and drier relative to recent historical conditions, with more intense droughts (Whitlock 1992; Briles, *et al.,* 2005). In many parts of the Northwest, these warmer and drier summer conditions were associated with higher fire frequency (Whitlock 1992; Walsh, *et al.,* 2008; Walsh, *et al.,* 2015).

Sediment charcoal analysis documented relatively frequent (across the paleoecological record) fire activity during the early Holocene in eight locations: North Cascade Range (Prichard, *et al.,* 2009), Olympic Peninsula (Gavin, *et al.,* 2013), Puget Lowlands (Crausbay, *et al.,* 2017), southwestern Washington (Walsh, *et al.,* 2008), Oregon Coast Range (Long, *et al.,* 1998), Willamette Valley (Walsh, *et al.,* 2010), Siskiyou Mountains (Briles, *et al.,* 2005), and Northern Rocky Mountains in Idaho (Brunelle and Whitlock 2003) (*Table 4*). Higher fire frequency in these locations was generally associated with higher abundance of tree species adapted to survive fire or regenerate soon after fire, including Douglas-fir, lodgepole pine, and Oregon white oak (*Quercus garryana* Douglas ex Hook.) (*Table 4*). Other pollen analyses (without parallel charcoal analysis) support the expansion of these species during the early Holocene (*e.g.,* Sea and Whitlock 1995; Worona and Whitlock 1995), in addition to the expansion of ponderosa pine and oak in drier interior forests (Hansen 1943; Whitlock and Bartlein 1997). Relatively frequent fire (across the paleoecological record) during the early Holocene likely resulted in a mosaic of forest successional stages, with species such as red alder (*Alnus rubra* Bong.) dominating early-successional stages in mesic forest types (Cwynar 1987).

Table 4

Dominant tree species (current [late twentieth to early twenty-first century] and during the Early Holocene, circa 10 500 to 5,000 yr BP) in select locations in the Pacific Northwest, USA, where charcoal analysis indicated increased fire activity in the warmer and drier summers of the Early Holocene. Locations are listed from north to south. These studies were selected to cover a range of geographic locations and forest types and do not represent a comprehensive list of charcoal analyses for the Northwest. For a more comprehensive list, see Walsh, *et al.* (2015)

Region (site)	Elevation (m)	Latitude, longitude (°)	Current dominant tree species [a]	Early Holocene dominant tree species [a]	Reference
North Cascade Range, Washington (Panther Potholes)	1100	48.658, −121.04	Douglas-fir, Pacific silver fir, western hemlock, western redcedar	Lodgepole pine	Prichard, *et al.,* 2009
Puget Lowlands, Washington (Marckworth State Forest)	~430	47.772, −121.811	Douglas-fir, western hemlock, western redcedar	Douglas-fir	Crausbay, *et al.,* 2017
Western Olympic Peninsula, Washington (Yahoo Lake)	710	47.677, −124.018	Pacific silver fir, western hemlock, western redcedar	Douglas-fir, red alder, Sitka spruce	Gavin, *et al.,* 2013
Southwestern Washington (Battle Ground Lake)	154	45.805, −122.494	Douglas-fir, western redcedar, western hemlock, grand fir, Sitka spruce	Oregon white oak, Douglas-fir	Walsh, *et al.,* 2008
Northern Rocky Mountains, Idaho (Burnt Knob Lake)	2250	45.704, −114.987	Subalpine fir, whitebark pine, lodgepole pine, Engelmann spruce	Douglas-fir, whitebark pine, lodgepole pine	Brunelle and Whitlock 2003
Willamette Valley, Oregon (Beaver Lake)	69	44.551, −123.17	Willow, black cottonwood, Oregon ash, Oregon white oak	Oregon white oak, Douglas-fir, beaked hazel, bigleaf maple, red alder	Walsh, *et al.,* 2010
Oregon Coast Range (Little Lake)	210	44.167,° −123.584	Western hemlock, Douglas-fir, western redcedar, grand fir, Sitka spruce	Douglas-fir, red alder, Oregon white oak	Long, *et al.,* 1998
Siskiyou Mountains, Oregon (Bolan Lake)	1600	42.022, −123.459	White fir, Douglas-fir	Western white pine, sugar pine, Oregon white oak, incense cedar	Briles, *et al.,* 2005

[a] Species names that are not otherwise indicated in the text: beaked hazel (*Corylus cornuta* ssp. cornuta Marshall), bigleaf maple (*Acer macrophyllum* Pursh), black cottonwood, (*Populus trichocarpa* Torr. & A. Gray ex Hook.), incense-cedar (*Calocedrus decurrens* [Torr.] Florin), Oregon ash (*Fraxinus latifolia* Benth.), Pacific silver fir (*Abies amabilis* Douglas ex J. Forbes), sugar pine (*Pinus lambertiana* Douglas), western redcedar (*Thuja plicata* Donn ex D. Don), western white pine (*Pinus monticola* Douglas ex D. Don.), willow (*Salix* spp. L.)

Paleoecological studies (covering the early Holocene and other time periods) indicate that climate has been a major control on fire in the Northwest over millennia, with interactions between fire and vegetation. During times of high climatic variability and fire frequency (*e.g.,* the early Holocene), fires were catalysts for large-scale shifts in forest composition and structure (Prichard, *et al.,* 2009; Crausbay, *et al.,* 2017). Species that persisted during these times of rapid change have life history traits that facilitate survival in frequently disturbed environments (Brubaker 1988; Whitlock 1992), including red alder, Douglas-fir, lodgepole pine, ponderosa pine, and Oregon white oak, which suggests that these species may be successful in a warmer future climate (Whitlock 1992; Prichard, *et al.,* 2009).

Fire-scar and tree-ring records

Fire-scar studies indicate that climate was historically a primary determinant of fire frequency and extent in the Northwest. Years with increased fire frequency and area burned were generally associated with warmer and drier spring and summer conditions in the Northwest (Hessl, *et al.,* 2004; Wright and Agee 2004; Heyerdahl, *et al.,* 2008; Taylor, *et al.,* 2008). Climate of previous years does not have a demonstrated effect on fire, unlike other regions such as the Southwest, most likely because fuels are not as limiting for fire across the Northwest (Heyerdahl, *et al.,* 2002; Hessl, *et al.,* 2004).

Warmer and drier conditions in winter and spring are more common during the El Niño phase of the El Niño-Southern Oscillation (ENSO) in the Northwest (Mote, *et al.,* 2014). The Pacific Decadal Oscillation (PDO) is an ENSO-like pattern in the

North Pacific, resulting in sea surface temperature patterns that appeared to occur in 20 to 30 year phases during the twentieth century (Mantua, *et al.,* 1997). Positive phases of the PDO are associated with warmer and drier winter conditions in the Northwest.

Associations between large fire years and El Niño have been found in the interior Northwest (*e.g.,* Heyerdahl, *et al.,* 2002), as have associations between large fire years and the (warm, dry) positive phase of the PDO (Hessl, *et al.,* 2004). Other studies have found ambiguous or non-significant relationships between fire and these climate cycles in the Northwest (*e.g.,* Hessl, *et al.,* 2004; Taylor, *et al.,* 2008). However, interactions between ENSO and PDO (El Niño plus positive phase PDO) were associated with increased area burned (Westerling and Swetnam 2003) and synchronized fire in some years in dry forests across the inland Northwest (Heyerdahl, *et al.,* 2008).

The PDO and ENSO likely affect fire extent by influencing the length of the fire season (Heyerdahl, *et al.,* 2002). Warmer and drier winter and spring conditions increase the length of time that fuels are flammable (Wright and Agee 2004). Although climate change effects on the PDO and ENSO are uncertain, both modes of climatic variation influence winter and spring conditions in the Northwest, whereas summer drought during the year of a fire has the strongest association with major fire years at the site and regional scales (Hessl, *et al.,* 2004). Summer drought conditions are likely more important than in other regions where spring conditions are more strongly related to fire, because the Northwest has a winter-dominant precipitation regime; fire season occurs primarily in late summer (August through September), and summer drought reduces fuel moisture (Hessl, *et al.,* 2004; Littell, *et al.,* 2016).

Contemporary climate and fire records

In the twentieth century, wildfire area burned in the Northwest was positively related to low precipitation, drought, and temperature (Littell, *et al.,* 2009; Abatzoglou and Kolden 2013; Holden, *et al.,* 2018). Warmer spring and summer temperatures across the western United States cause early snowmelt, increased evapotranspiration, lower summer soil and fuel moisture, and thus longer fire seasons (Westerling 2016). Precipitation during the fire season also exerts a strong control on area burned through wetting effects and feedbacks to vapor pressure deficit (a measure of humidity; Holden, *et al.,* 2018). Between 2000 and 2015, warmer temperatures and vapor pressure deficit decreased fuel moisture during the fire season in 75% of the forested area in the western U.S. and added about 9 days per year of high fire potential (defined using several measures of fuel aridity; Abatzoglou and Williams 2016).

Periods of high annual area burned in the Northwest are also associated with high (upper atmosphere) blocking ridges over western North America and the North Pacific Ocean. Blocking ridges occur when centers of high pressure occur over a region in such a way that they prevent other weather systems from moving through. These blocking ridges, typical in the positive phase of the PDO (Trouet, *et al.,* 2006), divert moisture away from the region, increasing temperature and reducing relative humidity (Gedalof, *et al.,* 2005). Prolonged blocking and more severe drought (Brewer, *et al.,* 2012) are needed to dry out fuels in mesic to wet forest types (*e.g.,* Sitka spruce [*Picea sitchensis* {Bong.} Carrière], western hemlock) along coastal Oregon and Washington. With increased concentrations of carbon dioxide in the atmosphere, the persistence of high blocking ridges that divert moisture from the region may increase (Lupo, *et al.,* 1997, as cited in Flannigan, *et al.,* 2009), further enhancing drought conditions and the potential for fire.

Lightning ignitions also affect wildfire frequency. However, research on lightning with recent and future climate change is equivocal. Some studies suggest that lightning will increase up to 40% globally in a warmer climate (Price and Rind 1994; Reeve and Toumi 1999; Romps, *et al.,* 2014), although a recent study suggests that lightning may decrease by as much as 15% globally (Finney, *et al.,* 2018).

Increases in annual area burned are generally associated with increases in area burned at high severity. Fire size, fire severity, and high-severity burn patch size were positively correlated in 125 fires in the North Cascades of Washington over a recent 25 year period (Cansler and McKenzie 2014). Other analyses have similarly shown a positive correlation between annual area burned and area burned severely (in large patches) in the Northwest (Dillon, *et al.,* 2011; Abatzoglou, *et al.,* 2017; Reilly, *et al.,* 2017). The annual extent of fire has increased slightly in the Northwest, although the proportion of area burning at high severity did not increase over the 1985 to 2010 period, either for the region as a whole or for any subregion (Reilly, *et al.,* 2017). Similarly, an analysis of recent fires (1984 to 2014) in the

Northwest found no decrease in the proportion of unburned area within fire perimeters (Meddens, *et al.,* 2018).

Many studies have found that bottom-up controls such as vegetation, fuels, and topography are more important drivers of fire severity than climate in Western forests (*e.g.,* Dillon, *et al.,* 2011; Parks, *et al.,* 2014). The direct influence of climate on fire severity is intrinsically much stronger in moister and higher-elevation forests, because drying of fuels in these systems requires extended warm and dry periods. Fire severity in many dry forest types is influenced primarily by fuel quantity and structure (Parks, *et al.,* 2014). However, fuel accumulations associated with fire exclusion in dry forests may be strengthening the influence of climate on fire severity, likely resulting in increased fire severity in drier forest types (Parks, *et al.,* 2016a).

Wildfire projections under changing climate

Historical patterns suggest that higher temperatures, stable or decreasing summer precipitation, and increased drought severity in the Northwest will likely increase the frequency and extent of fire. Models can help to explore potential future fire frequency and severity in a changing climate, with several types of models being used to project future fire (McKenzie, *et al.,* 2004). We focused here on models for which output is available in the Northwest-empirical (statistical) models and mechanistic (process-based) models. Both types of models have limitations as well as strengths, but they are conceptually useful to assess potential changes in fire with climate change.

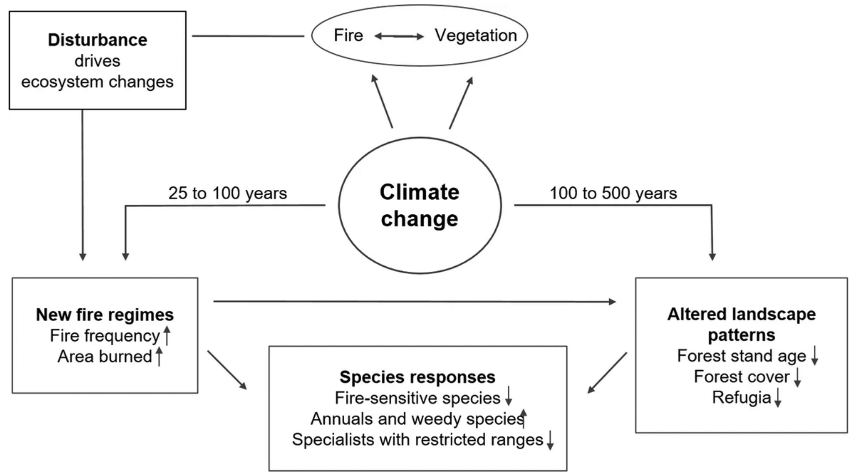
Fire projections by empirical models

Empirical models use the statistical relationship between observed climate and area burned during the historical record (the past 100 years or so) to project future area burned. Future area burned is based on projections of future temperature and precipitation, usually from global climate models. These models do not account for the potential decreases in burn probability in areas that have recently burned, or for long-term changes in vegetation (and thus flammability) with climate change (Parks, *et al.,* 2015; McKenzie and Littell 2017; Littell, *et al.,* 2018). They also do not account for human influence on fire ignitions (Syphard, *et al.,* 2017).

Numerous studies have developed empirical models to project future area burned or fire potential at both global (Krawchuk, *et al.,* 2009; Moritz, *et al.,* 2012) and regional scales (*e.g.,* western U.S.; McKenzie, *et al.,* 2004; Littell, *et al.,* 2010; Yue, *et al.,* 2013; Kitzberger, *et al.,* 2017). All studies suggest that fire potential, area burned, or both will increase in the western U.S. in the future with warming climate. Below we highlight a few examples that explicitly address the Northwest. These examples provide future fire projections at relatively coarse spatial scales, with changes in area burned being variable across landscapes.

McKenzie, *et al.,* (2004) projected that, with a mean temperature increase of 2 °C, area burned by wildfire will increase by a factor of 1.4 to 5 for most Western states, including Idaho, Montana, Oregon, and Washington. Kitzberger, *et al.,* (2017) projected increases in annual area burned of five times the median in 2010 to 2039 compared to 1961 to 2004 for the 11 conterminous Western states. Models developed by Littell, *et al.,* (2010) for Idaho, Montana, Oregon, and Washington suggested that area burned will double or triple by the 2080s, based on future climate projections for two global climate models (*Fig. 4*). Median area burned was projected to increase from about 0.2 million ha historically to 0.3 million ha in the 2020s, 0.5 million ha in the 2040s, and 0.8 million ha in the 2080s. The projections cited here are coarse scale, and area burned can be expected to vary from place to place within the area of the projections.

Fig. 4



Conceptual model showing that indirect effects of climate change via disturbance cause faster shifts in vegetation than do direct effects of climate change. Adapted from McKenzie, *et al.* (2004 (*https://fireecology.springeropen.com/articles/10.1186/s42408-019-0062-8#ref-CR129*)).

Littell, *et al.,* (2010) also developed empirical models at a finer (ecosection) scale for the state of Washington. The relatively low frequency of fire in coastal forests makes development of empirical models difficult, so the output from these models for coastal forests is uncertain. For drier forest types, potential evapotranspiration and water balance deficit were the most important variables explaining area burned. In forested ecosystems (Western and Eastern Cascades, Okanogan Highlands, and Blue Mountains ecosections), the mean area burned was projected to increase by a factor of 3.8 in the 2040s compared to 1980 to 2006. An updated version of these models, expanded to the western U.S. (Littell, *et al.,* 2018), also suggests that area burned will increase in the future for most forested ecosections of the Northwest, but increases in area burned may be tempered, or area burned may decrease, in areas that are more fuel limited (*e.g.,* in non-forest vegetation types).

Another application of empirical models is to project the future incidence of very large fires, often defined as the largest 5 to 10% of fires or fires >5,000 ha. Barbero, *et al.,* (2015) projected that the annual probability of very large fires will increase by a factor of four in 2041 to 2070 compared to 1971 to 2000. Projections by Davis, *et al.,* (2017) suggested that the proportion of forests highly suitable for fires >40 ha will increase by >20% in the next century for most of Oregon and Washington, but less so for the Coast Range and Puget Lowlands. The largest projected increases were in the Blue Mountains, Klamath Mountains, and East Cascades. The number of fires that escape initial attack will also likely increase (Fried, *et al.,* 2008).

Few empirical model projections are available for future fire severity. Using empirical models, Parks, *et al.,* (2016a) suggested that fire severity in a warming climate may not change significantly in the Northwest, because fuels limit fire severity. However, altered fire severity will depend partly on vegetation composition and structure (as they affect fuels), and climate change is expected to alter vegetation composition and structure both directly and indirectly (through disturbance). Empirical models do not account for these potential changes in vegetation and fuels (among other limitations; see McKenzie and Littell 2017). In the near term, high stem density as a result of fire exclusion and past management may increase fire severity in dry, historically frequent-fire forests (Haugo, *et al.,* 2019).

Fire projections by mechanistic models

Mechanistic models allow for exploration of potential interactions between vegetation and fire under changing and potentially novel climate. Mechanistic models can also account for elevated carbon dioxide concentration on vegetation, which could result in increased vegetation productivity (and fuel loading). Examples of mechanistic models that simulate fire include dynamic global vegetation models, such as MC1

(Bachelet, *et al.,* 2001), LANDIS–II (Scheller and Mladenoff 2008), and Fire-BioGeo-Chemical (Fire-BGC; Keane, *et al.,* 1996).

Using the MC1 dynamic global vegetation model for the western ¾ of Oregon and Washington, Rogers, *et al.,* (2011) projected a 76 to 310% increase in annual area burned and a 29 to 41% increase in burn severity (measured as aboveground carbon consumed by fire) by the end of the twenty-first century, with the degree of increase depending on climate scenario. These projected changes were largely driven by increased summer drought. Under a hot and dry climate scenario (with more frequent droughts), large fires were projected to occur throughout the twenty-first century (including the early part), primarily in mesic forests west of the Cascade crest.

Using the MC2 model (an updated version of MC1), Sheehan, *et al.,* (2015) also projected increasing fire activity in Idaho, Oregon, Washington, and western Montana. Mean fire return interval was projected to decrease across all forest-dominated subregions, with or without fire suppression. Projected decreases in mean fire interval were as high as 82% in the interior subregions without fire suppression; projected decreases in mean fire interval for the westernmost subregion were as high as 48% without fire suppression.

The MC1 and MC2 models have also been calibrated and run for smaller subregions in the Northwest. For the Willamette Valley, Turner, *et al.,* (2015) projected (under a high temperature increase scenario) increased fire frequency, with average area burned per year increasing by a factor of nine relative to the recent historical period (1986 to 2010); area burned over the recent historical period was very low (0.2% of the area per year). For a western Washington study region, MC2 projected a 400% increase in annual area burned in the twenty-first century compared to 1980 to 2010 (Halofsky, *et al.,* 2018a). Although the projected average annual area burned was still only 1.2% of the landscape, some fire years were very large, burning 10 to 25% of the study region.

The MC1 model projected increased fire frequency and extent in forested lands east of the Cascade crest (Halofsky, *et al.,* 2013; Halofsky, *et al.,* 2014). Fire was projected to burn more than 75% of forested lands several times between 2070 and 2100. On average, projected future fires burned the most forest under a hot, dry scenario. Applying the MC2 model to a larger south-central Oregon region, Case, *et al.,* (2019) suggested that future fire will become more frequent in most vegetation types, increasing most in dry and mesic forest types. For forested vegetation types, fire severity was projected to remain similar or increase slightly compared to historical fire severity.

The LANDIS–II model has been applied to the Oregon Coast Range in the Northwest. Creutzburg, *et al.,* (2017) found that area burned over the twenty-first century did not increase significantly with climate change compared to historical levels, but fire severity and extreme fire weather did increase.

Fire-BGC models have mostly been applied in the northern U.S. Rocky Mountains, which overlaps with the Northwest. For northwestern Montana (Glacier National Park), Keane, *et al.,* (1999) used Fire-BGC in a warmer, wetter climate scenario to project higher vegetation productivity and fuel accumulations that contribute to more intense crown fires and larger fire sizes. Fire frequency also increased over a 250 year simulation period: fire rotation decreased from 276 to 213 years, and reburns occurred in 37% of the study area (compared to 17% under historical conditions). In drier locations (low-elevation south-facing sites), low-severity surface fires were more common, with fire return intervals of 50 years.

Mechanistic modeling suggests that fire frequency and area burned will increase in the Northwest. Fire severity may also increase, depending partly on forest composition, structure, and productivity over time. Warmer temperatures in winter and spring, and increased precipitation during the growing season (even early in the growing season), could increase forest productivity. This increase in productivity would maintain or increase fuel loadings and promote high-severity fires when drought and ignitions occur. In mechanistic model projections for the region, some of the largest increases in fire severity (Keane, *et al.,* 1999; Case, *et al.,* 2019) and the largest single fire years (Halofsky, *et al.,* 2013; Halofsky, *et al.,* 2018a) occurred in wetter scenarios with increased forest productivity. Future increased fire frequency without increased vegetation productivity is likely to result in decreased fire severity because of reduction in fuels as well as the potential for type conversion to vegetation characterized by less woody biomass. However, in highly productive systems such as forests west of the Cascade crest, future fires will probably be high severity (as they were historically) and more frequent (Rogers, *et al.,* 2011; Halofsky, *et al.,* 2018a).

Short-interval reburns

A reburn occurs when the perimeter of a recent past fire is breached by a subsequent fire, something that all fire-prone forests have experienced. In the Northwest, reburns in the early twentieth century were documented in some of the earliest forestry publications (*e.g.,* Isaac and Meagher 1936). However, under a warming climate, increased frequency and extent of fire will increase the likelihood of reburns, increasing the need to understand how earlier fires affect subsequent overlapping fires and how forests respond to multiple fires. Recent concern about reburns centers on projections that short-interval, high-severity (*i.e.,* stand-replacing) reburns may become more common (Westerling, *et al.,* 2011; Prichard, *et al.,* 2017). Multiple fires can interact as linked disturbances (Simard, *et al.,* 2011), whereby the first fire affects the likelihood of occurrence, size, or magnitude (intensity, severity) of a reburn. Multiple fires can also interact to produce compound disturbance effects (Paine, *et al.,* 1998), in which ecological response after a reburn is qualitatively different than after the first fire.

Effects of past fire on future fire occurrence

Interactions between past forest fires and the occurrence of subsequent fires are generally characterized by negative feedbacks: fires are less likely to start within or spread into recently burned areas (*i.e.,* within the last 5 to 25 years) compared to similar areas that have not experienced recent fire. For example, lightning-strike fires within the boundary of recently burned areas in the U.S. Rocky Mountains (Idaho, Montana) were less likely to grow to fires larger than 20 ha than were lightning-strike fires in comparable areas outside recent fire boundaries (Parks, *et al.,* 2016b). This negative relation between past fires and likelihood of future fires is generally attributed to limits on ignition potential and initial spread of fires through fine woody fuels, which are sparse following fire. Fine fuels are consumed by the first fire and do not recover to sufficient levels until at least a decade later in many interior forest systems in the Northwest (Isaac 1940; Donato, *et al.,* 2013) and U.S. Rocky Mountains (Nelson, *et al.,* 2016, 2017). However, negative feedbacks can be short-lived (or non-existent) in productive west-side forests in the Northwest, where fuels are abundant in early-successional forests (Isaac 1940; Agee and Huff 1987; Gray and Franklin 1997).

Past fires in the northern U.S. Rocky Mountains have also been effective at preventing the spread of subsequent fires into their perimeters (Teske, *et al.,* 2012; Parks, *et al.,* 2015). Similar results have been found in mixed-conifer forests of the interior Northwest, where past wildfire perimeters inhibited the spread of the 2007 Tripod Complex Fire in eastern Washington (Prichard and Kennedy 2014). This limitation of fire spread decreases with time. The probability that reburns will be inhibited by earlier fires is near 100% in the first year post fire, but is only 30% by 15 to 20 years post fire (Parks, *et al.,* 2015). However, extreme fire weather can dampen buffering effects of reburns at any interval between fires, such that past fire perimeters become less effective at inhibiting reburns during warm, dry, and windy conditions (Parks, *et al.,* 2015).

Effects of past fire on future fire severity

Fire severity (fire-caused vegetation mortality) in a reburn is affected by interactions among severity of the first fire, climate setting and forest type, interval between fires, and weather at the time of the reburn. Reburns are typically less severe when the interval between fires is shorter than 10 to 15 years (Parks, *et al.,* 2014; Harvey, *et al.,* 2016b; Stevens-Rumann, *et al.,* 2016). After 10 to 15 years, the effects of past fires on reburn severity diverge in different ecological contexts.

In areas where tree and shrub regeneration is prolific following one severe fire (*e.g.,* moist Douglas-fir forests, subalpine forests dominated by lodgepole pine, some mixed-conifer forests [*e.g.,* southwest Oregon mixed conifer forests with a hardwood component]), fire severity can be greater in reburns than in comparable single burns once the interval between fires exceeds 10 to 12 years (Thompson, *et al.,* 2007; Harvey, *et al.,* 2016b). In lower-elevation, drier, and more fuel-limited forests (*e.g.,* ponderosa pine forests and woodlands, areas with slower woody plant establishment following fire), past fire limits future fire severity, often for 20 to 30 years (Parks, *et al.,* 2015; Harvey, *et al.,* 2016b; Stevens-Rumann, *et al.,* 2016). In these lower-productivity forests, the severity of past fire has been found to be the best predictor of reburn severity (Parks, *et al.,* 2014; Harvey, *et al.,* 2016b), but this is not necessarily the case in higher-productivity forests (Thompson, *et al.,* 2007; Stevens-Rumann, *et al.,* 2016). Surface fuel treatment followed by tree planting can greatly reduce the intensity of a reburn and allow most newly established trees to survive (Lyons-Tinsley and Peterson 2012).

Of particular concern for forest resilience is how and why forests may experience two severe fires in short succession. In the northern U.S. Rocky Mountains, the likelihood of experiencing two successive stand-replacing fires (*i.e.,* a severe fire followed by a severe reburn) is greatest (1) in areas with high post-fire regeneration capacity (*e.g.,* higher-elevation subalpine forests on moist sites), and (2) when the reburn occurs during warm, dry conditions (Harvey, *et al.,* 2016b). In high-productivity westside forests of Oregon and Washington, the potential for two successive high-severity burns may always exist (*e.g.,* Isaac 1940), but occurrence depends on ignition and low fuel moisture.

Effects of reburns on forest species composition and structure

Short-interval reburns can produce compound effects on tree regeneration, altering species composition in some cases and shifting to non-forest vegetation in others. For example, thin-barked species, which do not survive fire but instead regenerate from seed following fire-induced mortality (*e.g.,* lodgepole pine), can face "immaturity risk" if the interval between one fire and a reburn is too short to produce a sufficient canopy seedbank (Keeley, *et al.,* 1999; Turner, *et al.,* 2019). In northern U.S. Rocky Mountain systems, low- and moderate-severity reburns have shifted dominance from lodgepole pine toward thick-barked species that can resist fire, such as ponderosa pine (Larson, *et al.,* 2013; Stevens-Rumann and Morgan 2016).

In the western Cascades of southern Washington, areas that burned in the 1902 Yacolt Burn and subsequently reburned within 30 years were characterized by much lower conifer regeneration than areas that burned only once (Gray and Franklin 1997). However, in the Klamath and Siskiyou mountains of southwestern Oregon, a short-interval (15 years between fires), high-severity reburn had no compound effect on regeneration (2 years post fire) of Douglas-fir, the dominant tree species (Donato, *et al.,* 2009b), with no difference from areas that burned once at a longer interval (>100 years between fires). Plant species diversity and avian diversity were higher in reburns compared to once-burned areas, with hardwoods contributing to habitat diversity in the reburn areas (Donato, *et al.,* 2009b; Fontaine, *et al.,* 2009).

The effects of reburns on post-fire conifer regeneration seem to depend on legacy trees that survive both fires, providing seed across fire events (Donato, *et al.,* 2009b). In systems where legacy trees are rare (*i.e.,* thin-barked species easily killed by fire) or where shrubs and hardwoods can outcompete trees for long durations, reburns are more likely to produce lasting compound effects on forest structure and composition, possibly resulting in a shift to non-forest vegetation.

Disturbance and stress interactions

Combinations of biotic and abiotic stressors, or stress complexes, will likely be major drivers of shifts in forest ecosystems with changing climate (Manion 1991). A warmer climate will affect forests directly through soil moisture stress and indirectly through increased extent and severity of disturbances, particularly fire and insect outbreaks (McKenzie, *et al.,* 2009).

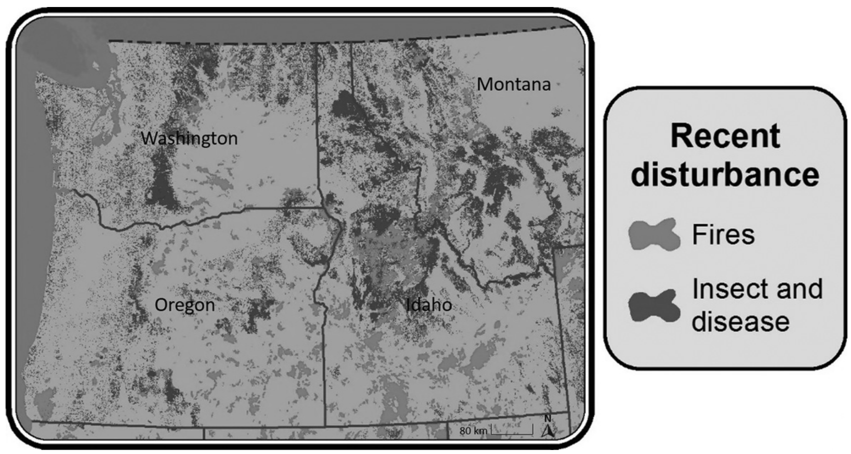
Water deficit and disturbance interactions

Although water deficit (the condition in which potential summer atmospheric and plant demands exceed available soil moisture) is rarely fatal by itself, it is a predisposing factor that can exacerbate the forest stress complex (Manion 1991; McKenzie, *et al.,* 2009). Water deficit directly contributes to potentially lethal stresses in forest ecosystems by intensifying negative water balances (Stephenson 1998; Milne, *et al.,* 2002; Littell, *et al.,* 2008; Restaino, *et al.,* 2016). Water deficit also indirectly increases the frequency, extent, and severity of disturbances, especially wildfire and insect outbreaks (McKenzie, *et al.,* 2004; Logan and Powell 2009). These indirect disturbances alter forest ecosystem structure and function, at least temporarily, much faster than do chronic effects of water deficit (*e.g.,* Loehman, *et al.,* 2017; *Fig. 4*).

Interactions among drought, insect outbreaks, and fire

During the past few decades, wildfires and insect outbreaks have affected a large area across the Northwest (*Fig. 5*). Increased area burned has been at least partly caused by extreme drought-wildfire dynamics, which will likely become more prominent as drought severity and area burned increase in the future (Parks, *et al.,* 2014; McKenzie and Littell 2017). Insect disturbance has likewise expanded across the Northwest since 1990, catalyzed by higher temperature and the prevalence of dense, low-vigor forests. Cambium feeders, such as bark beetles, are associated with prolonged droughts, in which tree defenses are compromised (Logan and Bentz 1999; Carroll, *et al.,* 2004; Hicke, *et al.,* 2006). Patches of fire-insect disturbance mosaic are starting to run into each other (*Fig. 5*), and similar to reburns, are an inevitable consequence of increasing disturbance activity, even in the absence of mechanistic links among disturbances.

Fig. 5



Recent disturbances in the Northwest, USA, showing wildfire extent for 1984 to 2017 (orange), and insect and disease extent for 1997 to 2017 (brown). Data sources: Monitoring Trends in Burn Severity (*https://www.mtbs.gov*) and U.S. Forest Service Insect and Disease Detection Survey (*https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/gis-spatial-analysis/detection-surveys.shtml*). Map credit: Robert Norheim.

In a review of the fire-bark beetle literature, Hicke, *et al.* (2012) noted that, despite varying research approaches and questions, much agreement existed on fire hazard (defined as changes to fuels and potential fire behavior) after bark beetle outbreaks. There was strong agreement that surface fire and torching potential increased during the gray phase (*e.g.,* 5 to 10 years following outbreaks, when snags remain standing; but see Woolley, *et al.,* 2019), but that crown fire potential was reduced in this phase. Similarly, there was agreement that fire hazard was lower in the old phase (*i.e.,* silver phase), which occurs 1 to several decades after outbreak, when beetle-killed snags have fallen, understory vegetation increases, and seedlings establish. However, there was disagreement regarding fire potential during the red phase (0 to 4 years after outbreak initiation), when trees retain their drying needles and changes in foliar chemistry can increase flammability. Many studies have concluded that during this approximately 1 to 4 year period, fire hazard increases (Klutsch, *et al.,* 2011 [but see Simard, *et al.,* 2011], Hoffman, *et al.,* 2012, Jolly, *et al.,* 2012; Jenkins, *et al.,* 2014). Fire hazard has been found to increase as the proportion of the stand killed by bark beetles increases, regardless of forest type (Page and Jenkins 2007; DeRose and Long 2009; Hoffman, *et al.,* 2012).

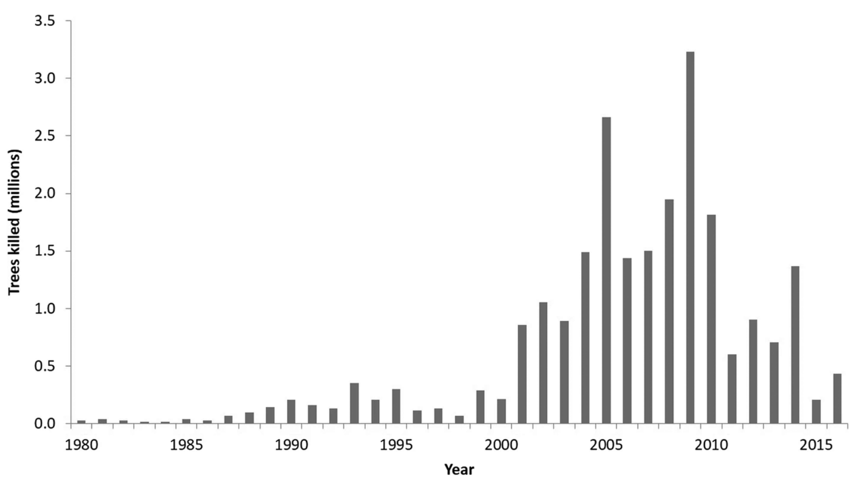
Concern has also risen as to whether fire occurrence and severity will increase following outbreaks of bark beetles (*e.g.,* Hoffman, *et al.,* 2013), although empirical support for such interactions has been lacking (Parker, *et al.,* 2006; Hicke, *et al.,* 2012). Insect outbreaks have not been shown to increase the likelihood of fire or area burned (Kulakowski and Jarvis 2011; Flower, *et al.,* 2014; Hart, *et al.,* 2015; Meigs, *et al.,* 2015). Further, when fire occurs in post-outbreak forests, most measures of fire severity related to fire-caused vegetation mortality are generally similar between beetle-affected forests and areas that were unaffected by pre-fire outbreaks. Field studies in Oregon showed that burn severity (fire-caused vegetation mortality) was actually lower in lodgepole pine forests affected by mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) than analogous unaffected forests that burned (Agne, *et al.,* 2016). In an analysis of recent (1987 to 2011) fires across the Northwest, Meigs, *et al.,* (2016) also found that burn severity (from satellite-derived burn severity indices) was lower in forests with higher pre-fire insect outbreak severity.

Field studies in California, the Rocky Mountains, and interior British Columbia, Canada, conducted in a range of forest types have also explored the relationship between beetle outbreak severity (pre-fire basal area killed by beetles) and burn severity (fire-caused vegetation mortality), and suggest relatively minor effects of beetle outbreaks on burn severity. When fire burned through red stages (1 to 4 years post outbreak, when trees retain red needles) in dry conifer forests of California, small increases (*e.g.,* 8 to 10% increase in fire-caused tree mortality) in burn severity were observed in areas of high outbreak severity (Stephens, *et al.,* 2018). In dry Douglas-fir forests in Wyoming, fire severity in the gray phase (4 to 10 years post outbreak) of Douglas-fir beetle (Dendroctonus pseudotsugae Hopkins) outbreak was unaffected by beetle outbreak severity (Harvey, *et al.,* 2013). Similar results of minimal beetle effect on fire severity were reported in gray-stage spruce-fir forests in Colorado, USA (Andrus, *et al.,* 2016). In lodgepole pine-dominated forests affected by MPB, outbreak effects on burn severity differed by weather and stage of outbreak. For example, in both green and red phases (when most beetle-killed trees retained crowns fading from green to red), fire severity increased with pre-fire beetle outbreak severity under moderate but not extreme (*e.g.,* hot, dry, windy) weather (Harvey, *et al.,* 2014a). Conversely, in the red and gray stages, fire severity increased with pre-fire outbreak severity under extreme but not moderate weather (Harvey, *et al.,* 2014b).

In British Columbia, gray-stage post-outbreak stands did not burn more severely than unaffected stands for most measures of burn severity (Talucci, *et al.,* 2019). The effects of beetle outbreaks on fire severity in forest types typified by stand-replacing fire regimes seem to be overall variable and minor, especially given that such forest types are inherently characterized by severe fire. The key exception to the otherwise modest effects of pre-fire beetle outbreaks on burn severity is the effect of deep wood charring and combustion on beetle-killed snags that burn. This effect has been reported across stages and forest type when measured, and consistently increases with pre-fire beetle outbreak severity (Harvey, *et al.,* 2014b; Talucci, *et al.,* 2019). Because fire intensity and thus severity are driven by topography, weather, and fuels, beetle-outbreak-induced changes to fuel structures may play a minor role in affecting fire severity. In all cases in studies above where topography and weather were quantified, fire severity responded strongly and consistently to these factors irrespective of pre-fire beetle outbreaks.

In the Northwest, lodgepole pine forests have been affected by MPB outbreaks, with high mortality in some locations (*e.g.,* Okanogan-Wenatchee Forest; *Fig. 6*). Widely distributed at mid to higher elevations in the Rocky Mountains, lodgepole pine is the dominant species over much of its range there, forming nearly monospecific stands. In the Northwest, lodgepole pine occurs at mid to higher elevations in the Cascade Range and eastward, and monospecific stands are limited to early seral stages and specific soil conditions (*e.g.,* Pumice Plateau in central Oregon). In some populations in the Northwest, lodgepole pine forests have also adapted to stand-replacing fires via cone serotiny.

Fig. 6



Number of trees killed by beetles in Okanogan-Wenatchee National Forest, Washington, USA, from 1980 to 2016. Data source: C. Mehmel, Okanogan-Wenatchee National Forest, Washington, USA.

Bark beetle outbreaks and subsequent fire may interact to affect post-fire forest recovery, but results differ depending on the dominant regeneration mechanism of the tree attacked by beetles. Species with a persistent canopy seedbank, such as lodgepole pine, are minimally affected by compound disturbances between beetle outbreaks and fire. For example, in the Cascade Range and Rocky Mountains, areas that experienced beetle outbreaks prior to fire had similar levels of post-fire lodgepole pine seedling establishment compared to areas that had fire only (Harvey, *et al.,* 2014a; Harvey, *et al.,* 2014b; Edwards, *et al.,* 2015; Agne, *et al.,* 2016). Species such as Douglas-fir, which do not have a persistent canopy seedbank, have been shown to have lower post-fire seedling establishment in areas affected by Douglas-fir beetle outbreaks and fire (Harvey, *et al.,* 2013), although effects may be transient and disappear with time since fire (Stevens-Rumann, *et al.,* 2015).

Interactions among fungal pathogens and other stressors

The effects of weather and climate on fungal pathogens vary by species, with the spread of some pathogens facilitated by drought and others by wet periods (Klopfenstein, *et al.,* 2009; Sturrock, *et al.,* 2011; Ayres, *et al.,* 2014). Forests with low vigor and physiologically stressed trees (*e.g.,* dense stands) are generally more susceptible to fungal pathogens. In the Northwest, a wide range of root rots and other native fungal pathogens exists in all forest types. For example, on the west side of the Cascade Range, laminated root rot (*Phellinus weirii* [Murrill] Gilb.) is widespread, causing small pockets of mortality in Douglas-fir (Agne, *et al.,* 2018). However, no evidence exists that this pathogen has been or will be accelerated by a warmer climate. Other pathogens, such as Swiss needle cast (*Phaeocryptopus gaeumannii* [T. Rohde] Petrak), may be favored by warmer and wetter winters (Agne, *et al.,* 2018). Fungal pathogens stress trees and may increase susceptibility to insect infestations. For example, Douglas-fir beetle is closely associated with laminated root rot centers in forests on the west side of the Cascades in Oregon and Washington (Goheen and Hansen 1993). Overall, interactions between fungal pathogens and fire with climate change are uncertain.

Stress complexes and forest mortality

Recent large-scale tree mortality events in the Southwest (Breshears, *et al.,* 2005), Texas (Schwantes, *et al.,* 2016), and California, USA (Young, *et al.,* 2017), have been caused by multi-year droughts weakening trees, followed by various beetle species acting as the mortality agents. It is likely that more intense and longer droughts will increase in the future under changing climate (Trenberth, *et al.,* 2014), and interactions between drought and other disturbance agents are likely to cause tree mortality. As noted above, fungal pathogens may contribute to increasing insect outbreaks (Goheen and Hansen 1993), along with increasing temperatures, shorter winters, and tree stress. Fire-caused tree mortality will also likely be affected by interacting disturbances. In some cases, fire severity has been marginally higher in areas affected by beetle mortality (Harvey, *et al.,* 2014a; Harvey, *et al.,* 2014b; Stephens, *et al.,* 2018). However, empirical studies examining the effects of large-scale tree mortality events on fire behavior are limited (Stephens, *et al.,* 2018). Modeling studies suggest that fire rate of spread may increase after mortality events (*e.g.,* Perrakis, *et al.,* 2014).

Effects of changing disturbance regimes on forest structure and composition

In Northwest forest ecosystems, warming climate and changing disturbance regimes are likely to lead to changes in species composition and structure, probably over many decades. In general, increased fire frequency will favor plant species with life history traits that allow for survival with more frequent fire (Chmura, *et al.,* 2011). These include (1) species that can resist fires (*e.g.,* thick-barked species such as Douglas-fir, western larch [*Larix laricina* Nutt.], and ponderosa pine); (2) species with high dispersal ability that can establish after fires (*e.g.,* Douglas-fir); and (3) species with serotinous cones that allow seed dispersal from the canopy after fire (*e.g.,* lodgepole pine) (Rowe 1983; Agee 1993).

In the forest understory, increased fire frequency and extent will likely create more opportunities for establishment by invasive species (Hellmann, *et al.,* 2008). Species that can endure fires (sprouters) and seedbank species (evaders) are also likely to increase with more frequent fire. For example, sprouting shrubs and hardwoods are prolific after fire in southwest Oregon (Halofsky, *et al.,* 2011). However, high-intensity fire can consume or kill seeds stored in the upper soil layers and kill shallow belowground plant parts, and repeated fires at short intervals can deplete seed stores and belowground plant resources (Zedler, *et al.,* 1983).

More frequent fire will likely decrease abundance of avoider species, including shade-tolerant species, species with thin bark, and slow invaders after fire (Chmura, *et al.,* 2011). Forest stands composed primarily of fire-susceptible evader species, such as western hemlock, subalpine fir, and Engelmann spruce (*Picea engelmannii*

Parry ex Engelm.), will likely have higher mortality for a given fire intensity than stands composed of more fire-resistant species, such as mature Douglas-fir and western larch. If fire-sensitive species are not able to re-seed into burned areas and re-establish themselves (because of short fire intervals, competition, or harsh conditions for seedling establishment), these species can be lost from a site (Stevens-Rumann and Morgan 2016). Direct mortality or lack of regeneration of fire-sensitive species with more frequent fire will favor more fire-adapted species that can survive fire or regenerate after fire. For example, in southwest Oregon, shrubs and hardwoods are likely to increase in abundance with increased fire frequency and reduced conifer regeneration in some locations (Tepley, *et al.,* 2017).

Changes in disturbance regimes can influence the structure of forests at multiple spatial scales (Reilly, *et al.,* 2018). Within forest stands, more frequent fire will likely decrease tree density in dry forests, and open savannas may increase in area. Forest understories may shift from being duff- or forb-dominated to shrub- or grass-dominated. Tree canopy base heights will likely increase as frequent fires remove lower branches. Across forested landscapes (*i.e.,* among stands), fire directly influences the spatial mosaic of forest patches (Agee 1993). More extreme fire conditions with climate change may initially lead to larger and more frequent fires, resulting in larger burn patch sizes and greater landscape homogeneity (Harvey, *et al.,* 2016a). More frequent severe fire will likely decrease forest age, the fraction of old-growth forest patches, and the landscape connectivity of old-growth forest patches (Baker 1995; McKenzie, *et al.,* 2004). However, more frequent low- and mixed-severity fires may eventually reduce fuels in drier forest ecosystems (*e.g.,* dry mixed conifer), leading to lower-intensity fires and a finer-scale patch mosaic (Chmura, *et al.,* 2011).

Effects of climate change on post-fire processes

Forest regeneration

Changing climate and fire frequency, extent, and severity are likely to influence forest regeneration processes, thus affecting the structural and compositional trajectories of forest ecosystems. First, climate change is expected to affect regeneration through increased fire frequency. As fire-free intervals shorten, the time available for plants to mature and produce seed before the next fire will be limited. Such changes in fire-free intervals can have significant effects on post-fire regeneration, because different plants have varied adaptations to fire. Species that resprout following fire may decline in density, but species that are fire-killed and thus require reproduction from seed may be locally eliminated.

Second, climate change may result in increased fire severity. If the size of high-severity fire patches increases, seed sources to regenerate these patches will be limited. Regeneration of non-serotinous species will require long-distance seed dispersal and may be slower in large, high-severity patches (Little, *et al.,* 1994; Donato, *et al.,* 2009a; Downing, *et al.,* 2019).

Third, climate change will likely result in increased forest drought stress. Warmer temperatures, lower snowpack, and increased evapotranspiration will increase summer drought stress. Warmer and drier conditions after fire events may cause recruitment failures, particularly at the seedling stage (Dodson and Root 2013). In this way, fire can accelerate species turnover when climatic conditions are unfavorable for establishment of dominant species (Crausbay, *et al.,* 2017) and seed sources are available for alternative species.

Regeneration in dry forests in the Northwest (*e.g.,* ponderosa pine) may be particularly sensitive to changing climate. Hotter and drier sites (*e.g.,* on southwestern aspects) may be particularly at risk for regeneration failures (Nitschke, *et al.,* 2012; Dodson and Root 2013; Donato, *et al.,* 2016; Rother and Veblen 2017; Tepley, *et al.,* 2017). High soil surface temperatures can also cause mortality (Minore and Laacke 1992). Forest structure (mainly shade from an existing canopy) can ameliorate harsh conditions and allow for regeneration (Dobrowski, *et al.,* 2015). However, after high-severity disturbance, dry forests at the warm and dry edges of their distribution (ecotones) may convert to grasslands or shrublands in a warming climate (Johnstone, *et al.,* 2010; Jiang, *et al.,* 2013; Savage, *et al.,* 2013; Donato, *et al.,* 2016; Stevens-Rumann, *et al.,* 2017).

In the Klamath-Siskiyou ecoregion of southwestern Oregon and northern California, Tepley, *et al.,* (2017) found that conifer regeneration was reduced by low soil moisture after fires. With lower soil moisture, greater propagule pressure (smaller high-severity patches with more live seed trees) was needed to achieve a given level of regeneration. This suggests that, at high levels of climatic water deficit, even small high-severity patches are at risk for low post-fire conifer regeneration. Successive fires could further limit conifer seed sources, thus favoring shrubs and hardwoods.

Germination of ponderosa pine is favored by moderate temperatures and low moisture stress, and survival increases when maximum temperatures are warm (but not hot) and when growing season rainfall is above average (Petrie, *et al.,* 2016; Rother and Veblen 2017). Empirical modeling by Petrie, *et al.,* (2017) projected that, with warming temperature in the middle of the twenty-first century, regeneration potential of ponderosa pine may increase slightly on many sites. However, by the end of the century, with decreased moisture availability, regeneration potential in the Northwest decreased by 67% in 2060 to 2099 compared to 1910 to 2014. In the eastern Cascade Range of Oregon, Dodson and Root (2013) found decreasing ponderosa pine regeneration with decreasing elevation and moisture availability, suggesting that moisture stress would limit regeneration.

Several studies in the Rocky Mountains have also found decreased post-fire regeneration with increased water deficits on drier, lower-elevation sites (Rother, *et al.,* 2015; Donato, *et al.,* 2016; Stevens-Rumann, *et al.,* 2017; Davis, *et al.,* 2019). Donato, *et al.,* (2016) found decreased regeneration of Douglas-fir 24 years after fire on drier, lower-elevation sites compared to more mesic sites at higher elevations. Regeneration declined with higher burn severity and was minimal beyond 100 to 200 m from a seed source. Similarly, Harvey, *et al.,* (2016c) found that post-fire tree seedling establishment decreased with greater post-fire drought severity in subalpine forests of the northern U.S. Rocky Mountains; post-fire subalpine fir and Engelmann spruce regeneration were both negatively affected by drought. Davis, *et al.,* (2019) modeled post-fire recruitment probability for ponderosa pine and Douglas-fir on sites in the Rocky Mountains, and found that recruitment probability decreased between 1988 and 2015 for both species, suggesting a decline in climatic suitability for post-fire tree regeneration.

In a study of annual regeneration and growth for 10 years following wildfire in the eastern Cascade Range of Washington, Littlefield (2019) found that establishment rates of lodgepole pine (and other species) were highest when growing seasons were cool and moist. A lagged climate signal was apparent in annual growth rates, but standardized climate-growth relationships did not vary across topographic settings, suggesting that topographic setting did not decouple site conditions from broader climatic trends to a degree that affected growth patterns. These results underscore the importance of favorable post-fire climatic conditions in promoting robust establishment and growth while highlighting the importance of topography and stand-scale processes (*e.g.,* seed availability and delivery). Although concerns about post-fire regeneration failure may be warranted under some conditions, failure is not a general phenomenon in all places and at all times (Littlefield 2019).

If warming climate trends continue as projected, without (or even with) tree planting, loss of forests may occur on the driest sites in the Northwest (Donato, *et al.,* 2016; Harvey, *et al.,* 2016c; Stevens-Rumann, *et al.,* 2017), particularly east of the Cascade crest and in southwestern Oregon. Individual drought years are not likely to alter post-fire successional pathways, especially if wet years occur between dry years (Tepley, *et al.,* 2017; Littlefield 2019). Recruitment of conifers following a disturbance can require years to decades in the Northwest (Little, *et al.,* 1994; Shatford, *et al.,* 2007; Tepley, *et al.,* 2014). Thus, shrubs or grasses may dominate during drought periods, but conifers could establish and overtop shrubs and grasses during wetter and cooler periods (Dugan and Baker 2015; Donato, *et al.,* 2016).

Management actions

More frequent and larger wildfires in Northwest forests will likely be a major challenge facing resource managers of public and private lands in future decades (Peterson, *et al.,* 2011a). Adapting forest management to climate change will help forest ecosystems transition to new conditions, while continuing to provide timber, water, recreation, habitat, and other benefits to society. Starting the process of adaptation now, before the marked increase in wildfire expected by the mid twenty-first century, will likely improve options for successful outcomes. Fortunately, some current forest management practices, including stand density management and surface fuel reduction in dry forests, and control of invasive species, are "climate smart" because they increase resilience to changing climate and disturbances (Peterson, *et al.,* 2011a; Peterson, *et al.,* 2011b).

Resource managers will likely be unable to prevent increasing broad-scale trends in area burned with climate change, but fuel treatments can decrease fire intensity and severity locally (Agee and Skinner 2005; Peterson, *et al.,* 2005). In drought- and fire-prone forests of the Northwest (*e.g.,* ponderosa pine and dry mixed-conifer forests east of the Cascades and in southwestern Oregon), reducing forest density can decrease crown fire potential (Agee and Skinner 2005; Safford, *et al.,* 2012; Martinson and Omi 2013; Shive, *et al.,* 2013), and negative effects of drought on tree growth (Clark, *et al.,* 2016; Sohn, *et al.,* 2016). Even in wetter forest types, reducing stand density can increase water availability, tree growth, and tree vigor by reducing competition (Roberts and Harrington 2008). Decreases in forest stand density, coupled with hazardous fuel treatments, can also increase forest resilience to wildfire in dry forest types (Agee and Skinner 2005; Stephens, *et al.,* 2013; Hessburg, *et al.,* 2015).

In dry forests, forest thinning prescriptions may need to reduce forest density to increase forest resistance and resilience to fire, insects, and drought (Peterson, *et al.,* 2011a; Sohn, *et al.,* 2016). For example, in anticipation of a warmer climate and increased fire frequency, managers in Okanogan-Wenatchee National Forest in eastern Washington are currently basing stocking levels for thinning and fuel treatments on the next driest forest type. Thinning and fuel treatments could also be prioritized in (1) locations where climate change effects, particularly increased summer drought, are expected to be most pronounced (*e.g.,* on south-facing slopes); (2) high-value habitats; and (3) high-risk locations such as the wildland-urban interface. Fuel treatments must be maintained over time to remain effective (Agee and Skinner 2005; Peterson, *et al.,* 2005). Insufficient financial resources, agency capacity constraints, and air quality constraints on prescribed burning are harsh realities that will in most cases limit the extent of fuel treatments (Melvin 2018), necessitating strategic implementation of treatments in locations where fuel reduction will maximize ecological, economic, and political benefits.

Fewer options exist for reducing fire severity in wetter, high-elevation and coastal forests of the Northwest, historically characterized by infrequent, stand-replacement fire regimes (Halofsky, *et al.,* 2018b). In these ecosystems, thinning and hazardous fuel treatments are unlikely to significantly affect fire behavior, because fires typically occur under extreme weather conditions (*i.e.,* during severe drought). However, managers may consider installing fuel breaks around high-value resources, such as municipal watersheds, key wildlife habitats, and valuable infrastructure, to reduce fire intensity and facilitate fire suppression efforts (Syphard, *et al.,* 2011). In addition, ecosystem resilience to a warmer climate is likely to improve by promoting landscape heterogeneity with diverse species and stand structures, and by reducing the effects of existing non-climatic stressors on ecosystems, such as landscape fragmentation and invasive species (Halofsky, *et al.,* 2018b).

The future increase in fire will put late-successional forest at risk, potentially reducing habitat structures (large trees, snags, downed wood) that are important for many plant and animal species. In dry forests, some structures can be protected from fire by thinning around them and reducing organic material at their base (Halofsky, *et al.,* 2016). To increase habitat quality and connectivity, increasing the density of these structures may be particularly effective in younger forests, especially where young forests are in close proximity to late-successional forest.

Regeneration failures after fire are a risk with changing climate, particularly for drier forests. A primary method to help increase natural post-fire regeneration is to increase seed sources by both reducing fire severity (through fuel treatments and prescribed fire) and increasing the number of live residual trees (Dodson and Root 2013). In areas adjacent to green trees, natural regeneration may be adequate. In locations farther than 200 m from living trees, managers may want to supplement natural regeneration with planting where costs are not prohibitive because of remoteness or topography (North, *et al.,* 2019). Where post-fire planting is desirable, managers may consider changes from current practices. For example, they may want to consider lowering stocking density and increasing the spatial heterogeneity of plantings to increase resilience to fire and drought (North, *et al.,* 2019). Planting seedlings on cooler, wetter microsites will also likely help to increase survival (Rother, *et al.,* 2015). Managers may also consider different genetic stock than has been used in the past to increase seedling survival (Chmura, *et al.,* 2011). Tools such as the Seedlot Selection Tool (*https://seedlotselectiontool.org/sst*) can help identify seedling stock that will be best adapted to a given site in the future.

In general, regeneration in the driest topographic locations may be slower in a warming climate than it has been in the past. Some areas are likely to convert from conifer forest to hardwoods or non-forest (shrubland or grassland) vegetation, particularly at lower treeline. Managers may need to consider where they will try to forestall change and where they may need to allow conversions to occur (Rother, *et al.,* 2015).

Finally, collaboration among many groups-land management agencies, rural communities, private forest landowners, Tribes, and conservation groups—is needed for successful adaptation to the effects of a warmer climate on wildfire (Joyce, *et al.,* 2009; Spies, *et al.,* 2010; Stein, *et al.,* 2013). Working together will ensure a common vision for stewardship of forest resources, and help produce a consistent, effective strategy for fuel treatments and other forest practices across large forest landscapes.

Uncertainties and future research needs

Changing disturbance regimes will accompany climate change in the Northwest (*Tables 1, 2* and *3*). However, uncertainties remain, many related to future human behavior relative to greenhouse gas emissions, the rate and magnitude of climate change, and effects on vegetation and fire regimes. Human activities will also affect fire through land use and management, fire ignitions, and fire suppression, all of which are difficult to predict. For example, societal priorities may change, affecting forest management and vegetation conditions. Fire suppression is likely to continue in the future, but may become less effective under more extreme fire weather conditions (Fried, *et al.,* 2008), affecting area burned.

Historical relationships between climate and fire in the Northwest indicate that the ENSO and PDO can influence area burned. However, it is unclear how climate change will affect these modes of climatic variability or how they may interact with the effects of climate change on natural resources; global climate models differ in how these cycles are represented and in how they are projected to change. The frequency and persistence of high blocking ridges in summer (which divert moisture from the region) will also affect fire frequency and severity in the region, and climate change may affect the frequency of these blocking ridges (Lupo, *et al.,* 1997).

The lack of fire over the last few centuries in forests with low-frequency and high-severity fire regimes creates uncertainty in fire projections for the future. Although the likelihood of a large fire event in these forests is low, if large fire events start occurring as frequently as some models project (*e.g.,* Rogers, *et al.,* 2011), then major ecological changes are likely. Updating models as events occur over time may help to adjust projections in the future.

Shifts in forest productivity and composition are highly likely to occur with climate change in the region, which could affect fuel levels. However, it is uncertain how carbon dioxide fertilization will interact with moisture stress and disturbance regimes to affect forest productivity (Chmura, *et al.,* 2011) and thus fuel levels. Increased forest productivity, combined with hot and dry conditions in late summer, would likely produce large and severe fires (Rogers, *et al.,* 2011). Continued research on the potential effects of carbon dioxide fertilization on forest productivity will help to improve fire severity projections.

Other high-priority research needs include determining forest ecosystem response to multiple disturbances and stressors (*e.g.,* effects of repeated fire and drought on forest regeneration), and determining post-fire regeneration controls across a range of forest types and conditions. Identifying locations where vegetation type shifts (*e.g.,* forest to woodland or shrubland) are likely because of changing climate and disturbance regimes will help managers determine where to prioritize efforts. Managers will also benefit from evaluation of pre- and post-fire forest treatments to increase resilience or facilitate transition to new conditions in different forest types.

Although this synthesis is focused on the effects of climate change on fire and vegetation, many secondary effects are expected for natural resources and ecosystem services, some of which are already occurring. Climate change is reducing snowpack (Mote, *et al.,* 2018) and affecting hydrologic function in the Northwest, including more flooding in winter and lower streamflow in summer (Luce and Holden 2009). Higher stream temperatures are degrading cold-water fish habitat (Isaak, *et al.,* 2010). Altered vegetation and snowpack are expected to have long-term implications for animal habitat (Singleton, *et al.,* 2019). Recreational opportunities (Hand, *et al.,* 2019), infrastructure on public lands (Furniss, *et al.,* 2018), and cultural values (Davis 2018) will likely also be affected by changing climate, fire, and other disturbances.

Uncertainties associated with climate change require an experimental approach to resource management; using an adaptive management framework can help address uncertainties and adjust management over time. In the context of climate change adaptation, adaptive management involves: (1) defining management goals, objectives, and timeframes; (2) analyzing vulnerabilities and determining priorities; (3) developing adaptation options; (4) implementing plans and projects; and (5) monitoring, reviewing, and adjusting (Millar, *et al.,* 2014). Scientists and managers can work together to implement an adaptive management framework and ensure that the best available science is used to inform management actions on the ground.

Availability of data and materials

Please contact the corresponding author for data requests.

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J.H. led the study and contributed to information collection, analysis, and interpretation, and co-wrote the paper. D.P. contributed to information collection, analysis, and interpretation, and co-wrote the paper. B.H. contributed to information collection, analysis, and interpretation, and co-wrote the paper. All authors read and approved the final manuscript.

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NATURE

Letter

Increasing CO_2 threatens human nutrition

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Dietary deficiencies of zinc and iron are a substantial global public health problem. An estimated two billion people suffer these deficiencies,[1] causing a loss of 63 million life-years annually.[2, 3] **Most of these people depend on C**$_3$ grains and legumes as their primary dietary source of zinc and iron. Here we report that C_3 **grains and legumes have lower concentrations of zinc and iron when grown under field conditions at the elevated atmospheric CO_2 concentration predicted for the middle of this century. C**[3] crops other than legumes also have lower concentrations of protein, whereas C_4 **crops seem to be less affected. Differences between cultivars of a single crop suggest that breeding for decreased sensitivity to atmospheric CO_2 concentration could partly address these new challenges to global health.**

In the 1990s, several investigators found that elevated atmospheric CO_2 concentration (hereafter abbreviated to [CO_2]) decreased the concentrations of zinc, iron and protein in grains of wheat,[4–7] barley [5] and rice [8] grown in controlled-environment chambers. However, subsequent studies failed to replicate these results when plants were grown in open-top chambers and free-air CO_2 enrichment (FACE) experiments. A previous study [9] found no effect of [CO_2] on the concentrations of zinc or iron in rice grains grown under FACE and suggested that the earlier findings had been influenced by 'pot effects', by which a small rooting volume led to nutrient dilution at the root-soil interface. Of the more recent studies,[10–13] most have indi-

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cated lower elemental concentrations in soybeans,[10] sorghum,[10] potatoes,[11] wheat[12] or barley[13] grown at elevated [CO_2], but with the exception of iron in one study on wheat,[12] these results were statistically insignificant, perhaps because of small sample sizes.

Small sample sizes have limited the statistical power of individual studies of many aspects of plant responses to elevated [CO_2], and metaanalyses involving larger samples of genotypes, environmental conditions and experimental locations have been important in resolving which elements of plant function respond reliably to altered [CO_2].[14, 15] A recent meta-analysis of published data concluded that only sulphur is decreased in grains grown at elevated [CO_2].[16]

Here we report findings froma meta-analysis of newly acquired data from 143 comparisons of the edible portions of crops grown at ambient and elevated [CO_2] fromseven different FACE experimental locations in Japan, Australia and the United States involving six food crops (see *Table 1*). We tested the nutrient concentrations of the edible portions of rice (*Oryza sativa,* 18 cultivars), wheat (*Triticum aestivum,* eight cultivars), maize (*Zea mays,* two cultivars), soybeans (*Glycine max,* seven cultivars), field peas (*Pisum sativum,* five cultivars) and sorghum (*Sorghum bicolor,* one cultivar). In all, forty-one genotypes were tested over one to six growing seasons at ambient and elevated [CO_2], where the latter was in the range 546–586 p.p.m. across all seven study sites. Collectively, these experiments contribute more than tenfold more data regarding both the zinc and iron content of the edible portions of crops grown under FACE conditions than is currently available in the literature. Consistent with earlier meta-analyses of other aspects of plant function under FACE conditions.[14, 15] we considered the response comparisons observed from different species, cultivars and stress treatments and from different years to be independent. The natural logarithm of the mean response ratio (r = response in elevated [CO_2]/response inambient [CO_2]) was used as themetric for all analyses. Meta-analysis was used to estimate the overall effect of elevated [CO_2] on the concentration of each nutrient in a particular crop and to determine the significance of this effect (see Methods).

We found that elevated [CO_2] was associated with significant decreases in the concentrations of zinc and iron in all C_3 grasses and legumes (*Fig. 1* and *Extended Data Table 1*). For example, wheat grains grown at elevated [CO_2] had 9.3% lower zinc (95% confidence interval (CI) −12.7% to −5.9%) and 5.1% lower iron (95% CI −6.5% to −3.7%) than those grown at ambient [CO_2]. We also found that elevated [CO_2] was associated with lower protein content in C_3 grasses, with a 6.3% decrease (95% CI −7.5% to −5.2%) inwheat grains and a 7.8% decrease (95% CI −8.9% to −6.8%) in rice grains. Elevated [CO_2] was associated with a small decrease in protein in fieldpeas, and therewas no significant effect in soybeans or C_4 crops (*Fig. 1* and *Extended Data Table 1*).

In addition to our own observations, we obtained data from 10 of 11 previously-published studies investigating nutrient changes in the edible portion of food crops (*Extended Data Table 6*) and combined these data with our own observations in a larger meta-analysis. Analysis of our results combined with previously published FACE data (*Extended Data Table 2*), or combined with previously published data from both FACE and chamber experiments (*Extended Data Table 3*), was consistent with the results obtained using only our new data. Combining our data with previously published data did not alter the significance or substantially alter the effect size of the nutrient changes for any crop or any nutrient.

In addition to nutrient concentrations, we also measured phytate, a phosphate storage molecule present in most plants that inhibits the absorption of dietary zinc in the human gut.[17] We had no *a priori* reason to assume that phytate concentrations would change in response to rising [CO_2]. However, formulae for calculating absorbed, or bioavailable, zinc depend on both the amount of dietary zinc and the amount of dietary phytate consumed,[17] making it important to interpret changes in zinc concentration in the context of possible changes in phytate. Phytate content decreased significantly at elevated [CO_2] only in wheat (P<0.01). This decrease might offset some of the declines in zinc for this particular crop, although the decrease was slightly less than half of the decrease in zinc. For other crops examined, however, the lack of a concurrent decrease in phytatemay further exacerbate problemsof zinc deficiency.

Table 1 | Characteristics of agricultural experiments

Crops	Country	Treatments used	Years grown	Number of replicates	Number of cultivars	CO_2 ambient/elevated (p.p.m.)
Wheat						
Site 1	Australia	2 water levels, 2 nitrogen treatments, 2 sowing times	2007–2010	4	8	382/546–550
Site 2	Australia	1 water level, 1 nitrogen treatment, 2 sowing times	2007–2009	4	1	382/546–550
Field peas	Australia	2 water levels	2010	4	5	382/546–550
Rice						
Site 1	Japan	1 nitrogen treatment, 2 warming treatments	2007–2008	3	3	376–379/570–576
Site 2	Japan	3 nitrogen treatments, 2 warming treatments	2010	4	18	386/584
Maize	United States	2 nitrogen treatments	2008	4	2	385/550
Soybeans	United States	1 treatment	2001, 2002, 2004, 2006–2008	4	7	372–385/550
Sorghum	United States	2 water levels	1998–1999	4	1	363–373/556–579

'Number of replicates' refers to the number of identical cultivars grown under identical conditions in the same year and location but in separate FACE rings.

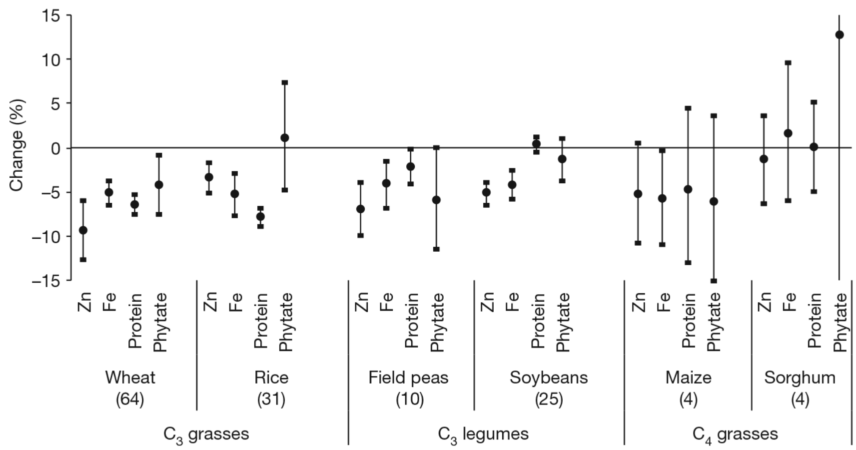
The global [CO_2] in the atmosphere is expected to reach 550 p.p.m. in the next 40–60 years, even if further actions are taken to decrease emissions.[18] At these concentrations, we find that the edible portions of many of the key crops for human nutrition have decreased nutritional value when compared with the same plants grown under identical conditions but at the present ambient [CO_2]. Analysis of the United Nations' Food and Agriculture Organization food balance sheets reveals that in 2010 roughly 2.3 billion people were living in countries whose populations received at least 60% of their dietary zinc and/or iron from C_3 grains and legumes, and 1.9 billion lived in countries that received at least 70% of one or both of these nutrients from these crops (*Extended Data Table 5*). Reductions in the zinc and iron content of the edible portion of these food crops will increase the risk of zinc and iron deficiencies across these populations and will add to the already considerable burden of disease associated with them.

The implications of decreased protein concentrations in non-leguminous C_3 crops are less clear. From a study of adult men and women in the United States, there is strong evidence that the substitution of dietary carbohydrate for dietary protein increased the risk of hypertension, lipid disorders, and 10 year coronary heart disease risk.[19] For the developing world, minimum protein requirements for different demographic groups are an area of active research and debate.[20] For countries such as India, however, inwhich up to ⅓ of the rural population is thought to be at risk of not meeting protein requirements [21] and in which most protein comes in the form of C_3 grains,[21] decreased protein content in non-leguminous C_3 crops may have serious consequences for public health.

Whereas zinc and iron were significantly decreased in all C_3 crops tested, only iron in maize was observed to decreaseamong the C_4 crops. No changes were found in sorghum. That zinc and iron declines were notable in C_3 crops but less so in C_4 crops is consistent with differences in physiology. C_4 crops concentrate CO_2 internally, which results in photosynthesis being CO_2-saturated even under ambient [CO_2] conditions, leading to no stimulation of photosynthetic carbon assimilation at elevated [CO_2] levels under mesic growing conditions.[22] Our finding that protein content was less affected in legumes than in other C_3 crops is also physiologically consistent with the general ability of leguminous crops to match the stimulation of photosynthetic carbon gain at elevated [CO_2] with greater nitrogen fixation, to maintain tissue carbon:nitrogen (C:N) ratios.[23] In contrast, most temperate non-legume C_3 crops are generally unable to extract and assimilate sufficient nitrogen from soils to maintain tissue C:N ratios.[24, 25]

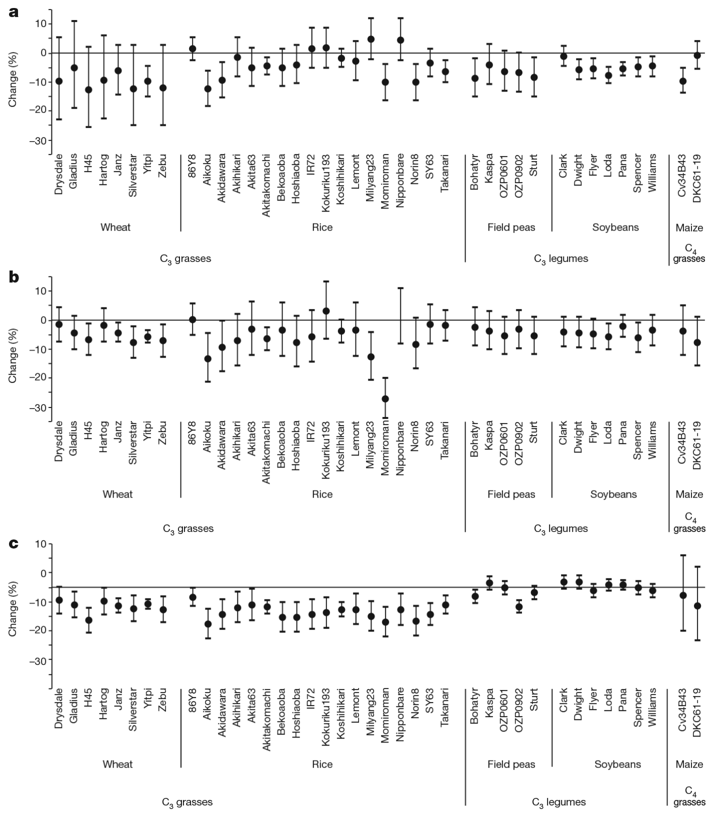
Little is known about the mechanism(s) responsible for the decline in nutrient concentrations associatedwith elevated [CO_2]. Someauthors have proposed 'carbohydrate dilution', by which CO_2-stimulated carbohydrate production by plants dilutes the rest of the grain components.[26] To test this hypothesis, we measured concentrations of additional elements for all crops except wheat (*Extended Data Table 4*). Our findings were inconsistent with carbohydrate dilution operating alone. If only passive dilution of nutrients were occurring, we would have expected to see very similar changes in the concentration of each nutrient tested for a given crop. In contrast, we found that elemental changes in the individual crops are distinct from each other. For example, in rice grains (*Extended Data Table 4*) the decrease in zinc concentrations associated with elevated [CO_2] was significantly different from the decreases in the concentrations of copper ($P \leq 0.001$), calcium ($P \leq 0.001$), boron ($P \leq 0.001$) and phosphate ($P = 0.010$). This heterogeneous response was also observed in recent analyses reviewing possible mechanisms for nutrient changes in both edible and non-edible plant tissues grown at elevated [CO_2].[27] It also seems that the mechanism(s) causing these changes operate distinctly in different species. In one instance, for example, we found boron to be significantly decreased in soybeans ($P \leq 0.001$), whereas itwas significantly elevated in rice grains ($P \leq 0.001$). Although these differences may, in part, have derived from different environmental conditions, they suggest that the mechanismismore complex than carbohydrate dilution alone. Of all the elements, changes in nitrogen content at elevated [CO_2] have been themost studied, and inhibition of photorespiration and malate production,[24] carbohydrate dilution,[26] slower uptake of nitrogen in roots[25] and decreased transpiration-driven mass flow of nitrogen[7] may all be significant.

Figure 1 | Percentage change in nutrients at elevated [CO_2] relative to ambient [CO_2]



Numbers in parentheses refer to the number of comparisons in which replicates of a particular cultivar grown at a specific site under one set of growing conditions in 1 year at elevated [CO_2] have been pooled and for which mean nutrient values for these replicates are compared with mean values for identical cultivars under identical growing conditions except grown at ambient [CO_2]. In most instances, data from four replicates were pooled for each value, meaning that eight experiments were combined for each comparison (see *Table 1* for details of experiments). Error bars represent 95% confidence intervals of the estimates.

Figure 2 | Percentage change (with 95% confidence intervals) in nutrients at elevated [CO_2] relative to ambient [CO_2], by cultivar



a, Zinc; **b,** iron; **c,** protein.

We also examined the effects of elevated [CO_2] on zinc, iron and protein content as a function of cultivar when data were available (*Fig. 2*). Whereas most crops showed negligible differences across cultivars, concentrations of zinc and iron across rice cultivars varied substantially (P=0.04 and P=0.03, respectively; *Fig. 2a, b*). Such differences between cultivars suggest a basis for breeding rice cultivars whose micronutrient levels are less vulnerable to increasing [CO_2]. Similar effects may occur in other crops, given that the statistical power of many of our other intercultivar tests was limited by sample size. We note, however, that such breeding programmes will not be a panacea for many reasons including the affordability of improved seeds and the numerous criteria used by farmers in making planting decisions that include taste, tradition, marketability, growing requirements and yield. In addition, as has been noted previously, there are likely to be trade-offs with respect to yield and other performance characteristics when breeding for increased zinc and iron content.[28]

The public health implications of global climate change are difficult to predict, and we expect many surprises. The finding that raising atmospheric [CO_2] lowers the nutritional value of C_3 food crops is one such surprise that we can now better predict and prepare for. In addition to efforts to limit increases in [CO_2], it may be important to develop breeding programmes designed to decrease the vulnerability of key crops to these changes. Nutritional analysis of which human populations are most vulnerable todecreased dietary availability of zinc, iron and protein from C_3 crops could help to target response efforts, including breeding decreased sensitivity to elevated [CO_2], biofortification, and supplementation.

Methods Summary

We examined the response of nutrient levels to elevated atmospheric [CO_2] for the edible portions of rice (*Oryza sativa,* 18 cultivars), wheat (*Triticum aestivum,* eight cultivars), maize (*Zea mays,* two cultivars), soybeans (*Glycine max,* seven cultivars), field peas (*Pisum sativum,* five cultivars) and sorghum (*Sorghum bicolor,* one cultivar). The six crops were grown under FACE conditions; in all six experiments the elevated [CO_2] was in the range 546–586 p.p.m.

In accordance with methods described previously,[14, 15] the natural logarithm of the response ratio (r=response in elevated [CO_2]/response in ambient [CO_2]) was used as the metric for analyses and is reported as the mean percentage change ($100\times(r-1)$) at elevated [CO_2]. Consistent with these earlier analyses of multiple species grown under FACE conditions, the responses of different species, cultivars and stress treatments and from different years of the FACE experiments were considered to be independent and suited to meta-analytic analysis.[14]

The meta-analysis was designed to estimate the effect of elevated [CO_2] on the concentration of each nutrient in a particular crop and to determine the significance of this effect relative to a null hypothesis of no change. All tests were conducted as two-sided; that is, not specifying which direction the nutrient concentrations were expected to change under elevated [CO_2]. Meta-analysis was conducted with a linear mixed model.

Parameter estimates were obtained by the restricted maximum-likelihood method, a standard approach for analysing repeated measurements[29] that, in our case, were of nutrient concentrations at the time of harvest. Results for all analyses are reported as the best estimate of percentage changes in the concentration of nutrients along with the 95% confidence intervals associated with each estimate. Two-tailed P values are also reported.

Online Content

Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions

S.S.M. conceived the overall project and drafted the manuscript. A.Z., I.K., J.S. and P.H. performed statistical analyses. P.H. and A.D.B.L. provided substantial input into methods descriptions. A.J.B., E.C. and V.R. analysed grain samples for nutrient content. G.F., T.H., A.D.B.L., R.L.N., M.J.O., H.S., S.S., M.T. and Y.U. conducted FACE experiments and supplied grain for analysis. N.M.H. and P.H. assisted with elements of experimental design. K.A.S. and L.H.D. assisted with data collection and analysis. All authors contributed to manuscript preparation.

Author Information

Reprints and permissions information is available at *www.nature.com/reprints*. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests formaterials should be addressed to S.S.M. (*smyers@hsph.harvard.edu*).

Methods

We examined the response of nutrient levels to elevated atmospheric [CO_2] for the edible portions of rice (*Oryza sativa,* 18 cultivars), wheat (*Triticum aestivum,* eight cultivars), maize (*Zea mays,* two cultivars), soybeans (*Glycine max,* seven cultivars), field peas (*Pisum sativum,* five cultivars) and sorghum (*Sorghum bicolor,* one cultivar). The six crops were grown under FACE conditions; in all six experiments, the elevated [CO_2] was in the range 546–586 p.p.m. (see the Agricultural Methods section below for details associated with individual trials).

Statistics. In accordance with methods described previously,[14, 15] the natural logarithm of the response ratio (r=response in elevated [CO_2]/response in ambient [CO_2]) was used as the metric for analyses and is reported as the mean percentage change ($100\times(r-1)$) at elevated [CO_2]. Consistent with these earlier analyses of multiple species grown under FACE conditions, the responses of different species, cultivars and stress treatments and from different years of the FACE experiments were considered to be independent and suited to meta-analytic analysis14.

The meta-analysis was designed to estimate the overall effect of elevated [CO_2] on the concentration of each nutrient in a particular crop and to determine the significance of this effect relative to a null hypothesis of no change. All tests were conducted as two-sided—not specifying which direction the nutrient concentrations were expected to change under elevated [CO_2]—to make the analysis as general as possible. Meta-analysis was conducted with a linear mixed model. A random intercept was included for each comparison, representing nutrient level variability unrelated to [CO_2] that was common to both treatment groups. Additional analyses indicated that the effect of [CO_2] on zinc concentration in rice was modified by cultivar and amount of nitrogen application, suggesting systematic variations across the pooled analysis of rice, and for these samples it was shown that the effect on zinc concentration was still significant when including interactions terms for cultivar and nitrogen. No other significant modifications of the [CO_2] effect were identified. We tested whether changes in different nutrients for particular crops were statistically different from each other, as has been described.[30] To address the issue of multiple comparisons when testing for differences between cultivars within a crop, we multiplied the *P* value by the number of independent comparisons. This approach follows the so-called Bonferroni correction and is conservative in the sense of biasing the P values high, but still shows that individual test results are significant despite their having been selected from multiple tests.

Parameter estimates were obtained by the restricted maximum-likelihood method, a standard approach for analysing repeated measurement data[29] that, in our case, were of nutrient concentrations at time of harvest. Results for all analyses are reported as the best estimate of percentage changes in the concentration of nutrients along with the 95% confidence intervals associated with each estimate. Two-tailed *P* values are also reported.

When combining our data with previously published data, we defined outliers as pairs in which the difference between an observation at ambient [CO_2] and elevated [CO_2] was at least three times the standard deviation from the mean differences for that crop and nutrient type when calculated using all observations. Using this criterion, we excluded a total of two pairs of previously published data fromall analyses; these included one observation of iron in rice and one observation of zinc in potato.

Agricultural methods. Rice (Oryza sativa, 18 cultivars), wheat (*Triticum aestivum,* eight cultivars), maize (*Zea mays,* two cultivars), soybeans (*Glycine max,* seven cultivars), field peas (*Pisum sativum,* four cultivars) and sorghum (*Sorghum bicolor,* one cultivar) were grown under FACE conditions during daylight hours. The experiments were conducted in Australia, Japan and the United States between 1998 and 2010. Ambient [CO_2] ranges were between 363 and 386 p.p.m.; elevated [CO_2] was between 546 and 584 p.p.m. With the exception of soybeans, each experiment involveed multiple cultivars of each crop and more than one set of growing conditions. Each experiment for each cultivar and set of treatments was replicated four times, with the exception of one of the rice sites, for which three replicates were performed. These data are summarized in *Table 1,* and additional details of the soil and growing conditions, FACE methods and experimental designs have been published for rice,[31] wheat,[32] maize,[33] soybeans,[34] field peas[32] and sorghum.[35]

Minerals method. Samples were analysed for minerals by heated closed-vessel digestion/dissolution with nitric acid and hydrogen peroxide followed by quantification with an inductively coupled plasma atomic emission spectrometer.[36] Nitrogen content was measured by flash combustion of the sample coupled with thermal conductivity/infrared detection of the combustion gases (N_2, NO_X and CO_2) with a LECO TruSpec CN Analyzer.[37] Protein values are based on measurement of nitrogen and conversion to proteinwith the equation below, where k=5.36 (ref. 38):

$$\text{protein (weight \%)} = k \times \text{nitrogen (weight \%)}$$

For phytic acid determination, amodified version of the method of ref. 39 was used. The accuracy of the method was monitored by the inclusion of tissue standards of known and varying levels of phytic acid.[40]

Dietary calculations. The United Nations Food and Agriculture Organization (UNFAO) publishes annual Food Balance Sheets, which provide country-specific data on the quantities of 95 'standardized' food commodities available for human consumption. Data, expressed in terms of dietary energy (kilocalories per person per day) were downloaded for 210 countries and territories with available information for the period 2003–2007 (available at *http://faostat.fao.org*). The percentage of dietary energy available from C_3 grasses (wheat, barley, rye, oats, rice and 'cereals, other' (excluding E*ragrostis tef*))was calculated globally with estimates weighted by national population size (188 countries available; UN 2011; 2012 revision available at *http://esa.un.org/wpp/*).

Dietary intake data from the UNFAO Food Balance Sheets (to year 2000) and food composition data fromtheUnited States Department of Agriculture National Nutrient Database for Standard Reference were used to calculate per-person nutrient intake for 95 food items; these were shared with us with permission.[41] This data set was used to calculate the contribution of each food itemto total dietary zinc and iron intake, and the proportions of all food items derived from C_3 grains and legumes were summed to identify countries that are highly dependent on plant sources of iron and zinc (*Extended Data Table 5*).

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Extended Data Table 1 | Percentage change in nutrient content at elevated [CO_2K] relative to ambient [CO_2K]

	N* (number of pairs)	Zn (µg/g)			Fe (µg/g)			Protein (mg/g)			Phytate (g/100g)		
		%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value
C_3 grasses													
Wheat	64	−9.3	(−12.7, −5.9)	<.0001	−5.1	(−6.5, −3.7)	<.0001	−6.3	(−7.5, −5.2)	<.0001	−4.2	(−7.5, −0.8)	0.009
Rice	31	−3.3	(−5.0, −1.7)	<.0001	−5.2	(−7.6, −2.9)	<.0001	−7.8	(−8.9, −6.8)	<.0001	1.2	(−4.6, 7.4)	0.697
C_3 legumes													
Field peas	10	−6.8	(−9.8, −3.8)	0.002	−4.1	(−6.7, −1.4)	0.003	−2.1	(−4.0, −0.1)	0.039	−5.8	(−11.5, 0.1)	0.055
Soybeans	25	−5.1	(−6.4, −3.9)	<.0001	−4.1	(−5.8, −2.5)	<.0001	0.5	(−0.4,1.3)	0.267	−1.3	(−3.7, 1.2)	0.303
C_4 grasses													
Maize	4	−5.2	(−10.7, 0.6)	0.077	−5.8	(−10.9, −0.3)	0.038	−4.6	(−13.0,4.5)	0.312	−6.1	(−15.0, 3.7)	0.215
Sorghum	4	−1.3	(−6.2, 3.8)	0.603	1.6	(−5.8, 9.7)	0.674	0.0	(−4.9, 5.2)	0.993	12.8	(−15.8, 51.1)	0.418

* 'Number of pairs' refers to the number of comparisons in which replicates of a particular cultivar grown at a specific site under one set of growing conditions in 1 year at elevated [CO_2] have been pooled and mean nutrient values for these replicates were compared with mean values for identical cultivars under identical growing conditions except grown at ambient [CO_2]. In most instances, data from four replicates were pooled for each value, meaning that eight experiments were combined for each comparison (see *Table 1* for details of experiments).

Extended Data Table 2 | Original data combined with previously published FACE data from studies 3, 4, 6 and 7

	N* (number of pairs)	Zn (µg/g)			Fe (µg/g)			Protein (mg/g)		
		%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value
C_3 grasses										
Wheat	70	−8.8	(−11.9, −5.6)	<.0001	−5.5	(−6.8, −4.1)	<.0001	−6.5	(−7.5, −5.4)	<.0001
Rice	32	−3.1	(−4.8, −1.5)	<.0001	−4.9	(−7.3, −2.6)	<.0001	−8	(−9.0, −6.9)	<.0001
Barley	4	−11.4	(−19.3, −2.7)	0.012	−10.5	(−12.2, −8.7)	<.0001	−11.9	(−13.1, −10.7)	<.0001
C_3 legumes										
Field peas	10	−6.8	(−9.8, −3.8)	0.002	−4.1	(−6.7, −1.4)	0.003	−2.1	(−4.0, −0.1)	0.039
Soybeans	25	−5.1	(−6.4, −3.9)	<.0001	−4.1	(−5.8, −2.5)	<.0001	0.5	(−0.4, 1.3)	0.267
C_3 tubers										
Potato	2	−3.9	(−12.9, 6.2)	0.440	2.3	(−3.8, 8.7)	0.472	−4.6	(−7.7, −1.4)	<.0001
C_4 grasses										
Maize	4	−5.2	(−10.7, 0.6)	0.077	−5.8	(−10.9, −0.3)	0.038	−4.6	(−13.0, 4.5)	0.312
Sorghum	4	−1.3	(−6.2, 3.8)	0.603	1.6	(−5.8, 9.7)	0.674	0.0	(−4.9, 5.2)	0.993

See Extended Data Table 6 for a list of experiments. Percentage change in nutrient content at elevated [CO_2] relative to ambient [CO_2].

* 'Number of pairs' refers to the number of comparisons in which replicates of a particular cultivar grown at a specific site under one set of growing conditions in 1 year at elevated [CO_2] have been pooled and mean nutrient values for these replicates were compared with mean values for identical cultivars under identical growing conditions except grown at ambient [CO_2]. In most instances, data from four replicates were pooled for each value, meaning that eight experiments were combined for each comparison (see *Table 1* for details of experiments).

Extended Data Table 3 | Original data combined with previously published FACE and chamber data from studies 1–10

	N* (number of pairs)	Zn (μg/g)			Fe (μg/g)			Protein (mg/g)		
		%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value
C_3 grasses										
Wheat	78	−9.1	(−12.1, −6.1)	<.0001	−5.9	(−7.8, −4.0)	<.0001	−7.2	(−8.6, −5.8)	<.0001
Rice	32	−3.1	(−4.8, −1.5)	<.0001	−4.9	(−7.3, −2.6)	<.0001	−8	(−9.0, −6.9)	<.0001
Barley	6	−13.6	(−19.3, −7.6)	<.0001	−10.0	(−12.4, −7.4)	<.0001	−15.0	(−19.1, −10.7)	<.0001
C_3 legumes										
Field peas	10	−6.8	(−9.8, −3.8)	<.0001	−4.1	(−6.7, −1.4)	0.003	−2.1	(−4.0, −0.1)	0.039
Soybeans	28	−5.0	(−6.1, −3.9)	<.0001	−5.2	(−7.9, −2.5)	<.0001	0.1	(−0.8, 0.9)	0.865
C_3 tubers										
Potato	5	−10.0	(−20.9, 2.4)	0.110	−4.1	(−16.6, 10.3)	0.555	−9.7	(−15.9, −3.1)	0.005
C_4 grasses										
Maize	4	−5.2	(−10.7, 0.6)	0.077	−5.8	(−10.9, −0.3)	0.038	−4.6	(−13.0, 4.5)	0.312
Sorghum	7	−0.6	(−4.5, 3.4)	0.764	33.8	(−10.2, 99.3)	0.153	−5.6	(−12.7, 2.1)	0.150

See Extended Data Table 6 for a list of experiments. Percentage change in nutrient content at elevated [CO_2] relative to ambient [CO_2].

* 'Number of pairs' refers to the number of comparisons in which replicates of a particular cultivar grown at a specific site under one set of growing conditions in 1 year at elevated [CO_2] have been pooled and mean nutrient values for these replicates were compared with mean values for identical cultivars under identical growing conditions except grown at ambient [CO_2]. In most instances, data from four replicates were pooled for each value, meaning that eight experiments were combined for each comparison (see *Table 1* for details of experiments).

Extended Data Table 4 | Percentage change in nutrient content at elevated [CO_2K] compared with ambient [CO_2K] for all nutrients

	C_3 grasses						C_3 legumes						C_4 grasses					
	Wheat			Rice			Field Peas			Soybean			Maize			Sorghum		
	%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value	%	95% CI	*P*-value
Zinc (ppm)	−9.3	(−12.7, −5.9)	<.0001	−3.3	(−5.0, −1.7)	<.0001	−6.8	(−9.8, −3.8)	<.0001	−5.1	(−6.4, −3.9)	<.0001	−5.2	(−10.7, 0.6)	0.077	−1.3	(−6.2, 3.8)	0.603
Iron (ppm)	−5.1	(−6.5, −3.7)	<.0001	−5.2	(−7.6, −2.9)	<.0001	−4.1	(−6.7, −1.4)	<.0001	−4.1	(−5.8, −2.5)	<.0001	−5.8	(−10.9, −0.3)	0.038	1.6	(−5.8, 9.7)	0.674
Phytate (mg/g)	−4.2	(−7.5, −0.8)	0.009	1.2	(−4.6, 7.4)	0.7	−5.8	(−11.5, 0.1)	0.055	−1.3	(−3.7, 1.2)	0.303	−6.1	(−15.0, 3.7)	0.215	12.8	(−15.8, 51.1)	0.418
Protein	−6.3	(−7.5, −5.2)	<.0001	−7.8	(−8.9, −6.8)	<.0001	−2.1	(−4.0, −0.1)	0.039	0.5	(−0.4, 1.3)	0.267	−4.6	(−13.0, 4.5)	0.312	0.0	(−4.9, 5.2)	0.993
Mn (ppm)				−7.5	(−12.0, −2.8)	<.0001	−2.5	(−4.2, −0.8)	0.005	−1.4	(−3.5, 0.8)	0.204	−4.2	(−10.5, 2.5)	0.215	1.7	(−4.5, 8.3)	0.596
Mg (%)				−0.9	(−2.3, 0.6)	0.24	0.0	(−1.3, 1.4)	0.960	−3.5	(−4.3, −2.8)	<.0001	−5.7	(−9.9, −1.3)	0.011	−0.2	(−5.1, 4.9)	0.944
Cu (ppm)				−10.6	(−13.8, −7.1)	<.0001	−2.7	(−5.1, −0.3)	0.025	−5.7	(−8.0, −3.4)	<.0001	−9.9	(−19.3, 0.7)	0.066	−2.9	(−7.1, 1.5)	0.190
Ca (%)				2	(−0.8, 4.9)	0.16	−0.5	(−4.2, 3.3)	0.787	−5.8	(−7.3, −4.2)	<.0001	−2.7	(−16.9, 13.9)	0.734	11.2	(−5.2, 30.3)	0.190
S (ppm)				−7.8	(−8.8, −6.8)	<.0001	−2.2	(−3.6, −0.7)	0.003	−2.9	(−3.5, −2.2)	<.0001	2.1	(−2.2, 6.7)	0.342	−0.2	(−5.4, 5.2)	0.936
K (%)				1.1	(−0.3, 2.5)	0.13	2.2	(0.6, 3.8)	0.008	0.1	(−0.8, 1.0)	0.857	−2.7	(−3.1, −2.2)	<.0001	3.0	(−2.7, 9.1)	0.308
B (ppm)				5.1	(1.9, 8.4)	0.002	−1.9	(−3.9, 0.1)	0.057	−6.4	(−9.1, −3.6)	<.0001	4.9	(−1.0, 11.1)	0.107	−0.3	(−9.3, 9.6)	0.952
P (%)				−1.0	(−2.4, 0.4)	0.160	−3.7	(−6.8, −0.5)	0.023	−0.7	(−2.2, 0.9)	0.379	−7.1	(−9.0, −5.1)	<.0001	0.3	(−4.0, 4.9)	0.881

Sample sizes for each crop type are identical to those listed in *Table 1*.

Extended Data Table 5 | Countries whose populations receive at least 60% of dietary iron and/or zinc from C_3 grains and legumes

Country	% Iron from C_3 grains & legumes	% Zinc from C_3 grains & legumes	Population (in thousands)
Afghanistan	78%	78%	31,412
Algeria	76%	79%	35,468
Iraq	74%	83%	31,672
Bangladesh	72%	88%	148,692
Iran, Islamic Rep. of	72%	77%	73,974
Pakistan	70%	72%	173,593
Tunisia	70%	77%	10,481
Jordan	69%	73%	6,187
Morocco	69%	78%	31,951
Syrian Arab Republic	67%	71%	20,411
Libya	67%	71%	6,355
Yemen	66%	75%	24,053
Myanmar	65%	81%	47,963
Tajikistan	62%	56%	6,879
India	59%	71%	1,224,614
Egypt	54%	65%	81,121
Indonesia	52%	65%	239,871
Sierra Leone	51%	70%	5,868
Cambodia	49%	68%	14,138
Sri Lanka	46%	69%	20,860
Laos	44%	66%	6,201
Viet Nam	43%	61%	87,848
Total			2,329,612

Source: United Nations Food and Agriculture Organization food balance sheets and 2010 United Nations estimated population.

Extended Data Table 6 | Literature reporting nutrient changes in the edible portion of crops grown at elevated and ambient [CO_2]

Study	Experimental Method	Associated Citations
1	Growth Chambers	Conroy, J., Seneweera, S.P., Basra, A., Rogers, G. & Nissen-Wooller, B. *Influence of rising atmospheric CO_2 concentrations and temperature on growth, yield and grain quality of cereal crops.* AUSTRALIAN JOURNAL OF PLANT PHYSIOLOGY 21, 741–758 (1994). Seneweera, S., Milham, P. & Conroy, J. *Influence of elevated CO_2 and phosphorus nutrition on the growth and yield of a short-duration rice. Australian Journal of Plant Physiology* 21, 281–292 (1994). Seneweera, S.P. & Conroy, J.P. *Growth, grain yield and quality of rice (**Oryza sativa** L.) in response to elevated CO_2 and phosphorus nutrition* (Reprinted from *Plant nutrition for sustainable food production and environment,* 1997). SOIL SCI. PLANT NUTR. 43, 1131–1136 (1997).
2	Temperature Gradient Tunnels	De la Puente, L.S., Perez, P.P., Martinez-Carrasco, R., Morcuende, R.M. & Del Molino, I.M.M. *Action of elevated CO_2 and high temperatures on the mineral chemical composition of two varieties of wheat.* AGROCHIMICA 44, 221–230 (2000).
3	Open Top Chambers & FACE	De Temmerman L., *et al. Effect of climatic conditions on tuber yield (Solanum tuberosum L.) in the European 'CHIP' experiments.* EUROPEAN JOURNAL OF AGRONOMY 17, 243–255 (2002). De Temmerman, L., Hacour, A. & Guns, M. *Changing climate and potential impacts on potato yields and quality 'CHIP': introduction, aims and methodology.* EUROPEAN JOURNAL OF AGRONOMY 17, 233–242 (2002). Fangmeier, A., De Temmerman, L., Black, C., Persson, K. & Vorne, V. *Effects of elevated CO_2 and/or ozone on nutrient concentrations and nutrient uptake of potatoes.* EUROPEAN JOURNAL OF AGRONOMY 17, 353–368 (2002). Högy, P. & Fangmeier, A. *Atmospheric CO_2 enrichment affects potatoes: 2. Tuber quality traits.* EUROPEAN JOURNAL OF AGRONOMY 30, 85–94 (2009).

Extended Data Table 6 |Literature reporting nutrient changes in the edible portion of crops grown at elevated and ambient [CO_2]—Continued

Study	Experimental Method	Associated Citations
4	FACE	Erbs, M., *et al. Effects of free-air CO_2 enrichment and nitrogen supply on grain quality parameters and elemental composition of wheat and barley grown in a crop rotation.* AGRICULTURE, ECOSYSTEMS AND ENVIRONMENT 136, 59–68 (2010).
5	Open Top Chambers	Fangmeier, A., *et al. Effects of elevated CO_2, nitrogen supply and tropospheric ozone on spring wheat. I. Growth and yield.* ENVIRONMENTAL POLLUTION 91, 381–390 (1996).
		Fangmeier, A., Grüters, U., Högy, P., Vermehren, B. & Jäger, H.-J. *Effects of elevated CO_2, nitrogen supply and tropospheric ozone on spring wheat—II. Nutrients (N, P, K, S, Ca, Mg, Fe, Mn, Zn).* ENVIRONMENTAL POLLUTION 96, 43–59 (1997).
		Fangmeier, A., *et al. Effects on nutrients and on grain quality in spring wheat crops grown under elevated CO_2 concentrations and stress conditions in the European, multiple-site experiment 'ESPACE-wheat'.* EUROPEAN JOURNAL OF AGRONOMY 10, 215–229 (1999).
		Jäger, H.-J., Hertstein, U. & Fangmeier, A. *The European Stress Physiology and Climate Experiment—project 1: wheat (ESPACE-wheat): introduction, aims and methodology.* EUROPEAN JOURNAL OF AGRONOMY 10, 155–162 (1999).
6	FACE	Högy, P. & Fangmeier, A. *Effects of elevated atmospheric CO_2 on grain quality of wheat.* JOURNAL OF CEREAL SCIENCE 48, 580–591 (2008).
		Högy, P., *et al. Does elevated atmospheric CO_2 allow for sufficient wheat grain quality in the future?.* JOURNAL OF APPLIED BOTANY AND FOOD QUALITY 82, 114–121 (2009).
		Högy, P., *et al. Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO_2 enrichment experiment.* PLANT BIOLOGY 11, 60–69 (2009).
		Högy, P., Zörb, C., Langenkämper, G., Betsche, T. & Fangmeier, A. *Atmospheric CO_2 enrichment changes the wheat grain proteome.* JOURNAL OF CEREAL SCIENCE 50, 248–254 (2009).
7	FACE	Kim , H., Lieffering, M., Miura, S., Kobayashi, K. & Okada, M. *Growth and nitrogen uptake of CO_2-enriched rice under field conditions.* NEW PHYTOLOGIST 150, 223–229 (2001).
		Kim, H., *et al. Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops.* FIELD CROPS RESEARCH 83, 261–270 (2003).
		Lieffering, M., Kim, H.-Y., Kobayashi, K. & Okada, M. *The impact of elevated CO_2 on the elemental concentrations of field-grown rice grains.* FIELD CROPS RESEARCH 88, 279–286 (2004).
8	Open Top Chambers	Pleijel, H., *et al. Effects of elevated carbon dioxide, ozone and water availability on spring wheat growth and yield.* PHYSIOLOGIA PLANTARUM 108, 61–70 (2000).
		Pleijel, H. & Danielsson, H. *Yield dilution of grain Zn in wheat grown in open-top chamber experiments with elevated CO_2 and O3 exposure.* JOURNAL OF CEREAL SCIENCE 50, 278–282 (2009).
9	Open Top Chambers	Prior, S.A., Runion, G.B., Rogers, H.H., Torbert, H.A. *Effects of atmospheric CO_2 enrichment on crop nutrient dynamics under no-till conditions.* JOURNAL OF PLANT NUTRITION 31, 758–773 (2008).
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NATURE

Communications

Over half of western United States' most abundant tree species in decline

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Abstract

Changing forest disturbance regimes and climate are driving accelerated tree mortality across temperate forests. However, it remains unknown if elevated mortality has induced decline of tree populations and the ecological, economic, and social benefits they provide. Here, we develop a standardized forest demographic index and use it to quantify trends in tree population dynamics over the last 2 decades in the western United States. The rate and pattern of change we observe across species and tree size-distributions is alarming and often undesirable. We observe significant population decline in a majority of species examined, show decline was particularly severe, albeit size-dependent, among subalpine tree species, and provide evidence of widespread shifts in the size-structure of montane forests. Our findings offer a stark warning of changing forest composition and structure across the western U.S., and suggest that sustained anthropogenic and natural stress will likely result in broad-scale transformation of temperate forests globally.

Introduction

Persistent shifts in forest composition, structure, and function depend largely on the demographic response of trees to changing environmental drivers and disturbance regimes.[1, 2] Across temperate forests—representing ~25% of the world's forested land area[3]—recent reports of increasing tree mortality have been attributed to complex interactions among climate, native insects and pathogens, and uncharacteristically severe wildfire.[4, 5, 6] Such pervasive changes in tree population dynamics can have substantial impacts on the ecosystem services provided by temperate forests, including carbon storage and sequestration,[7] climate regulation,[8] and provisioning of drinking water.[9] Sustained anthropogenic and natural stress is thus expected to result in broad-scale transformation of temperate forests and the services they provide.[10, 11] As such, a key challenge for ecological research is to quantify the patterns and underlying drivers of changing tree populations to better inform forest management and help ease ecological transitions.[12]

Tree demographic rates (*e.g.,* mortality) are important, widely used indicators of forest health.[12] However, tree demographic rates are confounded by stand development processes (*i.e.,* stand aging)[13, 14] and do not yield a comprehensive depiction of tree population dynamics when considered individually (*i.e.,* the net result of growth, recruitment, and mortality processes; tree abundance shifts).[15, 16, 17] Thus, while recent reports of elevated tree mortality are suggestive of broad-scale changes in the composition and structure of temperate forests,[4, 5, 18] such conclusions should not be accepted in the absence of information regarding tree recruitment, growth, and stand development.[1, 19] Previous efforts to quantify trends in tree population dynamics have often relied on observations from old forests to minimize the influence of stand development processes.[5, 18] Still, patterns of tree population dynamics observed in old forests are seldom characteristic of those in younger forests[20] and are thus unlikely to be representative of patterns emerging across forest landscapes (or forested regions) that are composed of a mosaic of stands in various stages of development.[21] As such, advancement in detection and prediction of forest health decline depends largely on the dissemination of methods that comprehensively de-

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scribe tree population dynamics and account for variation in tree demography arising from stand development processes.[14, 19]

To this end, we propose the forest stability index (FSI), a direct measure of temporal change in relative live tree density that is independent of stand development processes by design. Temporal change in absolute tree density (*e.g.,* trees per hectare (TPH)) emerges from the joint demographic response of tree populations to endogenous (*e.g.,* inter-tree competition) and exogenous drivers (*e.g.,* wildfire).[22] That is, change in absolute tree density is the net result of mortality, growth, and recruitment processes, and is thus a demographically comprehensive measure of tree population dynamics. Relative tree density may be defined as the proportion of absolute tree density observed in a stand relative to the maximum theoretical density the stand could achieve given its observed tree size-distribution. The maximum density that a population of trees may achieve is expected to decline as individuals grow in size, following well-established allometric scaling laws that drive stand development processes (*i.e.,* self-thinning).[15, 16, 17, 23, 24] Indices of relative tree density (*i.e.,* ratio of observed and maximum theoretical tree density) are thus independent of stand development processes by definition, as allometric tree size-density relationships are explicitly acknowledged in their denominator.

The FSI is defined as the change in relative density observed in a population of trees over time (*e.g.,* via remeasurement of forest inventory plots). Here stability is achieved when the relative density of a tree population is constant (*e.g.,* FSI equal to zero, stand remains at 50% stocking over time), despite underlying changes in absolute tree density and size distribution. Stability in this sense is uncommon at the stand-scale, as stands progress toward maximum relative density in the absence of exogenous stress (positive FSI, *e.g.,* tree growth exceeds mortality) and relative density is expected to decline given disturbance (negative FSI, *e.g.,* disturbances act as thinning agents). At the landscape-scale, however, stability represents a balance between disturbance and tree growth processes, and deviations from this dynamic equilibrium may be indicative of pervasive changes in forest structure, composition, and function.

We use the FSI to identify patterns in relative tree density shifts of the eight most abundant tree species in the western United States (U.S.) and determine the importance of major forest disturbances in driving the population dynamics of each species over the last 2 decades. Many forests in the western U.S. have experienced recent increases in the extent, severity, and frequency of wildfire,[25, 26] drought,[27, 28] and insect-pest outbreaks,[29, 30] owing in part to changing climate and past forest management (*i.e.,* fire suppression). Likewise, large-scale tree mortality events[5, 31] and recruitment failures[32, 33] indicate that widespread forest change is already underway in the region. Such issues are not, however, unique to forests of the western U.S. Increased disturbance activity has been documented in other regions of the temperate biome in recent decades,[12, 34, 35] and the broad spatial and climatic domain encompassed by the western U.S. suggests that patterns of forest change observed herein may be highly relevant to temperate forests across the globe.

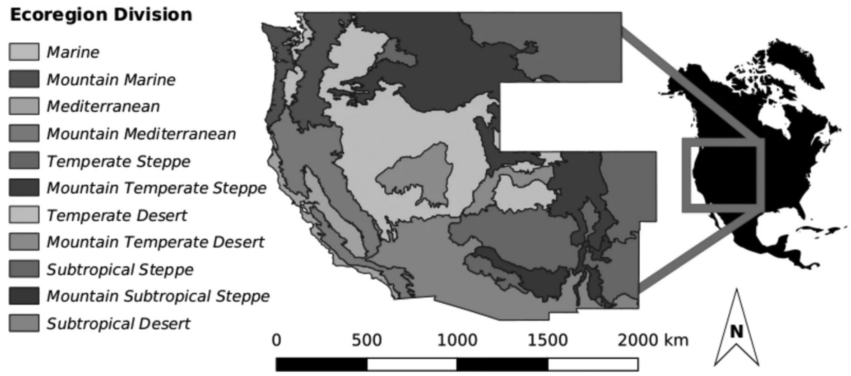
We draw upon over 24,000 repeated censuses of U.S. Forest Service Forest Inventory and Analysis (FIA) plots to address the following questions: (1) What is the current status of populations of the eight most abundant tree species in the western U.S. (*i.e.,* expanding, declining), and what do inter-specific differences in the rate of relative tree density shifts indicate about changes in forest composition? (2) Is the rate of relative tree density shifts size-dependent, and if so, what do these relationships indicate about changes in forest structure? (3) Does the rate of relative tree density shifts vary across space within species ranges, and what are the general patterns of change for each species? (4) How do major forest disturbances influence the populations of these dominant species, and what do these relationships suggest about species sensitivity to future changes in forest disturbance regimes?

Here, we show a majority of the most abundant tree species in the western U.S. experienced significant population decline over the last 2 decades. Further, we show the magnitude of change in tree populations diverges strongly across species, species-size distributions, and species ranges, and the patterns of such change are generally inconsistent with broad-scale reversion of forests toward historical conditions. Altogether, we provide empirical evidence of widespread, yet spatially varying, changes in forest composition and structure over the last 2 decades in the western U.S.

Results

We identified the eight most abundant tree species in the western U.S. by their estimated total number of live stems (*i.e.,* diameter ≥2.54 cm at 1.37 m above ground) across the region (*Fig. 1*). Top species represented six distinct genera and three families (*Table 1*). We categorized species by general ecosystem associations, including two woodland species (*i.e.,* characteristic of mid-high-elevation desert/steppe), three subalpine species (*i.e.,* commonly occurring in cool, moist high-elevation forests), and three montane species (*i.e.,* characteristic of mid-elevation forests climatically bounded by woodland (hotter, drier) and subalpine ecosystems (cooler, wetter)). Together these top eight species accounted for 61.6% of all live trees across the study region (62.3% of total live basal area).

Fig. 1: Study area colored by ecoregion divisions



Ecoregion divisions are differentiated by broad-scale patterns of precipitation and temperature. Our study area spans both the humid and dry domains of the western U.S. We exclude the state of Wyoming due a lack of data.

Table 1

Common name	Scientific name	Ecosystem association	Prevalence	No. plots
Douglas-fir	*Pseudotsuga menziesii* Mirb.	Montane	0.15	12,284
Lodgepole pine	*Pinus contorta* Doug.	Subalpine	0.11	4556
Subalpine fir	*Abies lasiocarpa* Hook.	Subalpine	0.09	3174
Ponderosa pine	*Pinus ponderosa* Doug.	Montane	0.06	7309
Common pinyon	*Pinus edulis* Engelm.	Woodland	0.05	3076
Quaking aspen	*Populus tremuloides* Michx.	Montane	0.05	1723
Engelmann spruce	*Picea Engelmannii* Parry	Subalpine	0.05	3079
Utah juniper	*Juniperus osteosperma* Torr.	Woodland	0.04	3446

Scientific and common names of the eight most abundant tree species across the western U.S., listed in order of decreasing prevalence (*i.e.,* the proportion of total number of stems represented by each species across the region).

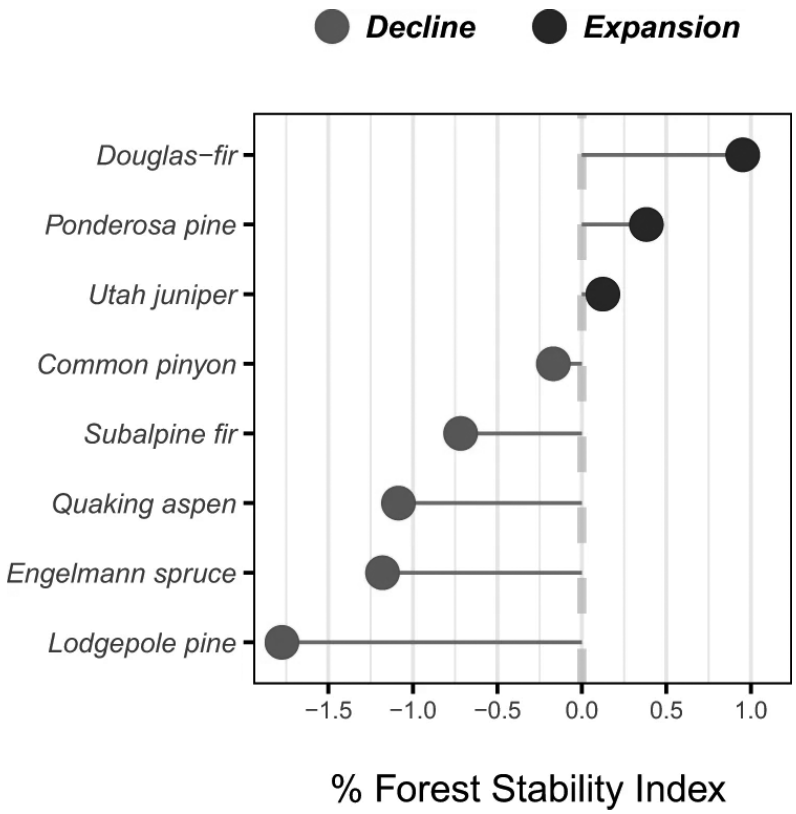
Commonly accepted ecosystem associations are reported for each species along with their respective sample size in the FIA plot network (remeasured plots only).

The FSI is defined as the average annual change in the relative density of a population of live trees, or the ratio of observed tree density to maximum potential tree density given site conditions and observed tree size-distributions. Hence, significant positive values of the FSI indicate increased relative density (*i.e.,* population expansion), significant negative values indicate decreased relative density (*i.e.,* population decline), and values of the FSI not significantly different from zero indicate population stability (*i.e.,* no change in relative density). Herein, we treat changes in population range boundaries and within-range density shifts as functionally equivalent processes. For example, range expansion (population occurrence on a site where it was previously absent) is represented by the FSI as a positive change in relative density (*i.e.,* where previous relative density is zero). Thus, when summarized across broad spatial domains the FSI represents a comprehensive measure of the net performance of a population of trees during the temporal frame of sampling (*i.e.,* in terms of net changes in relative abundance).

Broad-scale shifts in forest composition and structure

Species-level estimates of the mean FSI across the entire study region (*i.e.,* range-average estimates) reveal broad-scale patterns of rapid change in the composition of western U.S. forests (over 91 million hectares of forestland) over the last 2 decades (*Fig. 2*). Three of the eight most abundant species in the region (lodgepole pine, Engelmann spruce, and quaking aspen) exhibited average decreases in relative density (*i.e.,* population decline) at rates exceeding 1% per year over the 18 year study period (2001–2018), whereas Douglas-fir increased in relative density at nearly the same rate. For reference, a %FSI equal to 1% is equivalent to an 18% change in relative density over the duration of the study period. Across all species, population decline occurred more frequently (five of eight of species) and with greater magnitude (*Fig. 2;* leftward skew) than population expansion.

Fig. 2: Range-average % forest stability index (FSI) of the eight most abundant tree species in the western U.S. over the period 2001–2018

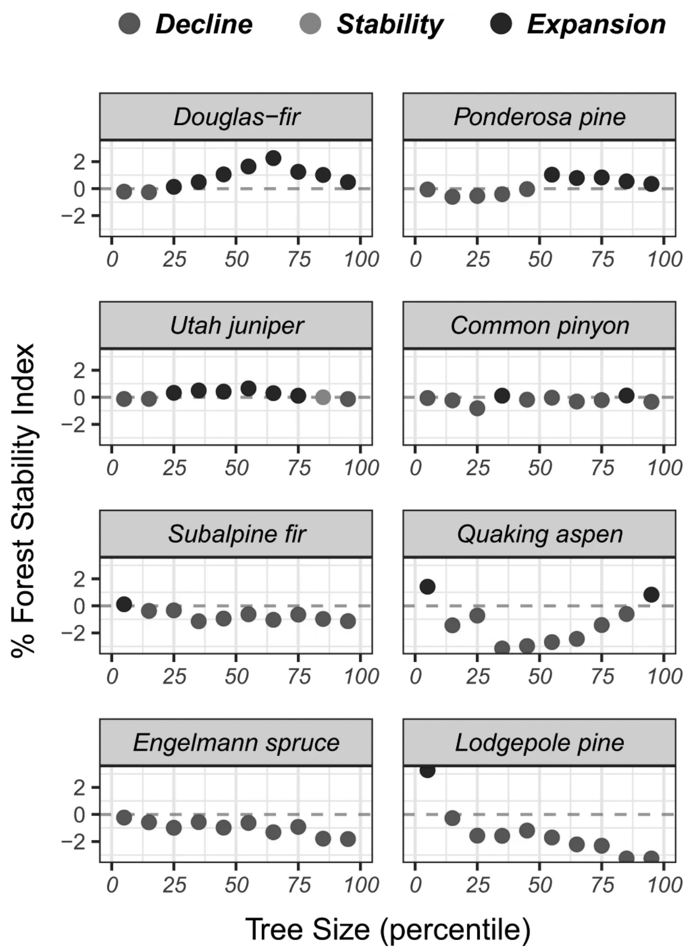


Population decline (red) occurs when the FSI is negative and the associated 95% confidence interval does not include zero. Conversely, population expansion (blue) occurs when the FSI is positive and the associated confidence interval does not include zero. Here, the %FSI is a direct measure of average annual percent change in the relative density of each species across their ranges in the western U.S. Thus, total % change in relative density can be estimated by multiplying the %FSI by the length of the study period (18 years). For reference, complete loss of a species over the study period would be indicated by a %FSI value of −5.56%. Source data are provided as a Source Data file.

Severe rates of population decline were apparent in all three subalpine species considered herein, with lodgepole pine and Engelmann spruce exhibiting the highest rates of decline among all species (lodgepole pine approaching decline of 2% annually, 36% over the entire study period). Douglas-fir and ponderosa pine, both montane species, exhibited the highest rates of range-wide population expansion. In contrast, quaking aspen populations declined at a rate exceeding the rate of expansion observed in other montane species. Woodland species exhibited the highest degree of population stability (range-average mean FSI values closest to zero) over the last 2 decades, although low rates (<0.20% annually, 3.6% over the duration of the study period) of population expansion and decline were observed for Utah juniper and common pinyon, respectively.

Variation in range-average estimates of the FSI across species-size distributions are indicative of extensive, complex shifts in the size-structure of forests of the western U.S. over the period 2001–2018 (*Fig. 3*). Rapid population decline was evident in nearly all size-classes of subalpine tree species (except the smallest 10% of subalpine fir and lodgepole pine). Further, the rate of population decline appeared to increase with increasing tree size across all subalpine species (*Fig. 3;* downward trend in FSI), and this trend was most severe in lodgepole pine (largest 20% of trees declined at rates exceeding 3% annually, 54% over the duration of the study period). The opposite pattern appeared for Douglas-fir and ponderosa pine, where the largest trees generally outperformed the smallest trees of each species (*i.e.,* higher or more positive changes in relative density).

Fig. 3: Range-average % forest stability index (FSI) across size distributions of the eight most abundant tree species in the western U.S. over the period 2001–2018



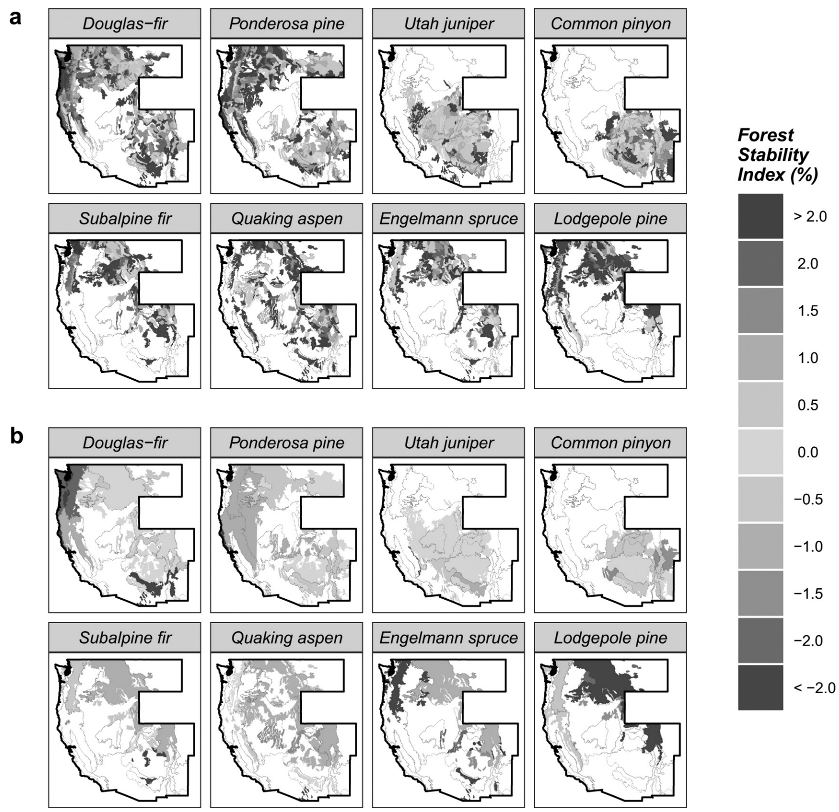
Population decline (red) occurs when the FSI is negative and the associated confidence interval does not include zero. Conversely, population expansion (blue) occurs when the FSI is positive and the associated confidence interval does not include zero. Here, the %FSI is a direct measure of average annual percent change in the relative density of each species across their ranges in the western U.S., and variation in the FSI across species-size distributions is indicative of shifts in forest structure during the study period. Total % change in relative density can be estimated by multiplying the %FSI by the length of the study period (18 years), with a maximum annual decline of −5.56% (complete loss of the population over the study period). Source data are provided as a Source Data file.

Interestingly, population decline was evident among the smallest size-classes of Douglas-fir (lower 20%) and ponderosa pine (lower 50%), whereas the largest size-classes of both species exhibited population expansion. Patterns of change in relative density across the size-distribution of quaking aspen appeared to follow an approximately quadratic trend, with population expansion evident in the smallest and largest 10% of stems and severe population decline (approaching 3% annually, 54% over the duration of the study period) apparent near the median (50%) tree size class. The size distribution of woodland species (*i.e.,* common pinyon and Utah juniper) appeared to be the most stable of all species examined, indicated by relatively low variation in relative density shifts across tree size-classes (*Fig. 3;* nearly flat trends).

Early indications of shifting species distributions

Summaries of the FSI within ecoregion divisions revealed broad-scale spatial patterns of change in the relative density of each species over the last 2 decades in the western U.S. (*Fig. 4b*). Population decline was spatially pervasive among all subalpine species and particularly severe for lodgepole pine in the mountain temperate steppe division (*i.e.,* central and northern Rocky Mountains). Though interestingly, lodgepole pine populations increased in relative density (*i.e.,* population expansion) in the mountain marine (*i.e.,* coastal Pacific Northwest) and mountain Mediterranean (*i.e.,* Sierra Nevada) divisions over the study period. Quaking aspen exhibited consistent rates of population decline across its range within the study region (~1% annually, 18% over the duration of the study period). Spatial patterns of relative density shifts of Douglas-fir and ponderosa pine were similar, with decline evident for both species in the mountain subtropical steppe division (*i.e.,* southern Rocky Mountains) and expansion in the northwestern portion of the study region (particularly strong for Douglas-fir in the marine and mountain marine divisions). In contrast, we found general patterns of population stability across the ranges of both woodland species, with the majority of each species' range characterized by FSI values near zero.

Fig. 4: Spatial variation in the % forest stability index (%FSI) of eight most abundant species across their ranges in the western U.S. over the period 2001–2018



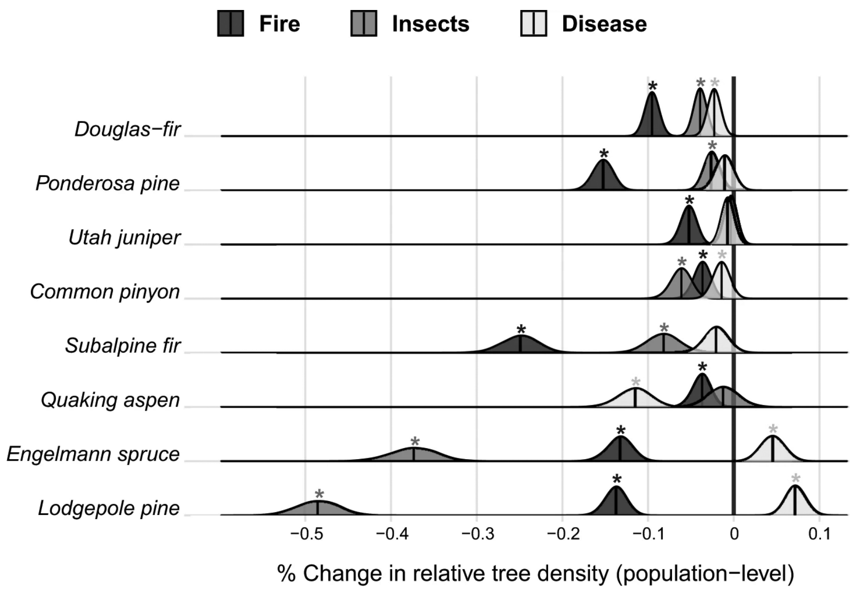
Mean %FSI values are mapped at two spatial scales: ecoregion subsection **a** and ecoregion division **b.** Boundaries of the study region are outlined in black, and white areas within the study area indicate absence of a species in the FIA plot network (*i.e.,* colored regions represent species' ranges). For reference, ecoregion division boundaries (as seen in *Fig. 1*) are outlined as gray dotted lines, and maps of the %FSI within ecoregion divisions (bottom) have been clipped to the extent of each species' range (*i.e.,* defined by ecoregion subsections where the species was detected on an FIA plot). Tree populations have been observed to expand in areas characterized by positive FSI estimates (blue), and decline in areas characterized by negative %FSI estimates (red) during the inventory period (approximately 2 decades). For reference, %FSI values −2% indicate a 36% decline in relative density over the duration of the study period. Source data are provided as a Source Data file.

While the general spatial patterns of the FSI observed in subsection-level summaries (*Fig. 4a*) mirrored those of division-level summaries, subsection-level summaries revealed patterns of change in species relative density at finer spatial scales than division-level summaries. Qualitatively, the FSI appears to exhibit strong, positive spatial auto-correlation across ecoregion subsections, and such local-scale variation is not well represented in division-level summaries. Specifically, local regions of population expansion and regions of population decline (*i.e.,* consisting of multiple adjoining ecoregion subsections with similar FSI values) emerge to varying degrees within the range of each species. However, spatial patterns of population performance were not always consistent among overlapping species, indicating shifts in local-scale forest composition.

Forest disturbances as drivers of relative tree density shifts

Estimated effects of forest disturbances on relative density highlight disturbances as important drivers of tree population dynamics in the western U.S., though the magnitude of disturbance effects varied strongly by tree species and disturbance type (*Fig. 5*). Here, we present effects of forest disturbances as percent change in relative tree density estimated to be caused by each disturbance type at the population-level (*i.e.,* product of disturbance severity and disturbance probability). Hence, high magnitude of estimated effects indicates a disturbance type is an important driver of the population dynamics of a tree species (*e.g., Fig. 5,* insect outbreaks in lodgepole pine).

Fig. 5: Posterior distributions of the estimated effects of forest disturbances on the relative density of live tree populations for the eight most abundant species in the western U.S. over the period 2001–2018



Change in relative tree density resulting from each disturbance type is estimated as the product of average disturbance severity and probability (annual), where disturbance severity is defined as the average difference in relative density shifts between undisturbed and disturbed sites. Posterior probability distributions of parameters are estimated via Markov chain Monte Carlo (5,000 samples). Posterior medians of each parameter are plotted as black vertical lines. Asterisks indicate the 95% credible interval of the mean effect excludes zero, and hence are considered statistically significant. Source data are provided as a Source Data file.

Across all species, fire and insect outbreaks generally emerged as more important drivers (*i.e.,* larger estimated effects) of relative density shifts than disease (*Fig. 5*), although the effects of disease exceeded those of fire and insects for quaking aspen. In most cases, disturbance was negatively associated with changes in relative density, however estimated effects of disease were positive in Engelmann spruce and lodgepole pine over the study period. Disturbance effects appeared to be most severe (*i.e.,* highest magnitude, exceeding 0.2% annually) among subalpine species, where insect outbreaks were determined to be dominant drivers of relative density shifts in Engelmann spruce and lodgepole pine, and fire was of heightened importance for subalpine fir. Fire also emerged as the most important disturbance type affecting the relative density of Douglas-fir and ponderosa pine, both montane species. The effects of disturbance appeared to be least severe among Utah juniper and common pinyon, relative to other species (<0.1% annually).

Discussion

Complex interactions between changing climate, forest disturbance regimes, and past forest management (*e.g.,* fire suppression) are driving accelerated change in tree demography in temperate forests.[4, 5, 36] However, a great deal of uncertainty remains regarding the net result of such demographic change and its consequences for forest composition and structure across broad spatial domains1. Herein, we develop the FSI, a standardized demographic index that weights observed changes in live tree density and tree size against those expected given well-established allometric size-density relationships in forests. We then apply the FSI to over 24,000 remeasured forest inventory plots in the western U.S. to quantify recent trends in tree population dynamics in the region. Our results indicate a majority of the most abundant tree species in the western U.S. experienced significant population decline over the period 2001–2018 (five of eight species, representing 60.7% of all stems of study species), where population decline is indicated by a net decrease in relative live tree density (*i.e.,* negative FSI). Furthermore, we found strong divergence in the magnitude of change in relative tree density across species (*Fig. 2*), species-size distributions (*Fig. 3*), and species ranges (*Fig. 4*). Such dramatic variation in relative density shifts provides empirical evidence of broad-scale, yet spatially varying, changes in forest composition and structure over the last 2 decades in the western U.S.

Importantly, the current composition and structure of many forests types in the western U.S. differ drastically from their historic range of variability, arising as a legacy of widespread fire suppression (early 20th century to present day) and intensive harvesting (19th to early 20th century).[37] Novel forest conditions (*e.g.,* abundance of high density, closed-canopy forests dominated by fire-intolerant species) have interacted with changing climate to incite rapid increases in disturbance activity in the western U.S. and other regions of the temperate biome.[29, 34] At face-value, it is therefore not inherently surprising to observe a net decrease in the relative density of many top tree species in the western U.S., as disturbances act as natural thinning agents in tree populations. However, the examination of patterns in live tree density shifts across species ranges and size-distributions offers a sobering line of evidence that is inconsistent with broad-scale reversion of forests toward historical conditions. Instead, our results support the following general trends in western U.S. forests over the last 2 decades: (1) severe, spatially pervasive decline of subalpine forests coinciding with density shifts towards smaller tree size-classes; (2) broad-scale expansion of large-diameter montane conifers and decline of small-diameter conspecifics; and (3) net population stability of woodland species.

The rate of population decline we observed in subalpine species is particularly severe (comprising 25.3% of all trees in the western U.S.). Over the duration of the 18 year study period, the relative density of lodgepole pine declined 32.2% (±0.05%) across its range in the western United States, while Engelmann spruce and subalpine fir declined 21.3% (±0.05%) and 13.2% (±0.04%) across their respective ranges, respectively (*Fig. 2*). Decline appears spatially pervasive at broad scales across the study region (ecoregion divisions), however local regions of intense population decline and expansion emerge at finer spatial scales (ecoregion subsections) for all subalpine species (*Fig. 4*). Such patterns may indicate the primary drivers of subalpine tree population dynamics operate at sub-regional scales, likely responding to local-scale variation in climate, topoedaphic conditions, and disturbance history.[37] Previous studies have indicated that subalpine tree species are among the most vulnerable to future changes in climate and forest disturbance regimes.[38, 39, 40] Our results indicate this heightened vulnerability is already manifesting across the western U.S., serving as an early warning of potentially widespread, rapid decline of subalpine forests in other regions of the temperate biome.

Interestingly, we show that severity of population decline increased with tree size for each subalpine species during the study period (*Fig. 3*). That is, population decline was most severe among the largest trees of each species. This result adds to an increasing body of evidence, suggesting that large, old trees are at high risk of decline in forests across the globe.[41] Large, old trees generally occur at low density but are of high ecological significance, influencing the rates and patterns of regeneration and succession, moderating microclimate and water use, and contributing disproportionately to forest biomass and carbon cycling at a global scale.[42] Hence, the rapid decline of large-diameter trees we observe in subalpine tree species of the western U.S. is of grave concern and may foreshadow broad-scale transformation in the structure and ecological function of subalpine forests.

In addition, we found population decline to be pervasive across all but the smallest size-classes of subalpine species (*Fig. 3*). Hence, our results indicate that subalpine forests of the western U.S. have, on average, become younger and thinner over the last 2 decades. Of all species examined herein, the size-density distributions of subalpine fir and Engelmann spruce are arguably the most likely to exist within their historic range of variability as both species tend to occur in cool, moist forests characterized by infrequent stand-replacing fires (*i.e.,* effects of fire suppression are marginal relative to dry forest).[43] The pervasive, size-dependent decline we observe in subalpine fir and Engelmann spruce is thus particularly concerning, indicating the size-distribution of each species may be beginning to depart from historically stable conditions. In contrast, decades of fire suppression and intensive harvesting in the western U.S. have resulted in an overabundance of mature, homogeneous lodgepole pine forest that is highly susceptible to native insect outbreaks.[37] As such, reversion to historical conditions would require an increase in heterogeneity in the size-distribution of lodgepole pine at the landscape-level. Instead, the size-dependent patterns of decline we observe in lodgepole pine is indicative of increased homogeneity in the species' size-distribution, where small-diameter stems have become increasingly common relative to large-diameter stems despite a decline in relative tree density across nearly all tree size-classes (younger, thinner, more structurally homogeneous forests).

Our results further indicate that insect outbreaks were >2.5 times more important than other disturbance types in driving relative density shifts of lodgepole pine and Engelmann spruce over the study period (*Fig. 5*), likely linked to recent outbreaks of mountain pine beetle (*Dendroctonus ponderosae*),[44] and spruce beetle (*Dendroctonus rufipennis*),[45] respectively. As both mountain pine beetle and spruce beetle have shown preference for large hosts (*i.e.,* large-diameter trees), heightened insect-pest activity may explain size-dependent patterns of decline in lodgepole pine and Engelmann spruce. In contrast, we determined wildfire to be more than three times more important than other disturbance types in driving relative density shifts of subalpine fir (*Fig. 5*), and recent increases in the extent and frequency of wildfire[25, 46] could potentially explain size-dependent decline observed in the species. Specifically, increases in fire probability (and disturbance probability more generally) are likely to coincide with reduced mean stand age[21] and subsequent decline in populations of large trees across a landscape. Interestingly, we found the relative density of lodgepole pine and Engelmann spruce increase, on average, in response to disease outbreaks, opposite their response to other disturbance types. We argue this result may arise from inter-specific compensatory responses to host-specific pathogens and/or mortality complexes. That is, one species may benefit from the targeted mortality of a competing species within a stand. It is likely that diseases affecting quaking aspen (*e.g.,* sudden aspen decline[47]) and subalpine fir (*e.g.,* subalpine fir decline[48]) may result in a positive growth response of competing lodgepole pine and Engelmann spruce, thereby increasing their relative density within affected stands.

We observed the highest rates of range-average population expansion in Douglas-fir (17.1%±0.02 over the study period) and ponderosa pine (6.9%±0.03 over the study period; *Fig. 2*), widespread montane conifers that together represent 21.2% of all trees across the western U.S. It is important to note the population expansion observed for Douglas-fir and ponderosa pine may not be desirable in many settings, particularly in dry forests where both species occur frequently as canopy dominants49,50. Across the western U.S., decades of fire exclusion have created overstocked stand conditions that increase the probability of high-severity disturbance (*i.e.,* wildfire, insect outbreak)[51, 52] and may degrade forest resilience.[37] In many cases, management aims to reduce tree density via stand thinning and fuels reduction. Hence high rates of relative density increases observed in Douglas-fir and ponderosa pine in the interior Pacific Northwest and portions of the Rocky Mountain region (*Fig. 4*), may be of substantial concern to forest managers. In contrast, patterns of decreased relative density of ponderosa pine and Douglas-fir observed in the Southern Rocky Mountains may be indicative of tree populations shifting nearer historic relative densities (*Fig. 4*).

Divergence in both sign and magnitude of relative density shifts across size-distributions of ponderosa pine and Douglas-fir is indicative of broad-scale shifts in the structure of montane coniferous forests in the western U.S. Specifically, a peak in population expansion is evident among the 50–75th percentile of tree size-classes in both species, and potentially arises as a legacy of widespread logging during the 19th and early 20th century (*i.e.,* owing to simultaneous maturation of stands across a broad spatial domain).[51] Furthermore, population decline in the smallest size classes of Douglas-fir and ponderosa pine may potentially be linked to heightened wildfire activity during the study period,[46] as fire was more than twice as important than other disturbance types in driving change in relative density in Douglas-fir, and more than five times as important in ponderosa pine (*Fig. 5*). That is, increased wildfire activity may have contributed to desirable change in the structure of montane coniferous forests (*i.e.,* reduced relative density of small trees) over the last

2 decades in the western U.S., underscoring the potential for fire (both managed fire and wildfire) to foster forest resilience and contribute to restoration efforts in fire-adapted forests.[53]

We found that large-diameter populations of Douglas-fir and ponderosa pine outperformed (*i.e.,* exhibited higher positive change in relative density) small-diameter populations of the same species between 2001 and 2018 in the western U.S. (*Fig. 3*), opposite the pattern observed in subalpine species. In fact, we observed significant expansion among the largest-diameter populations of both species across the region. This surprising result contradicts previously described patterns of global decline of large-diameter trees,[41] suggesting that such patterns may vary strongly across species and ecosystem associations in temperate forests (*e.g.,* subalpine vs. montane ecosystems). Yet, pervasive increases in the relative density of medium and large-diameter montane conifers may be highly undesirable in some settings. Specifically, the structure of many dry, fire prone forest types of the western U.S. have shifted towards dense, closed-canopy stand conditions that are highly susceptible to crown fire and outbreaks of native insect and pathogens.[52] As Douglas-fir and ponderosa pine are common canopy dominants in dry forest types, our results may indicate that such systems have diverged further from their historic natural range of variability over the last 2 decades.

Elevated rates of population decline were evident for quaking aspen during the study period, pervasive across the range of the species (*Fig. 4*) and across its size-distribution (*Fig. 3*) in the western U.S. It is not inherently surprising to observe population decline in quaking aspen given recent spikes in mortality associated with sudden aspen decline.[47, 54] However, the rate of population decline observed herein is particularly severe (20.2%±0.04% over the 18 year study period) and serves as a useful baseline to assess the performance of other species. Notably, the rates of range-average decline observed for Engelmann spruce and lodgepole pine exceed that of quaking aspen. Population decline of quaking aspen has received substantial attention in the forest ecology literature,[54, 55, 56] however decline of Engelmann spruce has received far less. The disproportionate focus on quaking aspen decline in the literature (and lack of focus on other declining species), emphasizes the need for large-scale, comprehensive assessments of changes in forest composition and structure in the western U.S. and temperate forests elsewhere.

We found woodland species (*i.e.,* Utah juniper and common pinyon) to exhibit the highest degree of population stability across their ranges in the western U.S., relative to other top species. Pinyon-juniper woodlands of the southwestern U.S., where both Utah juniper and common pinyon occur as dominant species,[50] have experienced dramatic expansions in tree density and equally dramatic tree mortality events over the past century.[57, 58] However, inadequate understanding of historic disturbance regimes and tree population dynamics of pinyon-juniper woodlands make it difficult to conclude if such changes are beyond their natural range of variation.[57] It is important to note that our results do not preclude such striking change at spatial and/or temporal domains not addressed herein. Rather, our results indicate the net responses of Utah juniper and common pinyon populations are relatively stable across broad spatial domains (species' ranges) and a relatively short period of time (18 years).

The development of methods to quantify the joint demographic response of tree populations to novel environmental and anthropogenic stressors is among the most important advances required to improve predictions of future change in forest composition, structure, and function, and hence inform the management of forest ecosystem services.[14, 19, 59] Herein, we present the FSI as one such method. The FSI is a standardized index of temporal change in relative live tree density that can be applied in forests of any community and or structural type. Specifically, the FSI weights observed changes in live tree density (*e.g.,* absolute change in tree abundance) and tree size (*e.g.,* tree basal area) against those expected under allometric size-density laws.[16, 17] Hence, although most common indices of forest change (*e.g.,* mortality rate) are confounded by transient dynamics in tree demography arising from metabolic scaling and density-dependent mortality,[15, 16, 20] the FSI is independent of these transient dynamics by design. As such, the FSI may yield simple, accurate measures of shifts in the structure and composition of forests when other common indices of forest change cannot.

The simplicity, flexibility, and highly informative nature of the FSI make it well suited for application in a wide range of ecological settings, and we expect the index to be applied in similar studies to assess broad-scale changes in forest composition and structure in other forested regions across the globe. The FSI relies on temporally replicated data (*i.e.,* ideally from a large number of samples) to derive inference of forest change, however the form of data required by the index are quite simple. For example, all estimates presented herein were derived from basic measures of tree density (*e.g.,* TPH), tree size (*e.g.,* diameter at breast height; DBH), and binary codes indicating the presence or absence of disturbance at measurement sites. As such, the FSI is uniquely well suited for applications using data collected in large-scale National Forest inventories. To this end, we provide a flexible implementation of the FSI in the publicly available R package, rFIA60, for application of the index using data collected by the U.S. Forest Service FIA program.

Increased disturbance activity has been documented across temperate forests in recent decades,[12, 34, 35] and forests of the western U.S. are no exception.[29, 46] As disturbances modify forest structure and regulate tree population dynamics,[21] our observation of recent broad-scale shifts in relative tree density across the western U.S. is not inherently surprising. However, the rate and pattern of change we observe across species, species-size distributions, and species ranges is alarming and in many cases undesirable. Furthermore, results of our efforts to quantify the importance of major forest disturbances in driving change in tree populations provide a unique opportunity to assess the vulnerability of tree species to sustained shifts in forest disturbance regimes, as expected under global climate change.[2, 12] Importantly, the temporal frame of this study (18 years) is relatively short given the long life-spans of many tree species in the western U.S. (*i.e.,* individuals may live for multiple hundreds of years). As such, it is unclear how the patterns of change we observe herein will translate to long-term trends in forest dynamics in the region, highlighting an important challenge for future research. Nevertheless, our results offer an early warning of recent, widespread change in forest composition and structure across the western U.S., and suggest that sustained anthropogenic and natural stress are likely to result in broad-scale change of temperate forests globally.

Methods

Field observations

Since 1999, the FIA program has operated an extensive, nationally consistent forest inventory designed to monitor changes in forests across all lands in the U.S.[61] We used FIA data from ten states in the continental western U.S. (Washington, Oregon, California, Idaho, Montana, Utah, Nevada, Colorado, Arizona, and New Mexico) to quantify shifts in relative live tree density, excluding Wyoming due to a lack of repeated censuses (*Fig. 1*). This region spans a wide variety of climatic regimes and forest types, ranging from temperate rain forests of the coastal Pacific Northwest to pinyon-juniper woodlands of the interior southwest.[62] Although the spatial extent of the FIA plot network represents a large portion of the current range of all species examined in this study (*Table 1*), substantial portions of some species ranges (*e.g.,* Douglas-fir) extend beyond the study region into Canada and/or Mexico and therefore were not fully addressed here.

The FIA program measures forest attributes on a network of permanent ground plots that are systematically distributed at a rate of ~1 plot per 2,428 hectares across the U.S.[61] For trees, 12.7 cm DBH and larger, attributes (*e.g.,* species, DBH, live/dead) are measured on a cluster of four 168 m^2 subplots.[61] Trees 2.54–12.7 cm DBH are measured on a microplot (13.5 m^2) contained within each subplot, and rare events such as very large trees are measured on an optional macroplot (1012 m^2) surrounding each subplot.[61] In the event a major disturbance (*i.e.,* >1 acre in size, resulting in mortality or damage to >25% of trees) has occurred between measurements on a plot, FIA field crews record the primary disturbance agent (*e.g.,* fire) and estimated year of the event. In the western U.S., 1⁄10 of ground plots are measured each year, with remeasurements first occurring in 2011. Please see Data Availability for more information on forest inventory data accessibility.

Forest stability index

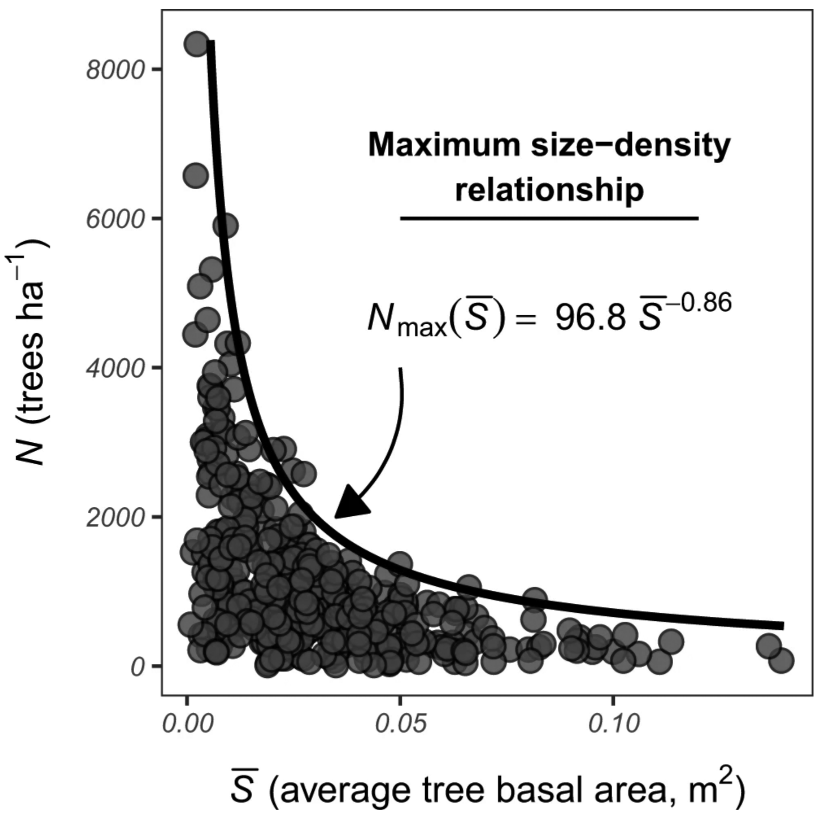
Allometric relationships between size and density of live trees make it difficult to interpret many indices of forest change.[19] Live tree density is expected to decline as trees grow in size, owing to increased individual demand for resources and growing space (*i.e.,* competition).[16, 23] The expected magnitude of change in tree density, given some change in average tree size, varies considerably across forest communities,[63] site conditions,[64] and stand age classes.[23] Thus, we posit it is useful to contextualize observed changes in live tree density relative to those expected given shifts in average tree size within a stand. To this end, we developed the FSI, a measure of change in relative live tree density that can be applied in stands of any forest community and/or structural type.

To compute the FSI, we first develop a model of maximum size-density relationships for tree populations in our study system (*Fig. 6*). This model describes the theoretical maximum live tree density (N_{max}; in terms of tree number per unit area) attainable in stands as a function of their average tree size ($\bar{S}$) and will be used as a reference curve to determine the proportionate live tree density of observed stands (*i.e.,* observed density with respect to theoretical maximum density). We use average tree basal area as an index of tree size (one, however, could also use biomass, volume, or other indices of tree size). For stand-type i, the general form of the maximum tree size-density relationship is given by

$$N_{\max}(\bar{S}_i) = a_i \cdot \bar{S}_i^{\,r_i} \quad (1)$$

, where a is a scaling factor that describes the maximum tree density at $\bar{S}$=1 and r is a negative exponent controlling the decay in maximum tree density with increasing average tree size. Such allometric size-density relationships (*i.e.,* power functions) are widely accepted as quantitative law describing the behavior of even-aged plant populations under self-thinning conditions,[16, 17] and have been used extensively to describe relative stand density in forests.[23, 24] As detailed below, we allow both a and r to vary with stand-type i, as maximum size-density relationships have been shown to vary across forest communities and ecological settings.*63, 65* Allowing a and r to vary by forest community type, for example, allows us to acknowledge that the maximum tree density attainable in a lodgepole pine stand is likely to differ from that of a pinyon-juniper stand with the same average tree size.

Fig. 6: Maximum size-density relationship for an example stand-type



Individual points represent observed stand-level indices of tree density (N) and average tree size ($\bar{S}$). Maximum tree density ($N_{\max}$) is modeled as a power function of average tree size within a stand. Here, we use quantile regression to estimate $N_{\max}$ as the 99th percentile of N conditional on $\bar{S}$. The resulting maximum size-density curve can then be used to compute the relative density of observed stands (RD), where relative density is defined as ratio of observed tree density (N) to maximum theoretical density ($N_{\max}$), given $\bar{S}$. Source data are provided as a Source Data file.

We next define an index of the relative density of a population of trees *j* (*e.g.,* species, *Pinus edulis*) within a stand of type *i* (*e.g.,* forest community type, pinyon/juniper woodland)

$$\text{(2)} \qquad \mathrm{RD}_{ij} = \sum_{h=1} \frac{N_{hij}}{N_{\max}(S_{hi})}$$

, where N is the density represented by tree h (in terms of tree number per unit area), and S is an index of individual-tree size (*e.g.,* basal area, as used here). The denominator of *Equation (2)* represents the maximum tree density attainable in a stand of type i with average tree size equal to the size of tree h. We therefore express the relative density of a population j within stand-type i as a sum of the relative densities represented by individual trees within the stand. RD can be interpreted as the proportionate density, or stocking, of a population of trees within stand, where values range from 0 (population j is not present within a stand) to 1 (population j constitutes 100% of a stand and the stand is at maximum theoretical density given its size distribution). As we do in this study, one may apply any range of estimators to summarize the expected relative density of a population of trees j across a range of different stand-types (*e.g.,* estimate the mean and variance of RD_j across a broad region containing many different stand-types).

It is important to note that Equation (2) is approximately equal to a simpler method using aggregate indices (*i.e.,* $\frac{\sum_{h=1} N_{hij}}{N_{\max}(S_i)}$ when tree size-distributions are normally distributed (even age-structures). However, the use of aggregate indices introduces class aggregation bias that results in overestimation of relative density in stands with non-normal size distributions (*i.e.,* uneven age-structures), consistent with other indices of relative tree density.[66] In contrast, summing tree-level relative densities eliminates such bias and allows RD to accurately compare density conditions across stands in very different structural settings (*e.g.,* even-aged plantation *vs.* irregularly structured old forest). Furthermore, the partitioning of relative density into tree-level densities allows RD to be accurately summarized within tree size-classes.[66] That is, it is possible to explicitly estimate the contribution of tree size-classes to overall stand density using RD.

For a given population j within stand-type i, we define the FSI as the average annual change in relative tree density observed between successive measurements of a stand

$$\text{(3)} \qquad \mathrm{FSI} = \frac{\Delta \mathrm{RD}}{\Delta t}$$

, where Δt is the number of years between successive measurement times t_1 and t_2 and ΔRD is the change in RD over Δt (*i.e.,* $\mathrm{RD}t_2$–$\mathrm{RD}t_1$). The FSI may also be expressed in units of percent change (%FSI), where average annual change in relative tree density is standardized by previous relative density

$$\text{(4)} \qquad \%\mathrm{FSI} = \frac{100 \cdot \mathrm{FSI}}{\mathrm{RD}_{t_1}}$$

. Here, stability is defined by zero net change in relative tree density over time (*i.e.,* FSI equal to zero), but does not imply zero change in absolute tree density or tree size distributions. For example, a population exhibiting a decrease in absolute tree density (*e.g.,* trees per unit area) may be considered stable if such decline is offset by a compensatory increase in average tree size. However, populations exhibiting expansion (*i.e.,* $\mathrm{RD}t_1 < \mathrm{RD}t_2$) or decline (*i.e.,* $\mathrm{RD}t_1 > \mathrm{RD}t_2$) in relative tree density will be characterized by positive and negative FSI values, respectively.

Statistical analysis

We computed the FSI for all remeasured FIA plots in the western U.S. (N = 24,229). We included plots on both public and private lands and considered all live stems (DBH ≥2.54 cm) in our analysis. As forest management can effect regional shifts in tree density, we excluded plots with evidence of recent (*i.e.,* within 5 years of initial measurement) silvicultural treatment (*e.g.,* harvesting, artificial regeneration, site preparation). All plot measurements occurred from 2001 to 2018, with an average remeasurement interval of 9.78 years (±0.005 years). For brevity, we restricted our analysis to consider the eight most abundant tree species in the western U.S. We identified the most abundant tree species using the rFIA R package,[60] defining abundance in terms of estimated total number of trees (DBH ≥2.54 cm) in the year 2018. We excluded species that exhibit non-tree growth habits (*i.e.,* shrub, subshrub) across portions of the study region. All statistical analysis was conducted in Program R (4.0.0).[67]

We developed a Bayesian quantile regression model to estimate maximum size-density relationships for stand-types observed within our study area. Here, we use TPH as an index of absolute tree density, average tree basal area ($\bar{BA}$; equivalent to tree basal area per hectare divided by TPH) as an index of average tree size, and forest community type to describe stand-types. We produced stand-level estimates of TPH and $\bar{BA}$ from the most recent measurements of FIA plots that (1) lack evidence of recent (within remeasurement period or preceding 5 years) disturbance and/or silvicultural treatment and (2) exhibit approximately normal tree diameter distributions (*i.e.,* even-aged). Here we define an approximately normal tree diameter distribution as exhibiting Pearson's moment coefficient of skewness between −1 and 1.

We transform the nonlinear size-density relationship to a linear function by taking the natural logarithm of TPH and $\bar{BA}$, and use a linear quantile mixed-effects model to estimate the 99th percentile of TPH conditional on $\bar{BA}$ (*i.e.,* in log-log space) for all observed forest community types. We allowed both the model intercept and coefficient to vary across observed forest community types (*i.e.,* random slope/intercept model), thereby acknowledging variation in the scaling factor (a) and exponent (r) of the maximum tree size-density relationship across stand-types. We place informative normal priors on the model intercept (μ=7, σ=1) and coefficient (μ=0.8025, σ=0.1) following the results of decades of previous research in maximum tree size-density relationships.[16, 23, 63, 65]

The FIA program uses post-stratification to improve precision and reduce non-response bias in estimates of forest variables,[68] and we used these standard post-stratified estimators to estimate the mean and variance of the FSI for each species across their respective ranges within the study area (see Code Availability for all relevant code). Further, the FIA program uses an annual panel system to estimate current inventories and change, where inventory cycles consist of multiple panels, and individual panels are comprised of mutually exclusive subsets of ground plots measured in the same year within a region. Precision of point and change estimates can often be improved by combining annual panels within an inventory cycle (*i.e.,* by augmenting current data with data collected previously). We used the simple moving average estimator implemented in the rFIA R package[60] to compute estimates from a series of eight annual panels (*i.e.,* sets of plots remeasured in the same year) ranging from 2011 to 2018. The simple moving average estimator combines information from annual panels with equal weight (*i.e.,* irrespective of time since remeasurement), thereby allowing us to characterize long-term patterns in relative density shifts. We determine populations to be stable if the 95% confidence intervals for range-averaged FSI included zero. Alternatively, if confidence intervals of range-averaged FSI do not include zero, we determine the population to be expanding when the estimate is positive and declining when the estimate is negative.

To identify changes in species-size distributions, we used the simple moving average estimator to estimate the mean and variance of the FSI by species and size class across the range of each species within our study area. We assign individual trees to size-classes representing 10% quantiles of observed diameter distributions (*i.e.,* diameter at 1.37 m above ground) of each species growing on one of seven site productivity classes (*i.e.,* inherent capacity of a site to grow crops of industrial wood). That is, we allow size class definitions to vary among species and along a gradient of site productivity, thereby acknowledging intra-specific variation in diameter distributions arising from differences in growing conditions. The use of quantiles effectively standardizes absolute size distributions, simplifying both intra-specific and inter-specific comparison of trends in relative density shifts along species-size distributions.

We assessed geographic variation in species relative density shifts at two scales: ecoregion divisions and subsections.[69] Ecoregion divisions (shown for our study area in *Fig. 1*) are large geographic units that represent broad-scale patterns in precipitation and temperature across continents. Ecoregion subsections are subclasses of ecoregion divisions, differentiated by variation in climate, vegetation, terrain, and soils at much finer spatial scales than those represented by divisions. We again used the simple moving average estimator to estimate the mean and variance of the FSI by species within each areal unit (*i.e.,* drawing from FIA plots within each areal unit to estimate mean and variance of the FSI). As a direct measure of changes in relative tree density, spatial variation in the FSI is indicative of spatial shifts in species distributions during the remeasurement interval (*i.e.,* range expansion/contraction and/or within-range relative density shifts). That is, the distribution of populations shift toward regions increasing in relative density and away from regions decreasing in relative density during the temporal frame of sampling. We map estimates of the FSI for each areal unit to assess spatial patterns of changes in relative density and identify regions where widespread geographic shifts in species distributions may be underway.

We sought to quantify the average effect of forest disturbance processes on changes in the relative density of top tree species in the western U.S. over the interval 2001–2018. To this end, we developed a hierarchical Bayesian model to determine the average severity and annual probability of disturbances (*i.e.,* wildfire, insect outbreak, and disease) on sites where each species occurs. Average severity was modeled as

$$y_{jk} \sim \text{normal}(\alpha_j + \sum_l \beta_{jl} \cdot x_{lk},\ \varsigma_j^2) \quad (5)$$

, where y_{jk} is the FSI of species j on plot k, α_j is a species-specific intercept, β_{jl} is a species-specific coefficient corresponding to the binary variable χ_{lk} that takes the value of 1 if disturbance l occurred within plot k measurement interval and 0 otherwise. The intercept and regression coefficients each received an uninformative normal prior distribution. The species-specific residual standard deviation ς_j received a uninformative uniform prior distribution.[70]

On average, disturbance will occur at the midpoint of plot remeasurement periods, assuming temporal stationarity in disturbance probability over the study period. As plots in this study are remeasured on 10 year intervals, we assume that tree populations have, on average, 5 years to respond to any disturbance event. Hence, our definition of disturbance severity, β_{jl}'s, cannot be interpreted as the immediate change in relative tree density resulting from disturbance. Rather, disturbance severity (as defined here) includes the immediate effects of disturbance, as well as 5 years of change in relative tree density prior to and following disturbance (where disturbance is assumed to be functionally instantaneous).

Annual probability of disturbance l on plot k was modeled as

$$x_{lk} \sim \text{binomial}(\Delta t_k, \psi_{jl}) \quad (6)$$

, where Δ_{tk} is the number of years between successive measurements of plot k, viewed here as the number of binomial "trials," and ψ_{jl} is the species-specific probability for disturbance which was assigned a beta(1,1) prior distribution. Hence, annual probability of disturbance is assumed to vary by species j and by disturbance type l.

We estimate the mean effect of forest disturbance processes on changes in species-specific relative tree density by multiplying the posterior distributions of β_{jl} and ψ_{jl}. That is, we multiply species-specific disturbance severity by disturbance probability to yield an estimate of the mean change in relative density caused by disturbance over the study period. We then standardize these values across species by dividing by the average relative density of each species at the beginning of the study period. Thus, standardized values can be interpreted as the annual proportionate change in the relative tree density of each species resulting from disturbance over the period 2001–2018.

Reporting summary

Further information on research design is available in the *Nature Research Reporting Summary* (*https://www.nature.com/articles/s41467-020-20678-z#MOESM2*) linked to this article.

Data availability

All forest inventory data used herein are publicly available in comma-delimited text format via the USDA Forest Service FIA data repository (*https://apps.fs.usda.gov/fia/datamart/CSV/datamart_csv.html*). Source data are provided with this paper.

Code availability

We have implemented computational routines for the FSI in the publicly available R package, rFIA.[60] In addition, all custom code used herein is publicly available in the following permanent GitHub repository: *https://github.com/hunter-stanke/Code-repository---NCOMMS-20-20430*.

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ARTICLE 5

Science Advances

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SCIENCE ADVANCES

Research Article

Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, andvitamin content of rice grains with potential health consequences for the poorest rice-dependent countries

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Abstract

Declines of protein and minerals essential for humans, including iron and zinc, have been reported for crops in response to rising atmospheric carbon dioxide concentration, [CO_2]. For the current century, estimates of the potential human health impact of these declines range from 138 million to 1.4 billion, depending on the nutrient. However, changes in plant-based vitamin content in response to [CO_2] have not been elucidated. Inclusion of vitamin information would substantially improve estimates of health risks. Among crop species, rice is the primary food source for more than two billion people. We used multiyear, multilocation *in situ* FACE (free-air CO_2 enrichment) experiments for 18 genetically diverse rice lines, including Japonica, Indica, and hybrids currently grown throughout Asia. We report for the first time the integrated nutritional impact of those changes (protein, micronutrients, and vitamins) for the ten countries that consume the most rice as part of their daily caloric supply. Whereas our results confirm the declines in protein, iron, and zinc, we also find consistent declines in vitamins B1, B2, B5, and B9 and, conversely, an increase in vitamin E. A strong correlation between the impacts of elevated [CO_2] on vitamin content based on the molecular fraction of nitrogen within the vitamin was observed. Finally, potential health risks associated with anticipated CO_2-induced deficits of protein, minerals, and vitamins in rice were correlated to the lowest overall gross domestic product per capita for the highest rice-consuming countries, suggesting potential consequences for a global population of approximately 600 million.

Introduction

One of the consequential impacts of rising carbon dioxide concentration ([CO_2]) and climate change is expected to be on food security.[1] This expected impact is due, in part, to the vulnerability of the global population to food supply: Depending on definition, up to one billion people are deemed food insecure.[2] For example, harvests of staple cereal crops, such as rice and maize, could decline by 20 to 40% as a function of increased surface temperatures in tropical and subtropical regions by 2100 without considering the impacts of extreme weather and climate events.[3] Overall, there has been a directed effort to understand the consequences of [CO_2] and climate on agricultural production.[4, 5]

However, the connection between food security and well-being extends beyond production *per se;* for example, dietary quality has a substantial influence on human health.[6] Globally, insufficient micronutrients, protein, vitamins, *etc.* can contribute to nutritional deficiencies among two billion people in developing and developed countries.[7] These deficiencies can directly (cognitive development, metabolism, and

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immune system) and indirectly (obesity, type 2 diabetes mellitus) affect human health on a panoptic scale.[8]

The elemental chemical composition of a plant (that is, ionome) reflects a balance between carbon, obtained through atmospheric [CO_2], and the remaining nutrients, obtained through the soil. As evidenced by over a hundred individual studies and several meta-analyses, projected increases in atmospheric [CO_2] can result in an ionomic imbalance for most plant species whereby carbon increases disproportionally to soil-based nutrients.[9–11] This imbalance, in turn, may have significant consequences for human nutrition [12, 13] including protein and micronutrients. However, at present, no information is available regarding a key constituent of nutrition, vitamin content; as a result, no integrated assessment (protein, micronutrients, and vitamins) is available.

The consequences of CO_2-induced qualitative changes may be exacerbated where food diversity is limited, that is, where populations rely heavily on a single plant-based food source. In this regard, rice supplies approximately 25% of all global calories, with the percentage of rice consumed varying by socioeconomic status, particularly in Asia.[14] Rice is considered among the most important caloric and nutritional sources particularly for low- and lower-middle-income Asian countries.[15]

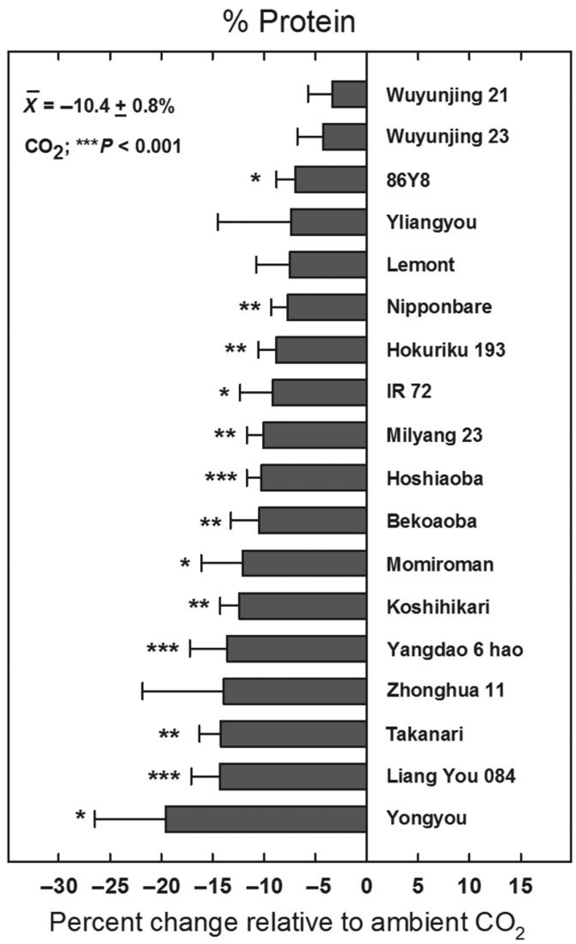
Therefore, for those populations that are highly rice-dependent, any CO_2-induced change in the integrated nutritional value of rice grains could disproportionally affect health. We use a multiyear, multilocation, multivarietal evaluation of widely grown, genetically diverse rice lines at ambient and anticipated end-of-century [CO_2] to (i) quantify varietal response to changes in dietary components, including protein, iron, calcium, zinc, vitamin E, and the vitamin B complex, and (ii) socioeconomically calculate any CO_2-induced deficits in these nutritional parameters for the ten most rice-centric countries globally, as a function of gross domestic product (GDP) per capita.

Although end-of-century [CO_2] projections vary, it is very likely that actual atmospheric [CO_2] will reach 570 μmol mol^{-1} before the end of this century.[16] Global [CO_2] is expected to reach these levels even as additional steps are taken to decrease emissions, due, in part, to the projected energy usage, the longevity of the CO_2 molecule in the atmosphere, and the temporal delay in reducing [CO_2] emissions before mid-century.[17] Overall, the experimental concentrations used here for the elevated [CO_2] treatment (568 to 590 μmol mol^{-1}) reflect the reality that those born today will be eating rice grown at [CO_2] of 550 μmol mol^{-1} (or higher) within their lifetimes.

Results

When grown under field conditions at these anticipated [CO_2] a significant reduction (an average of −10.3%) in protein relative to current [CO_2] was observed for all rice cultivars (*Fig. 1*). Similarly, significant reductions in iron (Fe) and zinc (Zn) were also observed (−8.0 and −5.1%, respectively) among all rice cultivars tested (*Fig. 2*). On the basis of [CO_2] assessment per se, there were no significant site difference effects on rice grain quality between Japan and China (P = 0.26, 0.17, and 0.10 for protein, iron, and zinc, respectively).

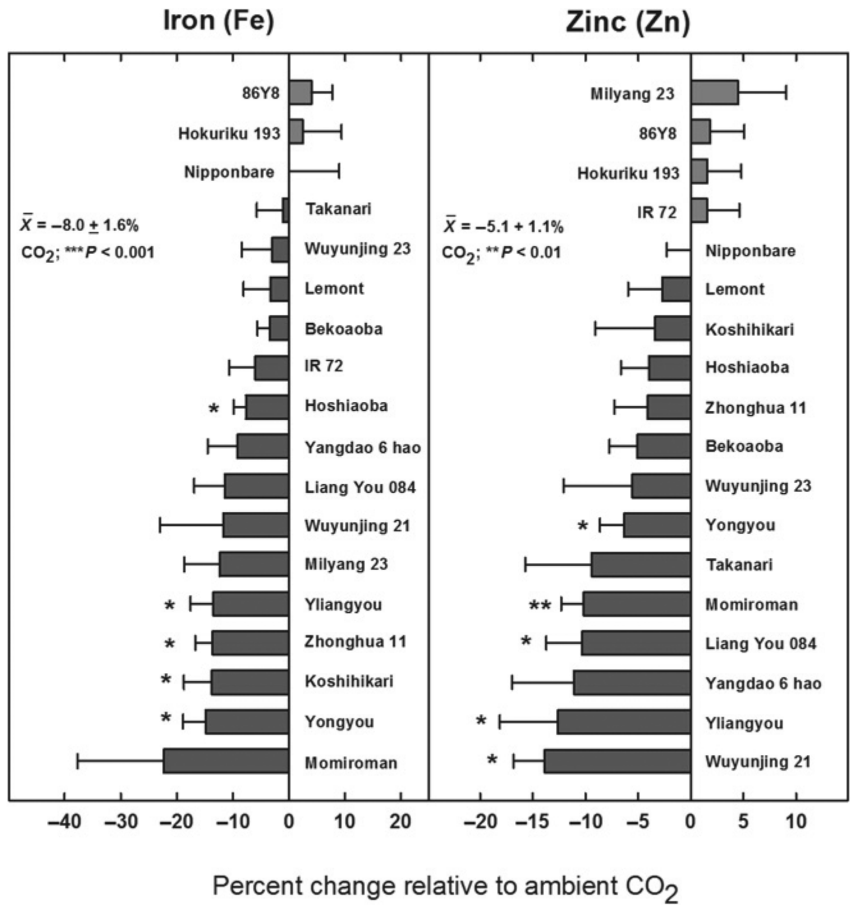
Fig. 1



Average reduction in grain protein at elevated relative to ambient [CO_2] for 18 cultivated rice lines of contrasting genetic backgrounds grown in China and Japan using FACE technology.

A country by [CO_2] effect on protein reduction was not significant (P = 0.26). Bars are ±SE. *P<0.05 and **P<0.01 (see Methods for additional details).

Fig. 2



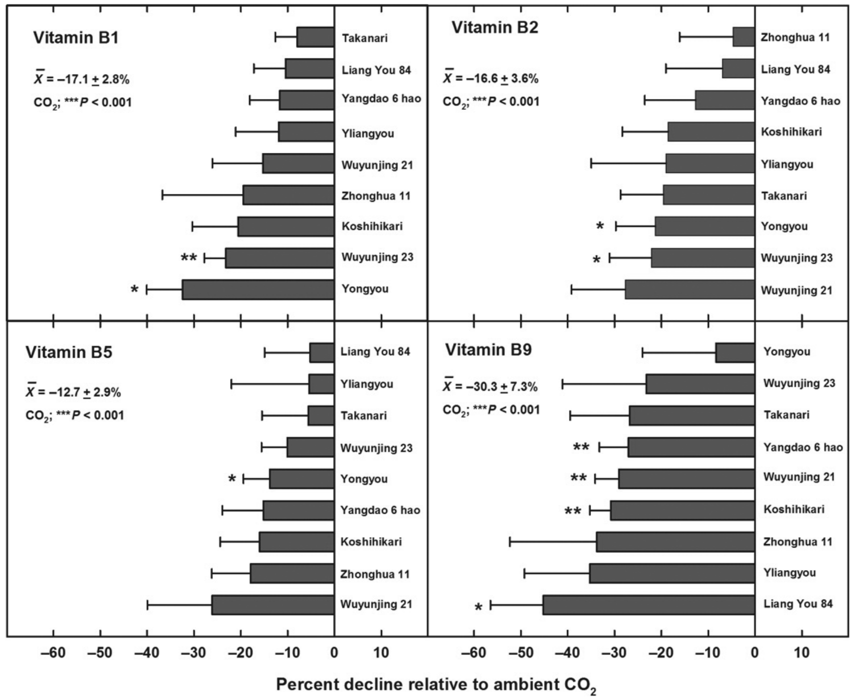
Average reduction in grain micronutrients, iron (Fe), and zinc (Zn) concentration at elevated relative to ambient [CO_2] for 18 cultivated rice lines of contrasting genetic backgrounds grown in China and Japan using FACE technology.

A country by [CO_2] effect was not significant for either micronutrient [$P = 0.17$ and 0.10 for iron (Fe) and zinc (Zn), respectively] so data from both locations are shown. Bars are ±SE. *$P<0.05$ and **$P<0.01$ for a given cultivar. CO_2; **$P<0.01$ is based on all cultivars (see Methods for additional details).

The rice lines chosen reflect a wide genotypic and phenological range, suggesting that the declines in nutrient parameters observed here are representative of rice in toto. However, a larger sample size would be of benefit both to confirm these findings and, if possible, to determine whether any lines may be preferred for improving protein or micronutrient availability as [CO_2] increases.

Regarding the B vitamin complex, significant reductions in vitamins B1 (thiamine), B2 (riboflavin), B5 (pantothenic acid), and B9 (folate) were observed in response to projected CO_2 levels with average declines among cultivars of −17.1, −16.6, −12.7, and −30.3%, respectively (*Fig. 3*). As observed for protein and minerals, no increase in these parameters was detected for any of the 18 rice lines evaluated; in addition, no significant [CO_2] by cultivar interactions were noted (*Fig. 3*). In contrast, increases were observed on average for vitamin E (α-tocopherol) (*fig. S1*).

Fig. 3

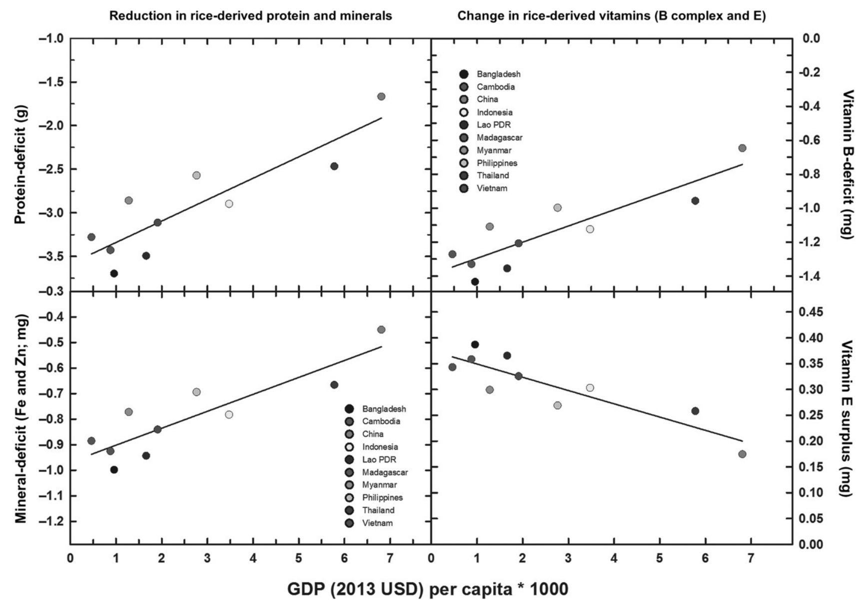


CO_2-induced reductions in vitamins B1 (thiamine), B2 (riboflavin), B5 (pantothenic acid), and B9 (folate) by cultivar.

No significant effect was observed for vitamin B6 (pyridoxine), and results are not shown. Analysis was conducted only for the China FACE location. Bars are ±SE. *P<0.05 and **P<0.01 for a given cultivar. CO_2; **P<0.01 is based on all cultivars (see Methods for additional details).

Although these data indicate that [CO_2] affects nutrient composition, the impact of these qualitative changes on health will vary as a function of rice consumed relative to the total caloric intake. Previous calculations of the impact of rising CO_2 on human nutrition relied on Food and Agriculture Organization (FAO) food balance sheets combined with Monte Carlo simulations run on the range of projected declines of zinc, protein, and iron.[12, 13] Here, we also rely on FAO food balance sheets but use an economic approach whereby average qualitative changes observed with [CO_2] as a function of rice consumption for the top ten rice-consuming countries as of 2013 are compared with GDP per capita of that country. In this context, any protein and mineral deficits (Fe + Zn), associated with higher CO_2 values, are observed to be greater for those countries with the lowest overall GDP per capita (for example, Bangladesh and Cambodia) (*Fig. 4*). The reductions in vitamin B (B1, B2, B5, and B9) availability were greatest for these same countries (*Fig. 4*). Similarly, the increase in vitamin E with higher CO_2 levels and the subsequent consumption is proportionally greater for those poorer countries that ingest greater quantities of rice (*Fig. 4*).

Fig. 4



Projected [CO_2]-induced deficits in protein and minerals (Fe and Zn) and cumulative changes in vitamin B and cumulative changes in vitamin E derived from rice as a function of GDP per capita.

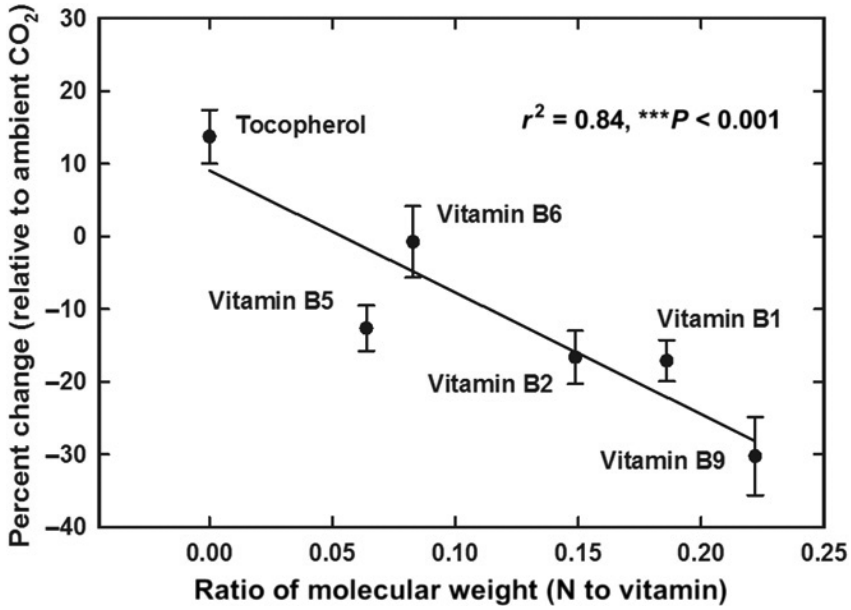
Data are based on 2011/2013 FAO food balance sheets for rice consumption and 2011/2013 World Bank estimates of GDP per capita per country.

There is growing evidence demonstrating a clear link between crop growth at projected increases in [CO_2] and changes in nutritional quality including, but not limited to, protein, secondary compounds, and minerals (for example, Zn).[9–11, 18, 19] The basis for the CO_2-induced changes in crop quality is still being elucidated, in part, because increasing [CO_2] influences several biophysical processes.[20] However, for near-term projections of [CO_2], the qualitative decline can be reasonably (given the accuracy of the current data) approximated as linear (for example, protein).[21]

The nutritional data reported here for elevated [CO_2] confirm that deficits in protein, zinc, and iron may occur even among genetically diverse rice lines grown in different countries.[11, 22] In addition, the current data indicate, for the first time, a pattern in the changes in vitamin content, that is, the extent of observed variation between vitamin B (B1, B2, B5, B6, and B9) and vitamin E (α-tocopherol).

Variation among [CO_2]-induced changes in secondary compounds, such as vitamins, may relate to the well-established decline of nitrogen in plants exposed to elevated [CO_2] [for example, see the study of Taub, *et al.*[9]]. The effect of increasing levels of [CO_2] on vitamin levels could therefore be inversely correlated with the molecular fraction of nitrogen within the vitamin. This was observed for rice in the current study ($r^2 = 0.82$) (*Fig. 5*), consistent with the carbon-nutrient balance hypothesis;[23] at least in the context of rapid increases in atmospheric [CO_2] and carbon availability [but see the study of Hamilton, *et al.*[24]], that is, the levels of nitrogen containing vitamins decreased (B vitamin group), whereas the level of carbon-based compounds (vitamin E) increased. Additional information regarding the effects of [CO_2] on nutritional quality is obviously desired; however, this relationship could provide initial guidance as to the aspects of rice grain chemistry affected by increasing atmospheric [CO_2].

Fig. 5



Average change in vitamin concentration (as percentage) in response to anticipated, relative to current, [CO_2] ±SE as a function of the ratio of the molecular weight of nitrogen (N) to the molecular weight of the vitamin.

There was a highly significant correlation between the amount of N present in the vitamin and the overall decrease or increase in response to higher [CO_2].

Discussion

As of 2013, approximately 600 million individuals, primarily in Southeast Asia [the countries of Bangladesh, Cambodia, Indonesia, Lao People's Democratic Republic (PDR), Madagascar, Myanmar, and Vietnam], consume ≥50% of their per capita dietary energy and/or protein directly from rice.[25, 26] The data shown here provide the first integrated assessment of [CO_2]-induced changes in nutritional quality (protein, minerals, and vitamins) for many of the most widely grown rice lines; as such, they indicate that, for key dietary parameters, the [CO_2] likely to occur this century will add to nutritional deficits for a large segment of the global population.

In assessing the outcome of the [CO_2]-induced dietary changes for rice in the current study, it is evident (*Fig. 4*) that the bulk of these changes, and the greatest degree of risk, will occur among the highest rice-consuming countries with the lowest GDP. However, as income increases, consumers prefer more diverse caloric sources, with a greater emphasis on protein from fish, dairy, and meat as per western foods.[27] Therefore, future economic development could potentially limit future CO_2-induced changes in rice nutrition. For example, in Japan, rice accounted for 62% of total food energy consumption in 1959, but that share fell to 40% by 1976 and, in recent years, is <20%;[28] in South Korea, per capita rice consumption almost halved since 1975.[29] However, strong, sustained economic growth cannot be assumed for all rice-consuming countries. For example, in Bangladesh, 75% of the total caloric supply per capita came from rice in 1990; 23 years later, in 2013, it was 70% (*http://faostat.fao.org/beta/en/#data/FBS*); in Madagascar, the percentage of rice consumption has increased since 1990.[25] In addition, other countries, such as Guinea, Senegal, and Côte d'Ivoire, have become more reliant on rice as a percentage of their caloric supply (20 to 40% as of 2011).[30] Overall, although the top rice-consuming countries are likely to change in the coming decades, the reliance on rice globally as a dietary staple will continue.

Specific health outcomes of consuming rice with reduced nutritional quality are also difficult to forecast. Staple foods, such as rice, are widely available and affordable for most of the world's population, particularly the poor. It is understood that undernutrition can put people at risk in low-income countries for a wide range of other adverse health outcomes, particularly stunting, diarrheal disease, and malaria.[31] For example, Kennedy, *et al.,*[15] found that the percentages of children under 5 years of age who suffer from stunting, wasting, or are underweight are generally high in countries with very high per capita rice consumption. Overall, the current data suggest that, for these countries, any [CO_2]-induced change in nutritional quality would likely exacerbate the overall burden of disease and could affect early childhood development.

It is difficult, without a great deal of additional socioeconomic data at the country level (which is often unavailable), to provide exact estimates of nutritional deficits (protein, minerals, and vitamins) and associated health consequences likely to incur for rice-dependent populations. Yet, CO_2-induced reductions in these qualities and associated risks of undernutrition or malnutrition are likely to transcend the entire food chain, from harvest to consumption, especially for the poorest people within a country or region.

Is there a way then to reduce—or negate—this risk? Cultivar selection, either through traditional breeding or genetic modification, to provide nutritionally superior rice with additional CO_2 is an obvious strategy. The current data for a genetically diverse set of rice lines suggest that, at least for some characteristics (for example, protein and vitamin B2), many additional lines would need to be screened; furthermore, at present, it can take many years, even decades, to identify, cultivate, and distribute new cereal lines that are adapted to a changing climate.[32] In addition, other aspects of climate change, especially temperature, would need to be considered. For example, previous work indicated that rising temperature per se can also reduce protein concentration in rice.[33] Although the extent of future surface temperatures would vary depending on location, temperature and [CO_2] should also be evaluated concurrently regarding rice nutritional impacts in future assessments.

In addition, management could include application of mineral fertilizers or postharvest biofortification. On the consumer side, education about the role of rising [CO_2] on nutrition, including opportunities to implement favorable nutrition practices and food fortification, may also provide opportunities to maintain nutritional integrity. Finally, there is an obvious need for the research community, including agronomists, physiologists, nutritionists, and health care providers, to accurately quantify the exact nature of the [CO_2]-induced changes in human nutritional status and their associated health outcomes.

Whereas much remains to be done, the current study provides the first evidence that anticipated [CO_2] will result in significant reductions in integrated rice quality, including protein, minerals, and vitamin B, for a genetically diverse and widely grown set of rice lines. Occurrence of these nutritional deficits will most likely affect the poorest countries that are the most rice-dependent. Overall, these results indicate that the role of rising [CO_2] on reducing rice quality may represent a fundamental, but underappreciated, human health effect associated with anthropogenic climate change.

Methods

Free-air CO_2 enrichment sites

The multiyear study was conducted at free-air CO_2 enrichment (FACE) facilities in two countries: (i) China [at Zhongcun Village (119°42′0″E, 32°35′5″N), Yangzhou City, Jiangsu Province; as part of the Yangtze River Delta region, a typical rice growing region[34]] and (ii) Japan [at Tsukuba (35°58°N, 139°60′E), in Ibaraki Prefecture within farmer's fields[35]]. Eighteen rice lines representing varietal groups of cultivated rice (Indica and Japonica) and new hybrid lines were chosen. These lines were, for the most part, representative and widely grown in the geographical regions where the FACE facilities were located (*Table 1*).

Table 1. Characteristics of rice lines used.

Cultivar	Origin	Subgroup	Comments
86Y8	China	Hybrid	Bred for disease-resistance; high ripening rate
Bekoaoba	Japan	Japonica	Bred for lodging resistance, used in silage
Hokuriku 193	Japan	Indica	High-yielding, blast-resistant
Hoshiaoba	Japan	Japonica	Cultivar used for silage and bioenergy
IR72	Philippines	Indica	Semi-dwarf, often used as check cultivar
Koshihikari	Japan	Japonica	Widely grown in Japan
Lemont	United States	Japonica	Semi-dwarf grown in Mississippi Delta
Milyang 23	Korea	Indica	High-yielding, cadmium accumulator
Momiroman	Japan	Japonica	Medium grain, high-yielding variety
Nipponbare	Japan	Japonica	Genome-sequenced

Table 1. Characteristics of rice lines used.—Continued

Cultivar	Origin	Subgroup	Comments
Liang You 084	China	Hybrid	Grown extensively in southeast China
Takanari	Japan	Indica	Widely grown in Japan
Wuyunjing 21	China	Japonica	Grown extensively in East China
Wuyunjing 23	China	Japonica	Grown extensively in East China
Yangdao 6 hao	China	Indica	Grown extensively in East and Central China
Yliangyou	China	Hybrid	Recently introduced (2008) hybrid line
Yongyou 2640	China	Hybrid	Widely planted in lower Yangtze River
Zhonghua 11	China	Japonica	Disease-resistant line used in breeding

CO_4 and environmental parameters

A complete description of CO_2 control for the China and Japan locations can be found in the studies of Zhu, *et al.,*[34] and Hasegawa, *et al.,*[35] respectively. The operation and control systems for the China FACE facilities were the same as those at the Japan FACE site. Briefly, each site consisted of identical octagonal rings imposed on farmer's fields with three rings (China) or four rings (Japan) receiving pure CO_2 supplied from polyethylene tubing installed horizontally on the periphery of the FACE ring at 30 cm above the rice canopy (elevated CO_2 treatment), with additional rings (three and four, respectively) that did not receive supplemental CO_2 (ambient CO_2 treatment). The concentration of CO_2 was monitored at the center of each ring, and using the ambient [CO_2] as the control, a proportional-integral-derivative algorithm was used (relative to the ambient control) to regulate the injection and direction of CO_2 in the elevated ring. Rings were spaced at 90-m intervals to prevent CO_2 contamination between plots. Ring diameters varied between locations (14 and 17 m for the Tsukuba and Zongcun sites, respectively); [CO_2] was controlled to within 80% of the set point for >90% of the time during the growing season for each location and year. For the China location, the average daytime [CO_2] levels at canopy height for the elevated treatment were 571, 588, and 590 µmol mol^{-1} for 2012, 2013, and 2014, respectively; for the Japan location, the season-long daytime average CO_2 was 584 µmol mol^{-1} (2010, Tsukuba); ambient [CO_2] varied from 374 to 386 regardless of location.

Rice fields in all locations were flood-irrigated and grown as "paddy" rice, as consistent with local practices. For the China location, the average growing season temperature was 24.4°, 24.8°, and 22.1 °C for 2012, 2013, and 2014, respectively; for Japan, the growing season temperature was 24.6 °C for the Tsukuba location in 2010. The soil type in the China location was classified as Shajiang-Aquic Cambiosol with a sandy loam texture. The soil type at Tsukuba, Japan is Fluvisols, typical of alluvial areas. Fertilizer was applied at rates to maximize commercial yield, consistent with location; any additional pesticides were consistent with cultural agronomic practices for the given region. Sowing and transplanting methods are described elsewhere.[34, 35] At seed maturity, 1 to 2 m^2 per CO_2 ring, per cultivar, per year, and per location were harvested for yield assessment.

Nutrient analysis

For the China FACE, a subsample (500 g) of grain was frozen before analysis. Dehusked (unpolished) brown (raw and uncooked) rice (100 g) was homogenized to a fine powder using a Mix/Mill Grinder, sifted through a 100-mesh sieve, and then dried to a constant weight at 70 °C. A 0·5-g sample was added to a graphite tube for digestion, 0.2 ml of pure deionized (DI) water was added, followed by 8 ml of HNO_3, and digested for 24 hours. An additional 2 ml of $HCLO_4$ was then added. Digestion temperature was regulated until clear color was obtained. Finally, DI water was added to increase any remaining solution to 50 ml. Inductively coupled plasma (ICP) atomic emission spectrometry (AES) (Optima 8000, PerkinElmer) was used to determine Ca content, whereas ICP-mass spectrometry (MS) (7700, Agilent) was used to determine Fe and Zn content. Elemental analyses for the samples from the Tsukuba FACE location are described by Dietterich, *et al.*[36] Briefly, the air-dried husked (but unpolished) brown rice grains were air-dried and ground as described previously. Nitrogen was analyzed with a Leco TruSpec CN analyzer. Fe, Zn, and Ca were determined with an ICP optical emission spectrophotometer. Note that brown rice was analyzed because previous publications [for example, the study of Myers, *et al.* [11]] had used brown rice as the standard for CO_2 effects on nutrition.

Elemental concentrations of carbon and nitrogen were determined for an additional 30 mg of harvest sample using an elemental analyzer (Vario, MAX CN, Element). Nitrogen content and carbon content were determined as a percentage of the dry weight of the sample. A factor of 5·61 was used for converting nitrogen to protein concentration in rice, consistent with previous studies.[37]

Vitamin extraction and analysis

Although rice does not supply the complete vitamin B complex, it is known to provide B1, B2, B5, B6, and B9, as well as vitamin E. These were extracted from dehusked, unpolished brown rice seed for the nine rice cultivars at the China FACE location. Brown rice (100 g) was homogenized to a fine powder using the previously described method; then, frozen sample was lyophilized using a VFD–1000 freeze dryer (Bilon). Lyophilization occurred in two cycles; drying at −20 °C for 48 hours, followed by secondary drying at 0 °C for 3 hours.

For thiamine, riboflavin, pantothenic acid, and pyridoxine determination, 0·05 g of ascorbic acid was added to homogenized samples (0·5 g) as an antioxidant and then followed by 10 ml of extracting solution (methanol/water/phosphoric acid = 100:400:0·5, v/v/v). After the suspension was vortexed, it was autoclaved at 100 °C for 20 min and then incubated under ultrasonic conditions for 30 min. The solution was allowed to cool to room temperature and then centrifuged at 11,945g for 15 min. Blank controls were generated following the same process without rice samples. The final supernatant was filtered through a 0·22-µm filter before high-performance liquid chromatography (HPLC)-MS analysis.

Folate determination was per Blancquaert, *et al.:* [38] 4 ml of extraction buffer was added to 0.5 g of homogenized samples, and the capped tube was placed at 100 °C for 10 min. A tri-enzyme treatment with 80 µl of α-amylase (20 min), 350 µl of protease (1 hour at 37 °C), and 250 µl of conjugase (2 hours at 37 °C) was used to degrade the starch matrix, to release protein-bound folates, and to deconjugate polyglutamylated folates. To stop protease and conjugase activity, additional heat treatments were carried out, followed by cooling on ice. The resulting solution was ultrafiltrated at 11,958*g* for 15 min. The final solution was filtered through a 0·22-µm filter before analysis.

Vitamin E (α-tocopherol) was extracted using an improved method, as described by Zhang, *et al.*[39] One gram of the homogenized fine powder was saponified under nitrogen in a screw-capped tube with 1 ml of potassium hydroxide (600 g/liter), 5 ml of ethanol, 1 ml of sodium chloride (10 g/liter), and 2.5 ml of ethanolic pyrogallol (60 g/liter) added as antioxidants. Tubes were placed in a 70 °C water bath and mixed at 5-min intervals during saponification. Following alkaline digestion at 70 °C for 30 min, the tubes were cooled in an ice bath, and 5 ml of sodium chloride (10 g/liter) was added. The suspension was extracted twice with 8 ml of *n*-hexane/ethyl acetate (4:1, v/v). The organic layer was collected and was dried using pure nitrogen (EVA 30A, Polytech Co.) and then dissolved in n-hexane/methanol (20:80, v/v; 1· ml). A similar procedure was used to generate a blank control. The final solution was filtered through a 0·22-µm filter before analysis.

HPLC-tandem MS (Thermo Finnigan TSQ) was used to quantify vitamin content. Column oven temperature was maintained at 25 °C, and the autosampler was maintained at 4 °C. Two separate Phenomenex Kinetex C18 columns (4.6 mm × 100 mm × 2.6 µm and 4.6 mm × 30 mm × 5 µm) were used for vitamins B and E, respectively. Injection volume was 20 µl. For gradient elution, the mobile phase consisted of eluent A (methyl alcohol) and eluent B (0·1% formic acid in water), with each eluent pumped at a flow rate of 0.6 ml min^{-1}. The mobile phase was linearly adjusted to separate the different vitamins (table S1).

For the MS setting, source conditions were optimized for vitamin B as follows: ion source, electrospray ionization; spay voltage, 3500 V; vaporizer temperature, 400 °C; capillary temperature, 350 °C; sheath gas pressure, 50; auxillary gas pressure, 10; scan type, selected reaction monitoring (SRM); collision pressure, 1.0-mtorr Ar. For vitamin E, the source conditions were optimized as follows: ion source, atmospheric pressure chemical ionization; discharge current, 10 µA; vaporizer temperature, 300 °C; capillary temperature, 350 °C; sheath and auxiliary gas pressure, 50 and 10, respectively; scan type, SRM; collision pressure, 1.0-mtorr Ar (*table S2*). Known standards for vitamin B1 (thiamine hydrochloride), vitamin B2 (riboflavin), vitamin B5 (calcium-D-pantothenate), vitamin B6 (pyridoxine hydrochloride), vitamin B9 (folic acid), and vitamin E (α-tocopherol) were purchased from Sigma-Aldrich Co. All vitamin analyses were performed in duplicate. Before sample analysis, the instrument was calibrated using seven standards (six standards and the blank control).

Estimate of nutritional deficits

The ten most rice-dependent countries were determined on the basis of the largest consumption of rice as a fraction of total available calories [Bangladesh, Cambodia, China, Indonesia, Lao PDR, Madagascar, Myanmar, Philippines, Thailand, and Vietnam (23)]. FAO food balance sheets (*http://faostat.fao.org/beta/en/#data/FBS;* food supply quantity, kilogram per capita per year and food supply, and kilocalorie per capita per day) from either 2011 (Cambodia and Lao PDR) or 2013 (all other countries) were used to determine rice consumption along with the U.S. Department of Agriculture (USDA) National Nutrient Database for Standard Reference data for raw brown long-grain rice (*https://ndb.nal.usda.gov/ndb/foods/show/305240?manu=&fgcd=&ds=SR*) to quantify any CO_2-induced differences in qualitative nutritional characteristics by individual country.

With respect to nutritional characteristics, we used a holistic approach to assess changes in a number of qualitative parameters including protein, minerals (Fe, Ca, and Zn), and vitamins B1 (thiamine), B2 (riboflavin), B5 (pantothenic acid), B6 (pyridoxine), B9 (folic acid), and E (α-tocopherol). Inadequate intake of the vitamins and minerals assessed were associated with specific physiological conditions and clinical manifestations.[40] Data for protein and minerals were available for all three experimental locations; however, vitamin analysis was only conducted for the rice lines from the China location. Because income level is the most important determinant of per capita rice consumption,[25] and because of the wide range of per capita incomes of the countries assessed, any significant CO_2-induced change in a nutritional characteristic was characterized with respect to GDP per capita (from 2013) for the ten countries examined (*https://data.worldbank.org/indicator/NY.GDP.PCAP.CD*).

Statistics

All field experiments at each location represented a completely randomized design with either three (China) or four (Japan) replicates. All measured and calculated parameters were analyzed using a two-way analysis of variance (ANOVA) with $[CO_2]$ and cultivar as fixed effects (Statview Software). Coefficient of determination (r^2) was calculated for protein, mineral (Fe and Zn), and vitamin (B1, B2, B5, B6, B9, and E) deficits as a function of $[CO_2]$ and GDP per capita. Each value is the mean ±SE. $^{**}P<0.01$; $^{*}0.01 \leq P<0.05$; $^{\dagger *}0.05 \leq P<0.1$; ns, not significant ($P \leq 0.1$). The figures were generated using Systat Software (SigmaPlot 10.0, Systat Software Inc.). No significant differences for $[CO_2]$ by cultivar interaction were found for calcium (Ca) or vitamin B6; consequently, these data are not shown separately. Every cultivar was grown only at a single site, which does not allow separation of cultivar effects from site effects. However, when averaged for all cultivars within a single location (Japan or China), no significant country interaction was observed for $[CO_2]$ impacts on noted reductions in protein, iron, or zinc (P = 0.26, 0.17, and 0.1 for protein, iron, and zinc, respectively). Because our purpose was to elucidate the effect of $[CO_2]$ on rice, but not on geographic area, cultivar effects are inclusive for the figures. Seasonal (yearly) variation was not significant for a given location and, consequently, was averaged across years for each FACE site. Original data are available at *https://doi.org/10.6084/m9.figshare.6179069*.

Supplementary Materials

Supplementary material for this article is available at *http://advances.sciencemag.org/cgi/content/full/4/5/eaaq1012/DC1*.

Table S1. Elution procedures for vitamin B and vitamin E.

Table S2. Compound parameters for vitamins B1, B2, B5, B6, B9 and E.

Fig. S1. As for *Fig. 3,* but for vitamin E (α-tocopherol) (see Methods for additional details).

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research funding from public and private sectors. N.K.F. is the Editor-in-Chief of Nutrition Reviews, an International Life Sciences Institute publication, and has received honoraria from Monsanto and the National Dairy Council before employment by the USDA. The other authors declare that they have no other competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Original data are available at *https://doi.org/10.6084/m9.figshare.6179069*.

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SUBMITTED REPORTS BY HON. DAVID SCOTT, A REPRESENTATIVE IN CONGRESS FROM GEORGIA *

1. Vose, J.M., D.L. Peterson, G.M. Domke, C.J. Fettig, L.A. Joyce, R.E. Keane, C.H. Luce, J.P. Prestemon, L.E. Band, J.S. Clark, N.E. Cooley, A. D'Amato, and J.E. Halofsky, 2018, *Forests.* In IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, D.C., USA, pp. 232–267. doi: 10.7930/NCA4.2018.CH6.
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* **Editor's note:** the reports listed are retained in Committee file.

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SUBMITTED LETTERS BY HON. DAVID SCOTT, A REPRESENTATIVE IN CONGRESS FROM GEORGIA

LETTER 1

ON BEHALF OF CHAD HANSON, PH.D., CHIEF SCIENTIST AND DIRECTOR; JENNIFER MAMOLA, D.C. FOREST PROTECTION ADVOCATE, JOHN MUIR PROJECT

March 12, 2021

Hon. DAVID SCOTT,
Chairman,
House Committee on Agriculture,
Washington, D.C.;

Hon. GLENN THOMPSON,
Ranking Minority Member,
House Committee on Agriculture,
Washington, D.C.

Re: House Agriculture Hearing on Climate Change and the U.S. Agriculture & Forestry Sectors

Dear Mr. Chairman, Ranking Member, Members and Staff;

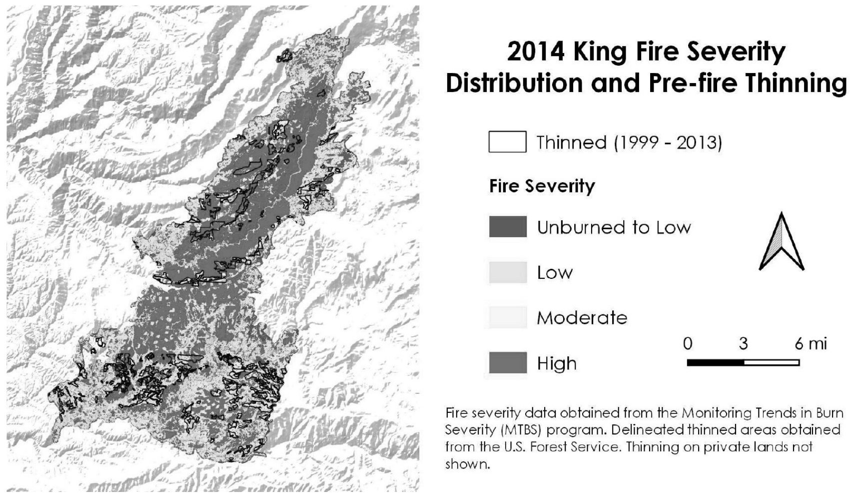
Last month we virtually attended your February 25th Agriculture *Hearing on Climate Change and the U.S. Agriculture and Forestry Sectors*. The majority of the focus was on how best to address issues within the agriculture sector which should be applauded as now more than ever we need to truly focus on those communities that feed us. Unfortunately, the brief mention of forests was often undermined by a demonization of nature, with a focus on logging under the guise of "fuel reduction",which releases more carbon into the atmosphere and often makes fires burn more intensely.

Unfortunately, at times the focus of the hearing veered away from solutions that would benefit society, the environment, and help us to solve the climate crisis. We are writing this letter to hopefully bring some balance to the testimony, verbal and written, that was presented and to address the problematic underlying narrative which appears to be shifting Members' attention away from actions that will actually make a difference for people and the planet.

1. **Vegetation is not driving wildfires: our forests aren't overstocked**

   Since the King Fire (see map below) was referenced and vegetation was blamed, it's probably one of the best examples of when the winds are blowing hard and the fire starts a major run, thinning or any other treatment (including prescribed fire) just doesn't prevent or stop fire. That fire burned almost exclusively at high severity in one particular portion of the fire on a huge run during a single day that was all due to a crazy localized wind event. That single day accounted for almost all of the high severity burned area in that fire, due to high wind.

Figure 1



(a) 2018, Coen, *et al., Deconstructing the King megafire;*† (b) *https://climate.nasa.gov/news/2771/local-winds-play-a-key-role-in-some-megafires/*.
Editor's note: entries annotated with † are retained in Committee file.

Meaning, the number one driver of fire behavior and extent is the climate, specifically high temperatures, extreme wind speeds and single digit humidity. Climate change is making these conditions more prevalent, more often. It is also important to appreciate the fact that we do not currently have an excess of fire in forests. We have always had fires in the West and always will, and there is wide agreement among scientists that we currently have less mixed-intensity fire in our forests than we did historically, before fire suppression and, while annual acres burned is incrementally getting slightly closer to historical levels, in part due to climate change, fire intensity in forests is not increasing.[1] The real issue is that, increasingly, climate and weather factors drive fires that humans are not able to suppress. Fires that cannot be suppressed, especially when they are started by human ignitions or infrastructure, have the potential to burn into and affect communities which have sprawled over time into our fire-adapted ecosystems.

There are several ways that we know it is climate conditions, rather than the vegetation, that is driving fire behavior. First, and most informative are the field-based studies that have looked at the effect, if any, that decades of successful fire suppression has had on fire intensity. Specifically, seven studies have investigated whether areas that have not experienced fire in a very long time (*i.e.,* areas that have had the chance for vegetation to grow unimpeded for a century or more) burn at higher intensity than areas which have experienced fire more recently. Three of the seven studies found unequivocally that areas that have not burned in a very long time *do not burn at higher intensities* than areas that have burned in recent decades, three of the remaining four studies found that the most long-unburned forests (the densest forests) *burned at lower intensities* than other forests, and the final of the seven studies speculated that long-unburned forests would burn *slightly* more intensely but would still be dominated by lower-intensity fire effects (and this study, unlike the other six, involved a theoretical model, and its conclusion was not based on actual fire data).[2]

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[1] (a) DellaSala, D.A., and C.T. Hanson (Editors). 2015. *The ecological importance of mixed-severity fires: nature's phoenix.* Elsevier Inc., Waltham, MA, USA; (b) Keyser, A.; Westerling, A. *Climate drives inter-annual variability in probability of high severity fire occurrence in the western United States.*† ENVIRON. RES. LETT. 2017, 12, 65003.

[2] (a) Miller J.D., Skinner C.N., Safford H.D., Knapp E.E., Ramirez C.M. 2012a. *Trends and causes of severity, size, and number of fires in northwestern California, USA.*† ECOLOGICAL APPLICATIONS 22, 184–203; (b) Odion, D.C., E.J. Frost, J.R. Strittholt, H. Jiang, D.A. DellaSala, and M.A. Moritz. 2004. *Patterns of fire severity and forest conditions in the Klamath Mountains, northwestern California.* CONSERVATION BIOLOGY 18: 927–936; (c) Odion, D.C., and C.T. Hanson.

Next we have empirical research which has investigated whether the number of dead trees in a given area drives fire behavior. The most comprehensive scientific studies (including one prepared by NASA) found that forests with more dead trees burn *the same* as other forests or burn at *lower* intensities.[3] While it may seem counterintuitive, soon after trees die (whether from drought or beetle activity), they shed their needles and small branches which fall to the ground and decay into soil and there is no real mechanism to carry flames.

Importantly, our forests currently have significantly *less* tree biomass in them than they did historically, due to decades of logging. Claims that our forests are "overstocked" are quite simply misleading.[4]

2. **Since vegetation is not driving wildfires, vegetation management, thinning and other forms of logging, and prescribed burning are not necessary**

Climate and weather are driving wildfire behavior, but to the extent that density of vegetation has an influence, it is the opposite of what many assume. Numerous studies have investigated this issue, measuring forest density directly and how it relates to fire behavior. These studies, similar to the ones referenced above, also found that *the densest mature forests generally burn at lower intensities.* This is because denser forests have more trees, which provide more shade, which keep conditions cooler and more moist. Whereas forests with fewer trees, often due to logging/mechanical-thinning, burned at higher intensities. This is because logging reduces the cooling shade of the forest canopy, creating hotter, drier conditions, while also removing trees which have a buffering effect on wind speeds, eliminating the forests ability to slow fire spread. Far from being a "fire" solution, logging/thinning does not stop fires, and fires often move more rapidly through these areas. Further, the most comprehensive scientific study ever conducted on this question found that forests with the most logging a.k.a "forest management" burn the most intensely, not the least.[5]

Prescribed fire does not stop wildland fires either. In fact, wildland fires can burn again even within as little as 1 or 2 year after a prescribed fire, as we just saw in Australia (the bushfires burned right through the largest prescribed burn in the nation's history, which was conducted in 2017). Historically, forests burned every few decades, not every 2 years.[6] If we attempt to "fireproof" the landscape with prescribed fire, we would be imposing far more fire than is natural on ecosystems, impacting biodiversity and damaging

2006. *Fire severity in conifer forests of the Sierra Nevada, California.* ECOSYSTEMS 9: 1177–1189; (d) Odion, D.C., and C.T. Hanson. 2008. *Fire severity in the Sierra Nevada revisited: conclusions robust to further analysis.*† ECOSYSTEMS 11: 12–15; (e) Odion, D.C., M.A. Moritz, and D.A. DellaSala. 2010. *Alternative community states maintained by fire in the Klamath Mountains, USA.*† JOURNAL OF ECOLOGY, doi: 10.1111/j.1365-2745.2009.01597.x; (f) van Wagtendonk, J.W., K.A. van Wagtendonk, and A.E. Thode. 2012. *Factors associated with the severity of intersecting fires in Yosemite National Park, California, USA.*† FIRE ECOLOGY 8: 11–32; (g) Steel, *et al.* 2015. *Ecosphere* 8: Article 8.

[3] (a) Hart, S.J., T. Schoennagel, T.T. Veblen, and T.B. Chapman. 2015. *Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks.*† PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE USA 112: 4375–4380; (b) Meigs, G.W., H.S.J. Zald, J.L. Campbell, W.S. Keeton, and R.E. Kennedy. 2016. *Do insect outbreaks reduce the severity of subsequent forest fires?*† ENVIRONMENTAL RESEARCH LETTERS 11: 045008.

[4] (a) McIntyre, P.J., *et al.* 2015. *Twentieth-century shifts in forest structure in California: Denser forests, smaller trees, and increased dominance of oaks.*† PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 112: 1458–1463; (b) Erb, K.H., *et al*. 2018. *Unexpectedly large impact of forest management and grazing on global vegetation biomass.* NATURE 553: 73–76.

[5] (a) Bradley, C.M. C.T. Hanson, and D.A. DellaSala. 2016. *Does increased forest protection correspond to higher fire severity in frequent-fire forests of the western USA?*† ECOSPHERE 7: article e01492; (b) Zald, H.S.J., and C.J. Dunn. 2018. *Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape.*† ECOLOGICAL APPLICATIONS 28: 1068–1080; (c) Meigs, G., D. Donato, J. Campbell, J. Martin, and B. Law. 2009. *Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon.*† ECOSYSTEMS 12: 1246–1267; (d) Cruz, M.G., M.E. Alexander, and J.E. Dam. 2014. *Using modeled surface and crown fire behavior characteristics to evaluate fuel treatment effectiveness: a caution.*† FOREST SCIENCE 60: 1000–1004; (e) DellaSala, D.A,, C.T. Hanson. 2019. *Are wildland fires increasing large patches of complex early seral forest habitat?*† DIVERSITY 11: Article 157.

[6] DellaSala, D.A., and C.T. Hanson (Editors). 2015. *The ecological importance of mixed-severity fires: nature's phoenix.* Elsevier Inc., Waltham, MA, USA.

soils and forest productivity all while creating vastly more smoke than currently occurs with wildland fires—and it would not stop wildland fires.

Pursuing a "forest management" approach to fire fundamentally ignores and denies that climate is driving fire behavior. These activities will not solve our community protection problem, or assist with climate adaptation and will exacerbate rather than mitigate the climate and extinction crises we currently face. Not to mention the colossal amounts of money that is burned in the backcountry. A witness even stated they'd love to see *more* money spent, yet all that would do is emit even more carbon into the atmosphere while communities continue to be ill-prepared for the inevitable fire season.

3. **To protect communities, we must focus on communities**

Fires are ultimately weather driven events, similar to tornadoes and hurricanes. Accepting this will enable us to do what is necessary to focus our efforts on community protection, resilience, disaster preparedness and mitigation. Outside of putting resources into stopping human ignitions via more patrols during high fire weather and educating the public about fire-safe activities, once a fire starts under extreme weather conditions it is going to burn.

According to the scientific research the only effective way to protect homes from wildland fire is to focus on making the homes themselves more fire-safe, and to conduct annual defensible space pruning within 100′ of homes. Beyond 100′ from houses, there is *no additional benefit* to home protection from vegetation management.[7] Congressional resources should be put into such efforts, similar to a bill from the 116th Congress that took a first step in this direction S. 2882/ H.R. 5091 *Wildfire Defense Act.*

Because we cannot suppress weather driven fires, we cannot stop the smoke that they create. What we can and must do is promote measures that will keep people safer and help communities adapt: by devoting resources to help create better fire and smoke warning and evacuation systems; develop programs which help homeowners in need with air filters for smoke, and access to appropriate respiratory masks (as mentioned at the hearing); create smoke relief centers for sensitive groups; have options for emergency housing; daycare; rideshares to work and always ensure that these services are available to everyone, regardless of income.

Unfortunately, employing forest management, by way of logging and removal of vegetation from our forests, as a "fire fix" diverts scarce resources away from measures that would actually make people safer, and it gives communities a dangerous and false sense of security because such actions will not stop fires or alter weather driven fire behavior. We saw a tragic example of this in the Camp fire of 2018, which burned so rapidly through several thousand acres of heavily managed forestland (which had been post-fire clearcut and/or thinned) during the first 6 hours of the fire that people within the towns of Paradise and Concow had very little time to evacuate, with tragic results. So called fuels reduction and post-fire "restoration" did not save these towns from this weather driven fire, it made the tragedy worse.[8]

4. **Forests, as they exist right now, are a climate solution *not* a climate problem**

Our forests are currently substantial carbon sinks, absorbing more carbon than they emit, but they could absorb much more carbon than they currently do, if they were protected from logging. Logging is the real source of carbon emissions from forests. In U.S. forests, for example, logging (of all types, thinning/post-fire/clearcutting/group-selection, *etc.*) emits ten times more carbon than is emitted from wildland fire and tree mortality from drought and native bark beetles *combined*. Dead trees and downed logs decay extremely slowly (decades to a century or more), and eventually return their nutrients to the soil, which helps maintain the productivity and carbon sequestration capacity of the forest.[9]

Wildland fires, including large mixed-severity fires, only consume about 1% to 2% of the biomass of trees in the forest, and therefore only release this

[7] Syphard, A.D., T.J. Brennan, and J.E. Keeley. 2014. *The role of defensible space for residential structure protection during wildfires.*† INTL. J. WILDLAND FIRE 23: 1165–1175.

[8] *https://johnmuirproject.org/2019/01/logging-didnt-stop-the-camp-fire/*.†

[9] (a) Harris, N.L., *et al.* 2016. *Attribution of net carbon change by disturbance type across forest lands of the conterminous United States.*† CARBON BALANCE MANAGEMENT 11: Article 24; (b) Meigs, G., *et al.* 2009. *Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon.*† ECOSYSTEMS 12: 1246–1267; (c) Meigs, G.W., H.S.J. Zald, J.L. Campbell, W.S. Keeton, and R.E. Kennedy. 2016. *Do insect outbreaks reduce the severity of subsequent forest fires?*† ENVIRONMENTAL RESEARCH LETTERS 11: 045008.

small portion of the carbon stored in trees into the atmosphere. We know this from field-based studies of actual fires in actual forests. The problem is that Federal and state agencies use theoretical models to estimate carbon emissions from forest fires and dead trees, but the models wildly exaggerate carbon emissions from decay and fire. For example, in the 257,000 acre Rim fire of 2013, field-based data determined that only *1/10 of 1% of the carbon in trees was actually consumed in typical fire conditions,* whereas the theoretical models falsely assume levels of consumption that are often dozens, or hundreds, of times higher than this.[10]

5. **The proposals supported by the witnesses will harm our environment, biodiversity and the climate**

There was discussion and written testimony at this hearing of logging as an answer to the "fire" problem. But we actually don't have a fire problem in our forest ecosystems. We have *substantially less* mixed-intensity fire now than we had historically, before fire suppression. ***In addition, wildland fires, especially the large fires that burn at mixed-intensity, transform forest ecosystems but do not destroy them. In fact these fires create natural heterogeneity across vast areas, rejuvenating wildlife habitat to such a degree that the biodiversity in mature forests that experience high-intensity fire is similar to levels of biodiversity found in unlogged old-growth forests, and the same is true for areas which have experienced drought and beetle related tree mortality.***[11] In addition, forests are naturally regenerating even in the largest high-intensity fire patches.

While we do not have a fire in our forests problem, we most certainly do have a problem with fire affecting our communities and a climate change problem. We therefore need solutions to protect and adapt communities and to combat climate change. *Logging, whether you call it thinning, vegetation management, forest management or biomass removal, will remedy neither of these problems and actually makes things worse.* It is simply another part of the carbon economy. Since no witness at the hearing addressed the carbon cost of logging we thought we would share some statistics here. Due to its industrial nature, approximately 81% of the carbon in trees that are logged quickly ends up in the atmosphere, with only 19% ending up being stored in wood products. Logging also removes nutrients from forests and compacts soils, reducing the overall productivity and function of the forest ecosystem as well as its carbon sequestration and storage capacity.[13] Notably, numerous studies find that logging conducted under the guise of "thinning", "fuels reduction" and fire management actually causes a large net loss of forest carbon storage and a substantial net increase in carbon emissions relative to wildland fire alone.[14]

We hope that you have found the above information helpful and we urge you to consider the foregoing, and to reject false climate solutions that would make climate change worse and increase risks to vulnerable communities. We need to increase protection of our forests from logging, and focus resources on directly protecting and helping vulnerable communities. The recommendations made by numerous speakers at the hearing, and the comments made by some Members, would take us in the wrong direction. We would be happy to answer questions or provide additional infor-

[10] Stenzel, J.E., *et al.* 2019. *Fixing a snag in carbon emissions estimates from wildfires.* GLOBAL CHANGE BIOLOGY 25: 3985–3994.

[11] DellaSala, D.A., and C.T. Hanson (Editors). 2015. *The ecological importance of mixed-severity fires: nature's phoenix.* Elsevier Inc., Waltham, MA, USA.

Editor's note: the letter submitted by the John Muir project ***does not*** have a footnote reference for footnote no. 12. It has been reproduced, as submitted, herein. Below is footnote 12 that was included at the end of the letter.

[12] Hudiburg, T.W., Beverly E. Law, William R. Moomaw, Mark E. Harmon, and Jeffrey E. Stenzel. 2019. *Meeting GHG reduction targets requires accounting for all forest sector emissions.*† ENVIRONMENTAL RESEARCH LETTERS 14: Article 095005.

[13] (a) Walmsley, J.D., *et al.* 2009. *Whole tree harvesting can reduce second rotation forest productivity.* FOREST ECOLOGY AND MANAGEMENT 257: 1104–1111; (b) Elliot, W.J., *et al.* 1996. *The effects of forest management on erosion and soil productivity.* SYMPOSIUM ON SOIL QUALITY AND EROSION INTERACTION. July 7, 1996, Keystone, CO.

[14] (a) Campbell, J.L., M.E. Harmon, and S.R. Mitchell. 2012. *Can fuel-reduction treatments really increase forest carbon storage in the western U.S. by reducing future fire emissions?*† FRONTIERS IN ECOLOGY AND ENVIRONMENT 10: 83–90; (b) Hudiburg, T.W., *et al.* 2013. *Interactive effects of environmental change and management strategies on regional forest carbon emissions.* ENVIRONMENTAL SCIENCE AND TECHNOLOGY 47: 13132–13140.

mation, so please feel free to contact us if you would like to have a dialogue on these issues.

Sincerely,

CHAD HANSON, Ph.D.,
Chief Scientist and Director,
John Muir Project;

JENNIFER MAMOLA,
D.C. Forest Protection Advocate,
John Muir Project.

LETTER 2

ON BEHALF OF JOHN LINDER, PRESIDENT, NATIONAL CORN GROWERS ASSOCIATION

March 5, 2021

Hon. DAVID SCOTT,
Chairman,
House Committee on Agriculture,
Washington, D.C.;

Hon. GLENN THOMPSON,
Ranking Minority Member,
House Committee on Agriculture,
Washington, D.C.

Dear Chairman Scott and Ranking Member Thompson:

On behalf of the National Corn Growers Association (NCGA), we appreciate the opportunity to submit this statement outlining corn grower priorities on policies related to climate change. We request this statement be included in the record for the February 25, 2021 hearing of the House Agriculture Committee, "Climate Change and the U.S. Agriculture and Forestry Sectors."

Founded in 1957, NCGA represents nearly 40,000 dues-paying corn farmers nationwide and the interests of more than 300,000 growers who contribute through corn checkoff programs in their states. NCGA and its 48 affiliated state organizations work together to create and increase opportunities for corn growers. Corn provides a nutritious and sustainable feed for the global livestock sector, supplies the world with renewable fuel and replaces petroleum and other non-renewable ingredients in a variety of industrial and consumer products.

NCGA supports the agriculture sector's opportunity to contribute to carbon reduction based on carbon offsets and carbon sequestration through crop production, as well as through further decarbonization of transportation fuels through increased use of renewable fuels. Further, NCGA supports market-based, voluntary opportunities for farmers to provide carbon reduction benefits.

A changing climate poses a unique threat to agriculture because weather has a direct impact on farm production and profitability. With weather likely to become even more unpredictable, a reliable and consistent food supply for a growing population is more important than ever before. Building upon the strong foundation of voluntary stewardship investments andsustainable farming practices, climate policy should support research and innovation needed todevelop new technologies that will help farmers respond to climate change and continuereducing greenhouse gas emissions.

Soil Carbon Sequestration Potential

Corn as a crop can serve as a carbon sink. As a photo-synthetically superior C_4 plant, corn has an extraordinary ability to sequester carbon and move fertilizer nutrients back to the surface for plant growth rather than into ground water. Corn's extensive, deep root system makes it one of the few plants with this important capability to make crop production more sustainable.

High-yield corn—combined with the steady adoption of best practices such as reductions in tillage intensity—is sequestering carbon from the atmosphere into the soil. This sequestration is increasing soil carbon levels and reducing atmospheric carbon. According to the *Journal of Soil and Water Conservation,* the potential to sequester atmospheric carbon in soil is greatest on lands currently used for annual crops where there is potential to sequester carbon in the soil at an annual growth rate of 0.4 percent each year. The results of tracking soil organic carbon advancements on select USDA-specified agricultural land areas is estimated to have sequestered an estimated 309 metric tons of CO_2-equivalent in less than a decade.

Research increasingly demonstrates the ability to account for the direct effects corn production has on soil carbon stocks, whether as part of climate change policy, carbon markets that support agriculture or in ethanol lifecycle assessment (LCA) accounting such as the Department of Energy's Argonne National Lab Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model.

NCGA's Soil Health Partnership and Climate

Soil health practices and management systems hold the potential to mitigate climate change but further research is needed to fully understand the benefits of soil health practices. There is a major gap in understanding how soil health practices impact soil health, water quality, air quality and greenhouse gas (GHG) emissions.

NCGA is working to bridge this gap through its flagship sustainability program, the Soil Health Partnership (SHP). SHP's mission is to utilize science and data to partner with farmers who are adopting agricultural conservation practices that improve economic and environmental sustainability. The partnership has more than 220 working farms enrolled in 15 states. It is the only farmer-led effort that focuses on supporting farmers as they experiment with new conservation practices like cover crops, reduced or no tillage and nutrient management with the benefit of support from SHP expert partners. SHP works with farmers to achieve the goal of broader adoption of conservation practices and understanding how varying practices affect the environment.

SHP is focused on soil health improvements as the key transformation that facilitates many subsequent improvements ranging from increased productivity, increased resilience to weather changes, improved water quality, reduced soil erosion and increased carbon sequestration. The soil health indicators measured are both quantitative and qualitative to gauge the intermediate and long-term impacts of these changes.

Farmers enroll to run research trials on their active farms, with data collected on 165 variables over 5 years. As a result, SHP has one of the most unique data sets in the country that combines information from diverse farms across 15 states, multiple years, and many soil types to allow for an analysis of trends. SHP will soon be able to analyze the impact of various conservation practices on the environment, coupled with an understanding of the management decisions made to put those practices in place and how they impact farmers economically.

Farmers are making major impacts on the environment in ways that have been historically underestimated. SHP's initial analyses show increases in soil organic matter of about ¼ of 1 percent over the first 2–3 years in the program, which suggests improved soil water holding capacity and possibly carbon storage over time. Currently, there is not sufficient longitudinal, diverse data to fully understand the long-term impacts of various conservation practices on climate outcomes, *e.g.,* GHG emissions, but through SHP's continued work, we will be able to understand the impact and better target our resources and energy to benefit farmers and the environment.

In addition to measuring changes in soil organic matter over time, SHP is also part of a multiyear, multi-partner Conservation Innovation Grant through USDA NRCS to create a carbon accounting and insetting framework that would enable companies along the supply chain to encourage farmers to adopt conservation practices such as reduced tillage and cover crops to sequester carbon in the soil. The framework employs the DeNitrification-DeComposition (DNDC) model to model GHG impacts from on-farm practice changes and uses the Operational Tillage Informational System (OpTIS) as a low-cost, low-touch verification tool for the framework.

Biotechnology, Crop Protection Tools and Climate Change

Prior to the introduction of transgenic seeds tolerant to broad-spectrum pesticides, farmers were forced to rely on tillage to manage weeds in their fields. When the first transgenic, or GMO, crops became commercially available, farmers were no longer forced to rely solely on tillage for weed control.

Transgenic seeds that contain a tolerance to certain pesticides could be used without the need for tillage because those crop protection products could be applied over the top of the seeds without damaging them. With this new option in place, farmers replace intense tillage previously required for control with conservation tillage practices. Conservation tillage, defined as tillage systems leaving at least 30 percent of the soil surface covered by crop residue at crop planting, has now been widely adopted by farmers around the country. The use of these practices substantially reduces soil erosion. GMOs also reduce the amount of pesticides that need to be sprayed.

Over the last 20 years, this technology has reduced pesticide applications by 8.2 percent and helped increase crop yields by 22 percent.

Maintaining access to innovative and effective products, including transgenic seeds and pesticides, is important for enabling agriculture to be part of the solution for global climate challenges. First, farmers using conservation tillage practices make fewer trips over their field over the course of a growing season, thus reducing energy consumption. Second, plants are known consumers of carbon dioxide, pulling it out of the atmosphere and storing it in the soil through their roots. Tillage breaks up the soil carbon which is then released back into the atmosphere. If farmers must revert to using heavy tillage to control weeds, agriculture will likely decrease its ability to capture and store carbon in the soil and, therefore, decrease its ability to positively address climate change.

Decarbonization From Renewable Fuels

NCGA supports the Renewable Fuel Standard (RFS), the only Federal statutory GHG reduction requirement. The RFS provides low carbon biofuels access into the closed transportation fuel market. Recent EPA administration of the RFS, with extensive waivers for refineries for biofuels blending, reduces renewable fuel demand and the emissions reductions provided by biofuels. NCGA supports upholding the integrity of the RFS to further reduce emissions in the transportation sector. The RFS has exceeded projections and resulted in cumulative carbon reduction savings of 980 million metric tons since 2007, due to greater than expected savings from conventional ethanol and despite lower than expected production of next generation fuels.

The transportation sector accounts for nearly a third of the nation's GHG emissions. Near-term achievable emissions reductions from this sector should be prioritized by increasing use of renewable fuels. Federal LCA models show that conventional ethanol's carbon footprint is shrinking, allowing renewable fuel use to contribute to greater decarbonization of transportation fuel.

The RFS requires renewable fuels to meet lifecycle GHG emission reduction thresholds. Models used to predict RFS impacts in 2010 projected that use of conventional ethanol would reduce GHG emissions by 21 percent compared to gasoline by 2022. However, updated analysis, based on actual corn and ethanol production, shows much greater GHG reductions than projected. As a result, corn-based ethanol is delivering far more GHG reductions today than anticipated in the RFS.

Ethanol's carbon footprint is shrinking due to advances in both corn and ethanol production. A 2018 USDA study shows that ethanol results in 39 to 43 percent fewer GHG emissions than gasoline. Building on this progress, additional improvements on farms and in ethanol production supported by expanding markets for low carbon fuels could result in ethanol with up to 70 percent fewer GHG emissions than gasoline, according to USDA's analysis.

The GREET model measures lifecycle emissions of transportation fuels and is considered the "gold standard" in lifecycle analysis. Updated annually, GREET shows steady improvement in corn ethanol's lifecycle GHG profile, with corn-based ethanol's carbon intensity (CI) currently about 41 percent below that of baseline gasoline, following steady improvement since 2010, when GREET showed ethanol's CI about 19 percent below that of gasoline.

Furthermore, according to California Air Resources Board (CARB) data, the CI of ethanol under the state's Low Carbon Fuel Standard (LCFS) is more than 30 percent lower today than it was in 2011 and at least 40 percent lower than the CI of gasoline. These significant improvements in ethanol's carbon intensity are the result of advancements and wider adoption of more efficient farming practices, improved efficiency in ethanol production and increased crop productivity that efficiently uses existing crop land and is not producing land cover change. For example, Argonne's recent updates to the GREET model incorporate the growing adoption of reduced tillage and no-tillage practices into the LCA for ethanol.

NCGA strongly supports using Argonne's GREET model as the basis for updated and accurate measurement of the decarbonization conventional ethanol provides in the transportation sector. With the benefit of real-world data on crop and ethanol production through the expansion of renewable fuels production since 2005, LCA should be based on experience, not estimates or projections. These updates to the LCA show that corn-based ethanol is far exceeding the GHG emissions reductions required and expected under the RFS.

Although electric vehicles have gained market penetration, liquid fuel powered vehicles will remain the dominant vehicle type for the foreseeable future. According to U.S. Energy Information Administration's 2020 Energy Outlook, gasoline and flex-fuel vehicles will make up 81 percent of vehicle sales in 2050. With continued use of liquid fuel vehicles, continued decarbonization can be accomplished through greater use of biofuels such as ethanol. NCGA views biofuels such as ethanol as a key part of the solution for further decarbonizing the transportation sector.

Low Carbon Octane Standard for Fuel Efficiency and Decarbonization

Matching new engine technologies with improved transportation fuels would make vehicles more fuel efficient and reduce emissions further. Establishing a Low Carbon Octane Standard (LCOS) for light duty vehicle fuel would reduce GHG emissions, improve fuel efficiency, improve air quality and further diversify the fuel supply—all while maintaining fuel and vehicle affordability and choice for drivers.

In the 116th Congress, Representative Cheri Bustos, an Agriculture Committee Member, introduced the Next Generation Fuels Act, legislation to establish a low carbon, high octane standard for fuel. This legislation would establish a minimum fuel octane standard of 98 Research Octane Number, or RON, for motor gasoline paired with a requirement that sources of additional octane result in at least 30 percent fewer GHG emissions than baseline gasoline and removal of barriers to higher ethanol blends.

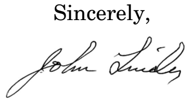
This low carbon, high octane fuel allows automakers to use advanced engine design features that increase engine performance and significantly improve fuel efficiency. These engine design features, such as higher compression ratios, are limited by current fuels because low octane fuels cannot mitigate engine knock. High octane fuel limits knock, enabling automakers to design more fuel efficient vehicles, leading to lower GHG emissions. Current fuel standards limit the use of these advanced engine technologies and leave automakers with fewer options to meet higher fuel economy standards.

Demonstrated through significant research, high octane fuel such as 98 RON supports fuel efficiency gains of five percent or more, and increased fuel efficiency reduces greenhouse gas emissions. By requiring that a fuel used to enhance octane also reduces GHG emissions compared with unblended gasoline, a LCOS further decarbonizes liquid fuels as vehicle technologies advance.

According to Department of Energy's analysis, because of ethanol's high octane rating, a low carbon, high octane mid-level ethanol blend would provide significant GHG reduction benefits through both increased vehicle efficiency and by offsetting petroleum with lower emissions renewable fuel. Priced lower than unblended gasoline, ethanol is the most cost-effective octane source, providing the greatest efficiency gains at the lowest cost to drivers. A 98 RON E25 blend, for example, would provide a further GHG reduction from additional ethanol offsetting petroleum on top of the GHG reduction from the fuel efficiency gains. We look forward to working on the Next Generation Fuels Act in the 117th Congress, demonstrating how agriculture can contribute to addressing climate change through the use of more low carbon renewable fuels, and carbon sequestration through sustainable farming practices.

NCGA stands ready to assist this Committee as it carves a path forward on this important policy issue. Thank you again for the opportunity to provide this statement for the record.

Sincerely,



JOHN LINDER,
President,
National Corn Growers Association.

LETTER 3

ON BEHALF OF JULIA OLSON, EXECUTIVE DIRECTOR, OUR CHILDREN'S TRUST

February 23, 2021

Chair Spanberger and Ranking Member LaMalfa, Full Committee on Agriculture

Re: Materials for February 25, 2021 Hearing on Climate Change and the U.S. Agriculture and Forestry Sectors

Dear Chair Spanberger and Ranking Member LaMalfa,

On behalf of Our Children's Trust ("OCT"), a nonprofit organization dedicated to securing the legal right to a stable climate system for youth and future generations, please find enclosed herewith materials for your consideration relevant to the House Committee on Agriculture's February 25, 2021 hearing, "Climate Change and the

U.S. Agriculture and Forestry Sectors." This submission will inspire you with the stories of courageous children and provide resources critical to developing science-based, technically and economically feasible solutions to the climate crisis.

Through youth-led constitutional legal actions, including *Juliana* v. *United States* ("*Juliana*")—the landmark Federal constitutional climate case filed by twenty-one youth plaintiffs, including eleven Black, Brown and Indigenous youth—OCT supports youth seeking to hold their governments accountable for policies and actions that have caused, and continue to cause, the climate crisis. Through these actions, youth seek science-based remedies to reduce greenhouse gas emissions at rates necessary to protect their fundamental human rights.

It is OCT's understanding that the materials submitted for the February 25th hearing will inform the Committee's outlook on climate impacts and future climate policy and legislation on sustainable practices in the agriculture and forestry sectors as it works in tandem with President Biden's bold actions to combat the climate crisis. Given our mission, OCT has a substantial interest in ensuring that any such legislation is consistent with what the best available science dictates is necessary to stabilize the climate system and protect the fundamental rights of youth and future generations.

We invite you to consult the materials enclosed herewith, which demonstrate that climate change is *already harming* the fundamental rights of young people in the United States and legislation which ensures emissions reductions and sequestration of excess CO_2 is necessary for the protection of the fundamental rights of American children. Please note in *Exhibit D* below, the prescription to stabilize the atmosphere is a return to atmospheric CO_2 levels to 350 ppm by 2100, limiting global warming to less than 1° Celsius by 2100. This requires that net negative CO_2 emissions be achieved before mid-century.

Specifically, enclosed as *Exhibit A* is a summary of the *Juliana* case, including plaintiffs' profiles. Enclosed as *Exhibit B* you will find impact statements of youth from the Federal case supported by OCT, *Juliana* v. *United States,* which demonstrates some of the profound ways that climate change is already affecting the fundamental rights of young people, including youth of color and indigenous youth in frontline and vulnerable communities. Jacob Lebel and Alex Loznak's family farms in Oregon have been impacted by increased heat waves and drought conditions, wildfire, and pest infestations. Due to drought, water scarcity and failed attempts at dryland farming, Jamie Butler's family moved away from their traditional lands and home on the Navajo Nation Reservation in Arizona.

Enclosed as *Exhibit C* is the expert report of Dr. G. Philip Robertson, University Distinguished Professor of Ecosystem Ecology in the Department of Plant, Soil and Microbial Sciences at Michigan State University and Scientific Director for the Department of Energy's Great Lakes Bioenergy Research Center at the University of Wisconsin and Michigan State University. This expert report estimates the potential for increased carbon sequestration from U.S. forest, range, and agricultural land management. Dr. Robertson concludes:

> Over the period 2020 to 2100, changes to land management practices in the U.S. could mitigate . . . over 30% of the negative and avoided emissions needed, after phasedown of fossil fuel emissions, to return Earth's atmosphere to a more stable state.
>
> Avoiding tillage with no-till technology is one well-recognized practice to rebuild soil carbon . . . Adding winter cover crops to avoid bare soil for most of the year can increase soil carbon, as can diversifying crop rotations . . . and applying compost or manure. Growing perennial grasses or trees on degraded or low value agricultural soils can also result in significant carbon gains.
>
> On pastures and rangeland, soil carbon storage can be improved by increasing plant productivity via improved plant species and by avoiding overgrazing via careful attention to the number of livestock per acre. About 43% of all pasture and rangeland in the U.S. is managed by Federal agencies.
>
> Forests can also be managed to enhance carbon sequestration in trees and soil. Faster growing species accumulate more carbon over their lifetimes and therefore planting more of these species will store more carbon in wood, as will growing trees in longer rotations (the number of years between harvests) . . . About 42% of all forestland in the conterminous U.S. is managed by Federal agencies.

Enclosed as *Exhibit D* you will find a document entitled "Government Climate and Energy Actions, Plans, and Policies Must Be Based on a Maximum Target of 350 ppm Atmospheric CO_2 and 1 °C by 2100 to Protect Young People and Future Generations." This document details the scientific basis underlying, and prescription for, stabilization of the climate system as necessary to protect the fundamental human rights of youth and future generations relative to the climate crisis and explains that allowing warming of up to 1.5 °C is not safe.

Enclosed as *Exhibit E* include reports published by the energy experts at Evolved Energy Research. *Exhibit E.1* is an executive summary entitled "350 PPM Pathways for the United States," which demonstrates multiple technologically and economically feasible pathways for transitioning to a 100 percent clean energy economy consistent with the science-based prescription for stabilizing the atmosphere and securing the fundamental rights of youth and future generations. The report demonstrates multiple technically and economically feasible pathways for transitioning to a 100 percent clean energy economy consistent with the science-based prescription for stabilizing the climate system and securing the fundamental rights of youth and future generations. The pathways reduce greenhouse gas emissions in the United States at a rate consistent with returning global concentrations of CO_2 in the atmosphere to 350 ppm by 2100, limiting global warming to less than 1.0 °C by 2100. This requires that net negative CO_2 emissions be achieved before mid-century. The report provides important policy guidance to achieve this steep and necessary level of emissions reductions in the United States. Enclosed as *Exhibit E.2* is an executive summary entitled "350 PPM Pathways for Florida" that mirrors the national study's target. Updated national data is included in the full report as the U.S. model was upgraded to reflect the newer and even lower costs for renewable technologies. The U.S. data from the Technical Supplement (page 71) is also included under this Exhibit.

Legislation which ensures emissions reductions and sequestration of excess CO_2 consistent with what the best available science dictates is necessary for the protection of the fundamental rights of young people and future generations. The information in these Exhibits are additionally relevant to a forthcoming reintroduction of a House concurrent resolution on *Children's Fundamental Rights and Climate Recovery*[1] supporting the *Juliana* youth plaintiffs. It recognizes the disproportionate effects of the climate crisis on children and their fundamental rights which demands renewed U.S. leadership and development of a national, science-based climate recovery plan. This resolution, sponsored by Representative Schakowsky and originally introduced in September 2020, had the support of 61 cosponsors from both chambers.

Should you have any questions regarding the enclosed materials, please feel free tocontact Liz Lee, OCT's government affairs staff attorney at [**Redacted**].

Sincerely,

JULIA OLSON,
Executive Director,
Our Children's Trust.

Exhibit A:* Juliana *v.* United States *Summary and Plaintiffs' Profiles

Juliana* v. *United States

Young Americans Fight for Their Constitutional Rights and Climate Recovery

Background

Represented by attorneys at *Our Children's Trust,*[1] **21 young Americans filed their constitutional climate lawsuit, *Juliana* v. *United States,* against the Executive Branch of the U.S. Government in 2015.** They assert that the government's affirmative actions causing climate change have violated their constitutional rights to life, liberty, property, and equal protection of the laws, and impaired essential public trust resources. They seek a court-ordered, science-based climate recovery plan, to put the U.S. on track to bring atmospheric carbon dioxide levels back to 350 parts per million (ppm) by 2100, which would limit long-term warming to less than 1 °C, which scientists say is the safe target to stabilize the planet's climate system.

In May 2019, a team of renowned energy experts, Jim Williams, Ben Haley, and Ryan Jones, published a *report*[2] that demonstrates the technical and economic viability of the U.S. to meet this standard by 2100. An October 2020 *report*[3] on specific pathways for Florida to meet this standard also provides updated U.S. data.

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[1] *https://www.congress.gov/bill/116th-congress/house-concurrent-resolution/119?r=1&s=6.*
[1] *https://www.ourchildrenstrust.org/.*
[2] *https://www.ourchildrenstrust.org/350-ppm-pathways.*
[3] *https://www.ourchildrenstrust.org/350-ppm-pathways-florida.*

History

The U.S. District Court has repeatedly found that the youth plaintiffs have legitimate claims for trial. **In a groundbreaking decision in November 2016, the court found that the U.S. Constitution secures the fundamental right to a climate system capable of sustaining life;** that plaintiffs' injuries give them standing to bring their claims; and that the Court has authority to remedy the youth's injuries.

Since that historic ruling, the defendants have relentlessly attempted to prevent *Juliana* v. *U.S.* from going to trial. Three times in 2018, the Ninth Circuit Court of Appeals ruled resoundingly against government attempts to stop the case. **The U.S. Supreme Court has also ruled in favor of the youth, twice refusing to halt the case.**

On January 17, 2020, a divided panel of the Ninth Circuit Court of Appeals found for the plaintiffs in nearly every respect, but ultimately ruled that the courts cannot stop the Executive Branch of government from harming children with its policies that cause climate change. The plaintiffs filed a petition for rehearing on March 2, 2020, supported by ten *amicus curiae* briefs, including 24 Members of Congress and constitutional law experts.

Looking Forward

On February 10, 2021, while a judge requested a vote, the Ninth Circuit denied the plaintiffs' request to rehear their lawsuit without explanation. **Plaintiffs are now planning to seek review in the U.S. Supreme Court.** The plaintiffs are also requesting that the **Biden-Harris Administration and the Department of Justice meet with the plaintiffs to discuss settling their claims,** and thereby protect their rights and the rights of children to come.

Support These Brave Plaintiffs

The youth plaintiffs deserve to have their constitutional claims heard, and need your support now. Please publicly support their right to have their constitutional claims upheld in a court of law. Support the Congressional resolution recognizing children's fundamental rights and the need for a national, science-based climate recovery plan at *ourchildrenstrust.org/congressionalresolution*. The resolution, originally introduced on September 23, 2020, was supported by 63 Members of Congress. Also, join future *amicus curiae* briefs in support of their constitutional rights and the judiciary exercising its Article III powers in their case. **Show our nation's children you care about their future, and the future of all generations to come.**

Juliana v. United States: *Meet the Plaintiffs*

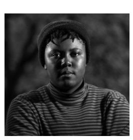
Meet all 21 Juliana *plaintiffs at* ourchildrenstrust.org/federal-plaintiffs

Learn more about their stories in this 60 Minutes[4] *segment (*bit.ly/60minsjuliana*) and their visit to Congress in* this video[5] *(*bit.ly/yearsprojectjuliana*) from The YEARS Project*

For over 5 years, these young plaintiffs, all of whom have been personally impacted by climate change, have been leading the game-changing litigation campaign to secure the legal right to a stable climate for young people, based on the best available science. In 2015, they filed their constitutional climate lawsuit against the U.S. government in the U.S. District Court for Oregon.

Kelsey Juliana, 24, Eugene, OR

Fighting climate change since she was 10, Kelsey has been increasingly exposed to hazardous wildfire smoke in her hometown. As a teenager, she participated in the Great March for Climate Action, marching 1,600 miles from Nebraska to D.C. *Time Magazine* recognized Kelsey as a Rising Star in its list of the Next 100 Most Influential People in the World.



Vic Barrett, 21, White Plains, NY

A Garifuna American, Vic has spoken about environmental justice issues and how his climate anxiety is increased because his identities—first generation, trans, indigenous, Latinx, Black, youth—make him uniquely vulnerable to the climate crisis. In 2019, he testified at a historic joint hearing of the House Foreign

[4] *https://www.youtube.com/watch?v=C1g2K4DRxLo&feature=emb*_title.

[5] *https://www.youtube.com/watch?feature=youtu.be&v=sd5K1ms1tOc*.

Affairs and Select Committee on the Climate Crisis alongside Greta Thunberg.

Jaime Butler, 20, Flagstaff, AZ

Jaime is of the Tangle People Clan, born of the Bitterwater Clan. She grew up in Cameron, Arizona on the Navajo Nation Reservation, but had to move due to water scarcity and failed attempts at dryland farming. Jaime knows firsthand the cultural and spiritual impacts of climate change as she and her tribe struggle to participate in their traditional ceremonies due to climate-related impacts.

Levi Draheim, 13, Satellite Beach, FL

Levi has lived most of his life on a barrier island in Florida, barely above sea level and literally washing away due to sea level rise and storms made worse by climate change. In 2019, Levi addressed a youth stakeholder's meeting with Members of the Senate Democrats' Special Committee on the Climate Crisis at the United Nations Foundation. His baby sister is a source of motivation and inspiration.

Xiuhtezcatl Martinez, 20, Boulder, CO

Xiuhtezcatl is a renowned hip-hop artist and activist. He is also the former Youth Director and now Co-Chair of the executive board for Earth Guardians. He has experienced extreme weather events that have been exacerbated due to climate change, such as catastrophic flooding. Raised in the Aztec tradition, Xiuhtezcatl has spoken at the United Nations several times, including in English, Spanish, and his Native language, Nahuatl.

Exhibit B: Impact statements for plaintiffs—Jacob Lebel, Alex Loznak, and Jamie Butler

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United States District Court
District Of Oregon
Eugene Division

KELSEY CASCADIA ROSE JULIANA; XIUHTEZCATL TONATIUH M., through his Guardian TAMARA ROSKE-MARTINEZ; *et al.,* Plaintiffs, v. The United States of America; BARACK OBAMA, in his official capacity as *President* of the United States; *et al.,* Federal Defendants.	Case No.: 6:15–cv–01517–TC Declaration of JACOB LEBEL In Support of Plaintiffs' Opposition to Defendants' Motion to Dismiss; Oral Argument: February 17, 2016, 2:00 p.m.

I, Jacob Lebel, hereby declare as follows:

1. I am an eighteen-year-old resident of Roseburg, Oregon and a United States citizen. In 2001, I moved with my family from Quebec, Canada to Roseburg. We

came to the West Coast to find a place of natural beauty and mild weather where we would be able to start a farm and live a sustainable lifestyle.

2. I am currently a 3.9 GPA student at Umpqua Community College and Vice-President of the College's Environmental Sustainability Club.

3. My family founded Rose Hill Farms in Roseburg, Oregon. The Farm extends over 350 acres, providing milk, eggs, meat, vegetables, fruits, nuts, and products such as wool and timber to me, my family, and members of the local community. Our animal breeding programs help preserve endangered and unique heritage livestock breeds. The Farm is currently transitioning towards meeting all of its energy needs through solar and hydroelectric power produced onsite.

4. I intend to continue working and living on the Farm as an adult and I currently take an active role in managing and growing the business. Thus, the economic future and sustainability of the Farm is very closely tied to my own future. The Farm provides me with fresh, healthy food and recreational opportunities and I would like to see my own children in the future have these same benefits.

5. My connection to the Oregon wilderness and to Rose Hill Farms is deeply personal. As a child, I was homeschooled and spent most of my free time playing in the fields and forests around our house. Family trips included swimming in the South Umpqua and hiking the forests around Crater Lake, Mount Thielsen, and Toketee Falls. As a teenager, I wrote poetry and composed songs drawing on the natural beauty that surrounded me on the Farm.

6. My recreational and aesthetic interests are harmed by Defendants' actions to continue producing greenhouse gases at a dangerous rate. I regularly see bird species on the Farm, such as the American Bald Eagle, the Allen's Hummingbird, the Spotted Owl, and the Ruffed Grouse. These species are seeing their survival threatened by a changing climate and their range may no longer extend to Douglas County. Drought conditions and wildfire activity also severely affect the plant biodiversity in Oregon, as well as the state's rivers, watersheds, and snowpack.

7. Defendants' enabling of and lack of action against climate change have created an unsafe climate for the future of Rose Hill Farms. In the summer of 2015, Douglas County experienced two major wildfires: the Cable Crossing and Stouts Creek Fires. Combined, these fires burnt 28,000 acres. The massive smoke cloud from the Stouts Creek Fire was clearly visible from my family's Farm. Smoky and hazy skies became a norm for me during the summer of 2015, affecting my enjoyment of outside work and hiking on my family's Farm. This was compounded by record temperatures and heat waves that stressed the garden crops and livestock and increased my workload, while also making it harder and more dangerous to work long hours in the heat.

8. Rose Hill Farms contains seven permanent structures and three greenhouses. These structures include the house where I grew up and currently live and a cabin hand built out of wood harvested from our own forests and milled in our workshop. As a young adolescent, I helped lay planking on the walls and roof and varnish the structure. This cabin and our entire infrastructure is now at heightened risk from increased wildfire activity in Douglas County.

9. Approximately four-hundred fruit and nut trees grow on our Farm, many of them over thirteen years old. I take special pleasure in walking through the groves of Asian pear and peach trees and picking ripe figs and pomegranates from our plantations. As a small boy, I helped plant many of these trees and they are part of the heritage I want to pass on to my children. In addition to the spiritual and aesthetic meaning these orchards have for me, they represent a significant economic asset for my family and me, bringing in roughly $20,000 in revenue every year.

10. In the past 4 years, Rose Hill Farms has experienced an infestation of a new invasive insect pest called the Spotted-Wing Drosophila (*Drosophila Suzukii*). The Suzuki fly, which lays its eggs in unripe soft fruits, has become a serious problem for the entire Northwest fruit and berry industry. A warmer climate promotes the spread of the Suzuki fly population and other insect pests by increasing their metabolisms and allowing them to overwinter safely. Weather extremes, such as droughts in summer and heavy rains in spring and winter, also stress the fruit trees and decrease their ability to defend themselves from fungal infections and pest attacks. Since the Suzuki fly infestation started, I have had to put in extra hours of labor each summer in order to cope with the increasing frequency of sprays needed to protect the crops.

11. As a result of the Suzuki fly invasion, the Farm has incurred crop losses to our nectarine, peach, and cherry orchards, amounting to approximately $20,000. More gravely, due to their foreign qualities, there is currently no organically approved pesticide that effectively combats these particular pests without relying on a repetitive usage leading to resistance. For the first time, we have been forced to spray non-organically approved pesticide on our trees in order to save the crops.

This spraying prevents us from attaining organic certification on any farm products for 5 more years after we stop using this pesticide and represents an incalculable loss of profit from our operation.

12. Rose Hill Farms contains five ponds that fill from rainfall and groundwater during the winter and provide all the water for our livestock, gardens, and orchards during the summer. During the summer of 2015, for the first time in the 10 years since the ponds were excavated, I watched them run dry due to drought conditions. We were forced to ration irrigation water during a summer which saw the highest June temperatures ever recorded across Oregon.

13. Water shortages due to drought conditions have forced my family to begin implementing an extended water collection and irrigation system, which includes three additional ponds and a large scale solar pumping and water transport system. Costs for the project are projected to reach $15,000.

14. I also enjoy winter recreation and sports, including snowboarding, sledding, and hiking in the snow. Having spent the first 3½ years of my life in Canada, recreating in cold weather and deep snow with my family helps me reconnect with my roots. I learned to snowboard at the Mount Hood ski resort and retain magical memories of soaking in the snowy outdoor spa and pool and enjoying the breathtaking winter vistas.

15. Rising global temperatures caused by Defendants as set forth in our Complaint are already affecting my ability to enjoy activities that require snow. Due to an historic lack of snow last year, the Mt. Ashland ski resort remained closed throughout the winter of 2014, Mount Hood received record low snowfall, and the Willamette Pass resort was only open for a handful of days. That winter, we had been planning a skiing/snowboarding trip to the Willamette Pass Resort, which we were forced to cancel.

16. Every year since 2010, my family has rented a cabin in Bandon on the Oregon coast for several days to a week. During these annual visits, I enjoy walking the shoreline and exploring the caves exposed by low tide. I want to be able to bring my own children to marvel at the sea stars and crabs in tidal pools. However, due to rising sea levels and changing ecology, this stretch of coastline and many of the species that inhabit it will not be available for recreation and enjoyment by my family and me.

17. I vividly remember going on my first crabbing trip. The excitement of reeling in a pot full of the brilliantly colored crustaceans and then being able to cook and eat them fresh off the boat was unprecedented for me. This opening of the 2015 Dungeness crab season in Oregon was unusually delayed from its usual December 1st date and was still closed on Jan 3rd. In California, the crab season traditionally starts even earlier (on November 15th); it also has yet to open. This has been officially attributed to an unprecedented toxic algae bloom triggered by warmer ocean temperatures. Ocean acidification is endangering the survival of the crabs and all the shelled seafood that I consume.

18. In addition to crab fishing, which I intend to continue if possible, my family and I receive monthly deliveries of fresh seafood from Port Orford Sustainable Seafood. These deliveries form an integral part of my regular diet and include Dungeness crab and clams. This winter we were told there would be no crab available for Christmas.

19. My family and I also often procure a permit to harvest mussels from seashore rocks in Bandon, Oregon. However, algae bloom biotoxins are forcing Oregon officials to restrict mussel harvesting for longer and longer periods. It is not easy for me to find a time for a seaside trip when the mussels are safe to eat. Furthermore, oyster, mussel, and clam populations are already shrinking due to ocean acidification and lack of oxygen. The effects of ocean acidification and ocean warming stemming from Defendants' actions are already affecting my food supply and my ability to personally participate in activities such as crab-fishing and mussel gathering.

20. The expansion and creation of new fossil fuel infrastructure, such as the proposed Jordan Cove Project in Southern Oregon, conducted as a result of Defendant's energy policies, also threaten my family's Farm and my way of life.

21. The border of the Farm is located approximately 1 mile from the route of the proposed Pacific Connector Pipeline. If built, the pipeline and the associated 100–150′ wide clear-cut may be visible from scenic points on the Farm where I regularly hike. This would cause me significant emotional distress and harm my enjoyment of the Farm.

22. According to testimony by oyster farmers such as Lili Clausen of Coos Bay, silt and water conditions that would be created by construction of the Pacific Connector Pipeline and Jordan Cove liquification factory would harm oyster beds. The oysters that I eat are mostly bought locally in Coos Bay and construction of this project would harm this important food supply.

23. If built, Jordan Cove would be the single biggest emitter of greenhouse gases in Oregon once the Boardman Coal-Fired Power Plant closes in 2020. The pipeline would require a clearcut through old-growth, carbon sequestering forests. This project would contribute to climate change and worsen its impacts on my life.

24. The danger of explosions along the length of the Pacific Connector Pipeline would heighten the risk of a wildfire starting nearby to our Farm. Williams Pipeline, the company that would build the pipeline, has already had four explosion incidents on its pipelines and facilities. Coupled with already severe fire seasons and drought conditions, the Pacific Connector Pipeline would put my family's Farm in constant danger. These extreme climate conditions created by Defendants and the continuation of fossil fuel production projects such as Jordan Cove are harming my daily life as well as my future ability to enjoy and sustain myself.

I certify under penalty of perjury in accordance with the laws of the State of Oregon, and to the best of my knowledge, that the foregoing is true and correct.

Dated this 5th day of January, 2016 at Roseburg, Oregon.

Jacob Lebel
JACOB LEBEL.

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United States District Court
District Of Oregon
Eugene Division

KELSEY CASCADIA ROSE JULIANA; XIUHTEZCATL TONATIUH M., through his Guardian TAMARA ROSKE-MARTINEZ; *et al.*,
Plaintiffs,

v.

The United States of America; BARACK OBAMA, in his official capacity as *President* of the United States; *et al.*,
Federal Defendants.

Case No.: 6:15–cv–01517–TC

Declaration of ALEXANDER LOZNAK In Support of Plaintiffs' Opposition to Defendants' Motion to Dismiss;

Oral Argument: February 17, 2016, 2:00 p.m.

I, Alexander Wallace Loznak, hereby declare as follows:

1. I am a nineteen-year-old Oregon resident, a United States citizen, and a Plaintiff in this action. My family lives on the Martha A. Maupin Century Farm in the unincorporated rural area of Kellogg, Oregon.

2. *My Educational Background:* I graduated as one of the valedictorians of the Class of 2015 at Roseburg High School in Roseburg, Oregon, and I am currently an undergraduate student at Columbia University in New York City. In the summer of 2014, I attended The American Legion's Oregon Boys State program. At Boys State, I was awarded an academic scholarship from The American Legion and Samsung "[f]or excellence in academic pursuits and dedication to the community, attributes which are in keeping with the efforts of the U.S. service men and women who helped maintain freedom for the citizens of South Korea."

3. *My History of Climate Advocacy:* Fighting climate change is one of the central objectives of my life. I chose to attend Columbia University to have an impact on issues of global significance, including the climate crisis. In my application to Co-

lumbia, I stated "young people—who will inherit either a broken world or a vibrant one—must take the lead" in addressing climate change.

4. In Oregon, I have advocated for local solutions to the climate crisis. I started the Climate Change Club at Roseburg High School, and the League of Umpqua Climate Youth ("LUCY"), with the goal of installing solar panels at Roseburg High School.

5. I have lobbied Oregon state legislators to pass House Bill 3470, which would create market-based incentives to reduce carbon dioxide emissions. Additionally, I have advocated for Federal policies to curtail climate change. In the summer of 2013, I wrote a letter to President Obama, asking him to take comprehensive action to limit fossil fuel extraction and carbon dioxide emissions. A true and correct copy of my letter to the President is attached as *Exhibit 1.**

6. *My Opposition to Jordan Cove:* I am actively opposed to the construction of the Pacific Connector Natural Gas Pipeline and the Jordan Cove Energy Project. In November 2013, I wrote an op-ed in the *Roseburg News-Review* to advocate that the Douglas County Planning Commission deny a permit for the pipeline. In December 2014, I spoke in opposition to the pipeline at a Federal Energy Regulatory Commission hearing in Roseburg.

7. *The Effects of Climate Change on My Family's Farm:* The Martha A. Maupin Century Farm, my permanent residence, contains 570 acres of land and sits along the Umpqua River. My great-great-great-great-grandmother, Martha Poindexter Maupin, founded the farm in 1868 after crossing the Oregon Trail. This farm is one of the few Century Farms in Oregon named for a woman.

8. My grandmother, Janet Fisher, is the current owner of the farm. In 2014, my grandmother had a book published by Globe Pequot Press about Martha's life, *A Place of Her Own: The Legacy of Oregon Pioneer Martha Poindexter Maupin.* The book describes Martha's experience when she discovered the Kellogg Crescent area along the Umpqua River, where the farm is located: "*She nudged her horse and rode over a gentle rise across a saddle of land to a broad overlook. Her breath caught. She could see the valley, the river, a plain on the far side, and mountains beyond. A breeze stirred, like a whisper saying, 'Come.'*"

9. The farm is my intellectual and spiritual base, and a foundational piece of my life and heritage. My family has passed the farm from generation to generation, and my identity and well-being depend on the preservation and protection of the farm. I want to explore the farm with my children someday, and I plan to eventually move back to the farm. Unfortunately, drought conditions, unusually hot temperatures, and climate-induced migration of forest species are harming and will increasingly harm my use and enjoyment of the Martha A. Maupin Century Farm.

10. Agricultural produce from the farm is an important source of revenue and food for my family and me. Because I am a student with little income, my financial survival depends in large part on the continued productivity of the farm. On the farm, my family grows timber trees, plum trees, and hazelnut trees. We rent pasture for grass-fed beef cattle. We also have a large garden, in which we grow many of the fruits and vegetables that we consume. We raise chickens for eggs we consume. Climate change, caused in substantial part by the Federal Defendants, adversely impacts the productivity of the farm and threatens my financial survival.

11. *How Defendants Are Harming My Use of the Farm:* Recordsetting heat waves, drought, and fire in the region of my farm, caused in substantial part by the Federal Defendants, harm my ability to work outside on the farm during the summer months. The heat waves and drought adversely impact the productivity of the farm, especially my family's hazelnut orchard and timber trees.

12. Exact temperature records are not available for the farm, but the temperature at the farm is usually very close to the temperature in Roseburg, Oregon. According to the National Weather Service, the average temperature in Roseburg for summer 2015 (June through August) was 74° Fahrenheit, making it the hottest summer ever recorded there. The two previous records were 71.8° and 71.6°, set in 2014 and 2013 respectively.

13. July 30, 2015 tied the record for the hottest day ever recorded in Roseburg, with a high of 108° Fahrenheit. June 27, 2015 set the record for the highest-ever low temperature. That means at night, the lowest it got was 74°. The lowest temperature at night had never been so high. At the end of June 2015, temperatures repeatedly exceeded 100°.

14. Drought came with the heat, and on June 11, 2015, Governor Brown declared a drought emergency for Douglas County, where Roseburg and the farm are located.

* **Editor's note:** *Exhibit 1* was not included in Our Children's Trust submission for the record of the hearing.

15. In 2011 and 2012, my family planted a 7 acre hazelnut orchard on the farm, in the fertile plain next to the Umpqua River. Hazelnuts have historically grown well in Oregon, and according to the Oregon Hazelnut Growers Office, our state produces 99% of the U.S. hazelnut crop. Planting the orchard on our farm required an investment of about $7,400.00 in capital costs. We also planted two new acres of plums, which required an investment of just over $1,000.00 in capital costs. The planting was also an investment of time and energy, and I dug holes in the ground for many of the baby trees. We have plans to plant as many as 15–20 additional acres of hazelnut trees in the future. Unusually hot temperatures and drought conditions, caused in substantial part by the Federal Defendants, adversely impact the health of the existing hazelnut orchard and diminish the viability of any additional plantings.

16. Record-setting heat in the summer of 2015 caused our new hazelnut trees on the farm to wither. The orchard is not irrigated, so my father and I had to provide more water than usual. We watered the trees one at a time with a tractor, which required considerable added man-hours of labor. Based on information from the late Jeff Olsen, a former horticulturist from Oregon State University, we had not expected to need to water the hazelnut trees that were planted in 2012 at all in 2015. We believed that the trees planted in 2012 would be old enough to survive the summer without watering. However, even the 2012 crop required extra water in the scorching-hot summer of 2015.

17. Every summer since they were planted, some trees have died, requiring my family to buy and plant new ones. Abnormal heat due to climate change added to these losses. Future heat waves and drought endanger our dream of a large, thriving hazelnut orchard.

18. Another source of revenue for my family is sustainable harvest of Douglas fir trees for lumber. Our farm is Sustainable Forestry Initiative-certified, and we take great pride in our role as keepers of the land. The total value of merchantable timber owned by my grandmother on the farm is approximately $400,000.00, using calculations based on a 2007 timber cruise conducted by Barnes and Associates, Inc. of Roseburg, Oregon. Additionally, there are roughly 128 acres of young trees, valued currently at about $120,000.00, which will steadily increase in value and become merchantable in the coming decades. Wildfires, which are increasing in frequency and intensity from the changing climatic conditions caused in substantial part by the Federal Defendants, threaten to destroy my family's timber.

19. Increased drought and heat waves, caused in substantial part by the Federal Defendants, make it difficult for new timber trees to grow after cutting. For example, last year my father replanted a small acreage of Douglas fir trees on the farm. These trees were located on a southwest-facing slope, which exposed them to the elements and made them especially sensitive to heat. Unusually high temperatures during the summer of 2015 killed most of the trees. We now have to replant this section again. While this particular planting was done by my father at no capital cost, other plantings have typically run about $176 per acre for trees and labor.

20. Increased fire risk and longer fire seasons make it difficult to operate machinery on the farm in the summer months. For example, hot temperatures limit the times of day when chainsaws can be used.

21. My family uses firewood to heat our home in the winter, and we typically cut firewood in the summer. The Douglas Forest Protective Association ("DFPA") issues rules for the use of machinery outdoors during fire season in Douglas County, where the farm is located. Due to high summer temperatures, the DFPA frequently issued Fire Precautions of Level II and above in 2015, prohibiting the use of chainsaws outdoors between the hours of 1:00 p.m. and 8:00 p.m. This forced my family to limit woodcutting to the morning and nighttime hours. Unusually hot temperatures, caused in substantial part by the Federal Defendants, have made it increasingly difficult to find times to cut sufficient firewood.

22. My family has designated certain wooded areas on the farm not to be cut, and these areas are of particular aesthetic and spiritual significance to me. I discovered these areas as a little boy, and I want these areas to remain intact into my old age. One protected area is a grove of Douglas Fir trees that are nearly 80 years old. A picture hangs in my grandmother's office of her late father, Gene Fisher, walking through these trees in his overalls and a baseball cap. Grandpa Gene named the area The Cathedral, perhaps because the trees look like pillars, or perhaps because of the way the light filters through their branches. Protected areas such as The Cathedral are threatened by the increased drought, heat waves, and wildfire risk caused in substantial part by the Federal Defendants.

23. The farm is home to many different species of wildlife, including bears, mountain lions, reptiles, amphibians, and birds, which I enjoy seeing. In particular, I enjoy visiting ponds in the spring and summer, when they are teeming with Pacific

Tree Frogs and Rough-Skinned Newts. My family hunts deer, elk, and wild turkeys to provide food. In the summer, I catch bass from the Umpqua River for food. Each of these species of wildlife is adversely impacted by climate change caused in substantial part by the Federal Defendants. Changing migration patterns and availability of food species harms my and my family's sources of sustenance and interest in living off of our land's bounty.

24. I enjoy fishing for steelhead and salmon on the Umpqua River where it runs by the farm. Sea level rise, increasing water temperature, ocean acidification, and drought, caused in substantial part by the Federal Defendants, are harming, and will increasingly harm, salmon and steelhead populations. In the summer of 2015, the Oregon Department of Fish and Wildlife curtailed salmon fishing on rivers including the Umpqua due to stress on salmon from abnormally high water temperatures and low stream flows.

25. I enjoy swimming in the Umpqua River where it runs past the farm. Increased summer temperatures contribute to toxic algae blooms, which can make it unsafe to swim in the river. In 2009, four dogs were killed by toxic blue-green algae in Elk Creek, a tributary of the Umpqua River, about 5 miles from my home. The state issued a health advisory for Elk Creek and adjacent sections of the Umpqua River, and I abstained from swimming in the river for several weeks after the incident for fear of toxic algae.

26. *How Defendants Are Harming My Recreational Interests:* In addition to recreating on the farm, I also enjoy recreating at other locations in Oregon, such as the forests surrounding the North Umpqua River. One of my favorite places to recreate is the area around Twin Lakes, along the North Umpqua River, where two bright-blue lakes are surrounded by old-growth forest. I enjoy hiking, swimming, camping, and other activities along the North Umpqua River and I have plans to continue doing these activities each year in the immediate future. The forests surrounding the North Umpqua River are threatened by the increased number and severity of wildfires caused in substantial part by the Federal Defendants.

27. In the summer of 2015, two large wildfires—the Cable Crossing and Stouts Creek Fires—burned a combined total of over 28,000 acres in Douglas County. Massive columns of smoke from both fires were visible from Roseburg, and the plume from the Stouts Creek fire was visible from my family's farm. Seeing the columns of smoke caused significant distress for my family and me.

28. Both fires burned in areas where I had previously recreated. Due to the Cable Crossing Fire, my friends and I were unable to camp along the North Umpqua River on the weekend of July 30, 2015, which we would have done but for the fires.

29. In the winter, I enjoy recreating with my friends in the snow in the Oregon Cascades. I have many fond memories of sledding, snow fights, and hot chocolate at Diamond Lake, including one time in eighth grade, when two of my friends tried to bury me in the snow. Decreased snowpack as a result of warmer temperatures caused in substantial part by the Federal Defendants will adversely impact my enjoyment of the forest in winter. My participation in winter sports such as skiing and snowshoeing will be particularly affected.

30. I also enjoy recreating along the Oregon Coast. My family occasionally goes crabbing for food, and I enjoy eating fresh seafood at restaurants on the coast. Some of my favorite activities include beachcombing and tide-pooling. Sea-level rise and ocean acidification, caused in substantial part by the Federal Defendants, are increasingly harming the delicate coastal ecosystems where I recreate.

31. When I was eleven years old, my family and I visited a beach at Cape Arago State Park, along the Southern Oregon Coast. To my wonderment, I found dozens of Purple Shore Crabs, each no more than 1″ or 2″ in length, hiding under the rocks. There are thousands of crabs there, all of them along just a small section of shoreline. I have returned to that beach several times, and plan to do so again in the immediate future. If the Federal Defendants' actions to allow and promote unsafe levels of carbon pollution are not stopped, sea level rise and ocean acidification will dramatically alter the narrow ecological band in which the crabs exist.

32. Another location on the coast where I enjoy recreating with my family is Sea Lion Caves, near Florence, Oregon. Sea Lion Caves is the largest sea cave in the United States, and it is inhabited by dozens of elegant Stellar Sea Lions. The sea lions are visible as they rest on rocks inside the cave. Multi-meter sea level rise could permanently submerge many of the rocks, making the cave inhospitable to the sea lions. The ocean ecosystem that supports the sea lions will also be increasingly damaged by ocean acidification and abnormally high sea surface temperatures due to climate change. I plan to return to Sea Lion Caves with my own children someday and hope that a healthy population of sea lions continues to live there.

33. I enjoy hiking in Northern Washington and Glacier National Park, where I have seen glaciers receding due to climate change. I plan to return to Montana and

Washington in the next several years, and I also want to travel to Alaska. My recreational and aesthetic interests are harmed as the glaciers continue to disappear before I can visit them.

34. In the summer of 2012, I hiked to the top of Desolation Peak in North Cascades National Park in Washington. At the top of the mountain is a fire-spotting cabin where author Jack Kerouac served as a lookout in 1956 and drew the inspiration for his books *The Dharma Bums* and *Desolation Angels.* In *The Dharma Bums,* Kerouac describes the land surrounding Desolation Peak as "hundreds of miles of pure snow-covered rocks and virgin lakes and high timber." I met a fire-spotter from the National Park Service there. He told me that, if you look at a picture from one hundred years ago, the glaciers on the surrounding mountains are twice the size they are today. In that moment, I knew that climate change would become a central theme of my life.

35. *My Health Has Been Affected:* Recent summers at home have become increasingly smoky due to the increased severity and number of wildfires in southern Oregon. I have asthma, which is aggravated by the smoke. Increased pollen due to unusually warm temperatures also aggravates my asthma and allergies. When I am suffering from asthma and allergies, my outdoor activities are limited, which harms both my ability to work on the farm and my ability to recreate and enjoy the special forests and rivers surrounding my home. My asthma and allergies will continue to worsen as climate change worsens and air quality during the summer months continues to decline.

36. *How I Am Affected By the Export Authorizations for the Jordan Cove Project:* My family's farm is only about 30 miles from the route of the proposed Pacific Connector Natural Gas Pipeline, which would connect to the Jordan Cove Liquefied Natural Gas Terminal at Coos Bay. The Jordan Cove Terminal would be the largest single source of greenhouse gas emissions in the State of Oregon after the scheduled closure of the Boardman Coal-Fired Power Plant in 2020.

37. The potential climate impact of the Jordan Cove Energy Project becomes much larger when one also considers upstream emissions from the extraction and transport of the natural gas, as well as downstream emissions from the combustion of the fuel. Natural gas is made up primarily of methane, which is a potent greenhouse gas. This means that significant emissions would result from methane leakage during extraction and transport of natural gas for the Jordan Cove Project. Additionally, according to the Pacific Connector website, the pipeline would carry up to 1 billion cubic feet of natural gas per day. The CO_2 released from burning that much natural gas would be equivalent to the emissions from over four million typical passenger cars. Clearly, the construction of the Jordan Cove Energy Project would contravene Governor Brown's stated goal to reduce Oregon's greenhouse gas emissions.

38. The pipeline would cross 400 bodies of water in Oregon, including two locations along the South Umpqua River where I have visited and recreated and intend to return in the immediate future. I have visited sections of the route in Southern Douglas County and the intersection of the route with the famous Pacific Crest Trail. A roughly 100–150′ wide clearcut would be required for the pipeline, causing substantial damage to these wild places that I enjoy for recreation and aesthetic value. I would particularly love to hike the Pacific Crest Trail again in the near future, and I hope not to see it scarred by the pipeline project. A true and correct picture of me at the intersection of the Pacific Crest Trail and the proposed pipeline route is included as *Exhibit 2.***

39. While walking along the pipeline route, I was shocked to discover that workers on public land had already spray-painted numbers and markers on old-growth trees to be cut, even though the pipeline has not yet received all necessary local, state, and Federal permits. I was particularly horrified that workers had spray-painted trees adjacent to the Pacific Crest Trail. In my view, this defacement of trees demonstrates the pipeline company's confidence-based on its existing authorization from the Department of Energy to export the LNG—that it will receive the rest of its permits, despite the project's severe impacts on the climate and local environment.

40. One specific location on the pipeline route that I visited was near Callahan Ridge, on Bureau of Land Management property in southern Douglas County (Township 31s, Range 3w, the NW quarter of section 25). A few weeks after I visited the location, the Stouts Creek Fire burned this area of the forest. The Stouts Creek Fire directly impacted at least a dozen miles of the pipeline route, with the proposed location for an aboveground valve inside the fire perimeter. If constructed, the pipe-

** **Editor's note:** *Exhibit 2* was not included in Our Children's Trust submission for the record of the hearing.

line would carry highly pressurized, explosive natural gas through Oregon's fire-prone forests, with 17 valves located above ground. This would further harm my interests in protecting the places where I recreate from the increasing ravages of climate change caused in substantial part by the Federal Defendants.

41. In an April 6, 2015 letter to the Federal Energy Regulatory Commission ("FERC"), the U.S. Army Corps of Engineers asked that FERC assess "the impacts of large trees, stumps or slash catching on fire during a forest fire event and landing over the buried pipeline and how that could affect the ground temperature and buried pipeline integrity/safety." Additionally, in a September 9, 2015 letter to FERC, Douglas County Commissioner Chris Boice asked that FERC evaluate "[h]ow . . . a wild land fire [would] impact the integrity of pipeline construction and infrastructure both before and after a wild land fire."

42. Williams Pipeline, the company that would construct Pacific Connector, has had four explosions at other pipelines and facilities in the past. Leaking pipelines around the country, like the now-infamous Sempra pipeline in Porter Ranch, California, demonstrate how common and likely pipeline accidents are, and the risks they will pose in my community in southern Oregon. The increased possibility of wildfires in places I have visited, such as the area around Callahan Ridge, would compound the risk of catastrophic accidents.

43. The Federal Defendants' disregard for the impacts of wildfires on the pipeline mirrors the Federal Defendants' broader disregard for the impacts of fossil fuel extraction and combustion on our climate system. Changes to the climate system increasingly harm my way of life, and direct environmental impacts from the construction of the Jordan Cove Energy Project threaten to do so as well.

I certify under penalty of perjury in accordance with the laws of the State of Oregon, and to the best of my knowledge, that the foregoing is true and correct.

Dated this 5th day of January, 2016 at Kellogg, Oregon.

Alex Loznak

ALEXANDER WALLACE LOZNAK.

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United States District Court
District Of Oregon
Eugene Division

KELSEY CASCADIA ROSE JULIANA; XIUHTEZCATL TONATIUH M., through his Guardian TAMARA ROSKE-MARTINEZ; *et al.,* Plaintiffs, v.	Case No.: 6:15–cv–01517–TC Declaration of JAIME B. In Support of Plaintiffs' Opposition to Defendants' Motion to Dismiss;

The United States of America; BARACK OBAMA, in his official capacity as *President* of the United States; *et al.,* Federal Defendants.	Oral Argument: February 17, 2016, 2:00 p.m.

I, Jaime Lynn Butler, hereby declare as follows:

1. I am a 15-year-old citizen of the United States and resident of Window Rock, Arizona. I am a freshman in high school at Colorado Rocky Mountain School in Carbondale, Colorado. My family and I are already experiencing harm caused by climate change and I am worried we'll experience even more severe climate impacts in the immediate future.
2. I am a member of the Navajo Nation. My clan is Tangle People Clan, born for the Bitter Water Clan, with my maternal grandfathers of the Red House Clan and my paternal grandfathers of the Towering House Clan. I am a member of the Grand Canyon Sierra Club, which is where I first learned about climate change. In 2011, frustrated by my state's lack of action to combat climate change, I filed a lawsuit against the governor of Arizona for violating her duty to protect the atmosphere as a resource under the public trust doctrine.
3. I grew up in Cameron, Arizona, on the Navajo Nation Reservation. In 2011, my mom and I had to move from Cameron to Flagstaff because of drought and water scarcity. My extended family on the Reservation remember times when there was enough water on the Reservation for agriculture and farm animals, but now the springs they once depended on year-round are drying up. My mom and I were not able to live sustainably on the Reservation because of the costs of hauling water into Cameron for us and our animals. I am worried that my extended family, all of whom live on the Reservation, will also be displaced from their land, which would erode my culture and way of life. Participating in sacred Navajo ceremonies on the Reservation is an important part of my life, and climate impacts caused by the acts of Defendants are starting to harm my ability, as well as the ability of my family and tribe, to participate in traditional ceremonies. Ceremonies are governed by phases of the moon and seasons. The dry climate and extreme winds have spread the invasive plant species (Camel Thorn) and they have replaced grasslands, river banks are in accessible due to Tamarack, water wells need to be replaced with deeper wells etc. All of this affects our ability to offer livestock, food and water for ceremonies. Ceremonies often require objects secured in nature that were once plentiful IE. medicinal plants, hides, and feathers *etc.* Now they are not, scarcity means they cost more or are no longer available.
4. Once we moved off the reservation, we moved to the outskirts of Flagstaff, along the Kaibab National Forest. The forest there, was my favorite place to spend time. I find peace being outside in the forest surrounding my home, and when I was home I spent hours each day walking in the forest.
5. Large parts of the Kaibab National Forest have been destroyed due to pine beetle infestations and forest fires, both of which are caused by, or exacerbated by, fossil fuel emissions authorized by the Federal Defendants. The emissions cause warmer temperatures, which lower the resistance of the trees to the infestations. The hotter temperatures, drought, and pest infestations dry the forest, making it more susceptible to wildfires. I have seen the beetles and they are huge and ugly.
6. In 2014, my mom and I were evacuated from our home for 2 days because of the Oak Creek Canyon fire north of our home. Winds brought smoke and ash into our neighborhood. I'm worried that the area surrounding my home is becoming unsafe due to an increase in drought conditions and forest fires caused by the acts of Defendants in permitting, subsidizing, and otherwise allowing unrestrained fossil fuel emissions.
7. As a result of the pine beetle infestations and forest fires caused by the acts of Defendants, my ability to spend time in the Kaibab National Forest has been limited and will be limited in the immediate future.
8. I have been negatively affected by the increasing temperatures, which limits the time I'm able to safely spend time outdoors. Hotter temperatures and drought also negatively impact the vegetables we grow for food on our property in Flagstaff. Our water bills go up to irrigate our little garden, but the worst problem is how quickly the garden dries up if we are away for an extended time. Also the forest animals (raccoons, coyotes and rabbits) come into

our yard, over the fencing to access our water or garden. On the reservation we simply stopped farming. Although we had dryland farmed using drought resistant corn, relying on winter snow, the dry topsoil was too deep to find damp earth over 12 inches in most places. Nothing would grow, so we stopped our efforts. Fewer and fewer people farm, especially dryland farming.

9. My severe allergies have become increasingly worse over the last several years. I take over-the-counter medication to combat my symptoms. In the forest it is spring and summer pollens, in the desert on the reservation, it is the dust and sandstorms that make life very hard. I find my family gets sore throats during windy times, especially summer, as the dust affects our breathing.
10. With record-setting temperatures and a drought that has lasted several years, I fear for my future and for the future of my family, our history, our traditions, and our way of life.

I certify under penalty of perjury in accordance with the laws of the State of Arizona, and to the best of my knowledge, that the foregoing is true and correct.

Dated this 5 day of January, 2016 at Flagstaff, Arizona.

JAIME LYNN BUTLER.

Exhibit C: Expert Report of Dr. G. Philip Robertson

Expert Report of

G. PHILIP ROBERTSON
University Distinguished Professor of Ecosystem Ecology
Michigan State University

KELSEY CASCADIA ROSE JULIANA; XIUHTEZCATL TONATIUH M., THROUGH HIS GUARDIAN TAMARA ROSKE-MARTINEZ; *et al.,*

Plaintiffs,

v.

The United States of America; DONALD TRUMP, in his official capacity as President of the United States; *et al.,*

Defendants.

In the United States District Court
District Of Oregon
(Case No.: 6:15–cv–01517–TC)

Prepared for Plaintiffs and Attorneys for Plaintiffs:

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Table of Contents

Table Of Acronyms, Abbreviations, and Definitions

BECCS:	bioenergy with carbon capture and storage
C:	carbon
C_{eq}:	carbon equivalent; used to quantitatively compare greenhouse gases via a common metric based on global warming potentials for individual gases
CO_2:	carbon dioxide; contains 27.3% carbon
CO_{2eq}:	carbon dioxide equivalent
EPA:	U.S. Environmental Protection Agency
DOE:	U.S. Department of Energy
GtC:	gigatonne of carbon, equivalent to 1 billion tonnes of carbon, or 1 PgC; 1 GtC = 1,000 MtC
ha:	hectare, equivalent to 2.47 acres
IPCC:	United Nations Intergovernmental Panel on Climate Change
Mha:	million hectares, 1 Mha is equivalent to 2.47 million acres
MtC:	million tonnes of carbon, sometimes abbreviated MMTC; 1,000 MtC = 1 GtC
N_2O:	nitrous oxide
NRCS:	Natural Resources Conservation Service
PgC:	petagram of carbon, equivalent to 10^{15} gC
ppm:	parts per million
tC:	tonne of carbon, equivalent to 1,000 kgC or 10^6 gC
USDA:	U.S. Department of Agriculture

Avoided Emissions: Greenhouse gas emissions not yet released that could be avoided if practices were altered from conventional practices. This includes fossil fuel emissions that are avoided by substituting biofuel combustion for fossil fuel combustion.

Carbon Sequestration: Any process that removes carbon dioxide from the atmosphere and stores the carbon portion in natural sinks like soils.

Negative Emissions: Greenhouse gas (CO_{2eq}) removed from the atmosphere with the carbon portion sequestered for long periods of time—sometimes indefinitely—within natural carbon sinks like soils and forests. In this report, negative emissions are those above and beyond the existing rate of natural sinks.

Federal Land: All U.S. federally-owned or federally-managed lands including forest lands, range lands, other agricultural lands, wetlands, and waterways.

Lands of the United States: All lands, both publicly owned and privately owned, within the boundaries of the United States.

Conterminous lands of the United States: All lands, both publicly and privately owned, within the 48 adjoining states plus the District of Columbia; also known as the contiguous U.S.

U.S. Forests: All forestlands within the United States Federal Forestland: All U.S. federally-owned or federally-managed forestlands.

Introduction

I, G. Philip Robertson, have been retained by the Plaintiffs in the above-captioned matter to provide expert testimony about the potential capacity for improved management of United States forest, range and agricultural lands to achieve net negative carbon emissions and avoid future greenhouse gas emissions. In this report I provide background on the global carbon cycle, describe how different land management practices can contribute to negative and avoided emissions, and provide a quantitative assessment of the potential for changes in management practices to provide meaningful greenhouse gas mitigation.

I have worked in the field of carbon and nitrogen biogeochemistry for 40 years since beginning my Ph.D. studies in 1976. I am currently University Distinguished Professor of Ecosystem Ecology in the Department of Plant, Soil and Microbial Sciences at Michigan State University, where I have held a regular faculty position since 1987. I have been a University Distinguished Professor for the last 7 years. Since 2017 I have also held the title of Scientific Director for the Department of Energy's Great Lakes Bioenergy Research Center at the University of Wisconsin and Michigan State University. For my entire career the main focus of my research has been studying the processes that regulate biogeochemical cycles of carbon and nitrogen at multiple scales, including plant, soil, and microbial interactions that affect the delivery of important ecosystem services such as climate stability, water quality, and plant productivity. I work primarily in agricultural ecosystems, and more broadly on the issue of agricultural sustainability, which includes the responses of cropping systems to climate change and the potential for land management to contribute to greenhouse gas mitigation. My CV, which includes a statement of my qualifications, is contained in **Exhibit A*** to this expert report. A list of publications I authored within the last 10 years is attached as **Exhibit B*** to this expert report.

In preparing my expert report and testifying at trial, I am not receiving any compensation and am providing my expertise pro bono to the Plaintiffs given the financial circumstances of these young Plaintiffs. I have not provided previous testimony within the preceding 4 years as an expert at trial or by deposition. My report contains citations to all documents that I have used or considered in forming my opinions, listed in **Exhibit C*** to this report.

The opinions expressed in this report are my own, not necessarily the opinions of any of the institutions for which I work or donate my time. The opinions expressed herein are based on the data and facts available to me at the time of writing, as well as based upon my own professional experience and expertise. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

Executive Summary

Earth's carbon is found in six reservoirs: rocks, oceans, atmosphere, plants, soil, and fossil deposits. In the carbon cycle, carbon moves from one reservoir to another. The human-induced transfer of carbon from fossil deposits to the atmosphere is causing Earth to warm. Even when that transfer ceases, in order to return the atmospheric reservoir to a point conducive to human well-being, we will need to remove carbon from the atmosphere and store it in other reservoirs. This is known as carbon sequestration or negative emissions. The potential for increased carbon sequestration from U.S. forest, range, and agricultural land management is, at peak, around 0.414 GtC_{eq} per year (414 MtC_{eq} per year). This could result in negative emissions within the U.S. totaling about 21 GtC_{eq} by 2100. Changes to land management practices could avoid the emissions of another 0.12 GtC_{eq} per year, totaling 9.7 GtC_{eq} by 2100. All told, over the period 2020 to 2100, changes to land management practices in the U.S. could mitigate more than 30 GtC_{eq} between 2020 and 2100, which is over 30% of the negative and avoided emissions needed, after phasedown of fossil fuel emissions, to return Earth's atmosphere to a more stable state.

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* **Editor's note:** the Our Children's Trust submission for the record for this hearing ***does not*** include **Exhibits A–C.** It has been reproduced, as submitted, herein. The full report is retained in Committee file and is available at: *http://blogs2.law.columbia.edu/climate-change-litigation/wp-content/uploads/sites/16/case-documents/2018/20180628_docket-615-cv-1517_exhibit-11.pdf*.

Three types of CO_2 removal are most widely discussed today: (1) Improved land management, (2) Bioenergy with CO_2 capture and storage (referred to as BECCS), and (3) Direct air capture. BECCS and direct air capture are both theoretically possible but currently unproven at any meaningful scale, and thus are not analyzed in this report. Of these three, improved land management represents the most mature, technically feasible, widely deployable, and lowest cost option currently available. Thus, this report focuses on improving land management to remove and store CO_2 and to reduce future emissions of three key greenhouse gases—CO_2, nitrous oxide, and methane.

Soil represents one of the largest actively cycling reservoirs of carbon on earth, most of which is stored in the form of soil organic matter, largely comprised of decomposing plant residue. Almost everywhere, conversion of native forest and grasslands to agriculture has resulted in a 30–50% loss of this carbon to the atmosphere as further decomposition to CO_2 is accelerated. Almost all soils actively managed for agriculture, as well those that have been abandoned from agriculture due to degraded fertility, have soil carbon levels well below their original levels, providing significant opportunities to sequester additional carbon.

There are a number of well-tested methods to increase soil carbon through agricultural practices on land used to grow annual crops. Avoiding tillage with no-till technology is one well-recognized practice to rebuild soil carbon. Other practices can be just as effective: adding winter cover crops to avoid bare soil for most of the year can increase soil carbon, as can diversifying crop rotations—growing more than one or two crops in sequence—and applying compost or manure. Growing perennial grasses or trees on degraded or low value agricultural soils can also result in significant carbon gains. On pastures and rangeland, soil carbon storage can be improved by increasing plant productivity via improved plant species and by avoiding over grazing via careful attention to the number of livestock per acre. About 43% of all pasture and rangeland in the U.S. is managed by Federal agencies.

Forests can also be managed to enhance carbon sequestration in trees and soil. Faster growing species accumulate more carbon over their lifetimes and therefore planting more of these species will store more carbon in wood, as will growing trees in longer rotations (the number of years between harvests). A number of management factors can increase forest soil carbon. About 42% of all forestland in the conterminous U.S. is managed by Federal agencies.

In addition to increasing carbon sequestration, changes in land management practices on Federal and private lands can also reduce the amount of greenhouse gas emissions stemming from land use. Nitrous oxide is a greenhouse gas 250–300 times more potent than CO_2. Agriculture is responsible for 84% of global anthropogenic nitrous oxide emissions, and most agricultural emissions (62%) come from soils amended with nitrogen from fertilizers, manures, or legumes. Reducing nitrogen fertilizer rates to those needed for optimum yields is the most reliable means to reduce nitrous oxide emissions from fertilized cropping systems.

Methane is 28–36 times more potent than CO_2. Agricultural methane emissions come from digestive fermentation by livestock (52%), rice cultivation (22%), biomass burning (19%), and livestock manure handling (8%). Rice cultivation practices and livestock management offer important land-use related methane mitigation opportunities. Methane from rice production can be minimized through periodic drainage of flooded rice fields.

Finally, there is an opportunity to reduce greenhouse gas emissions and increase carbon sequestration by growing cellulosic bioenergy crops such as switchgrass on marginal lands that were formerly in agriculture and on lands now used to grow corn for grain ethanol.

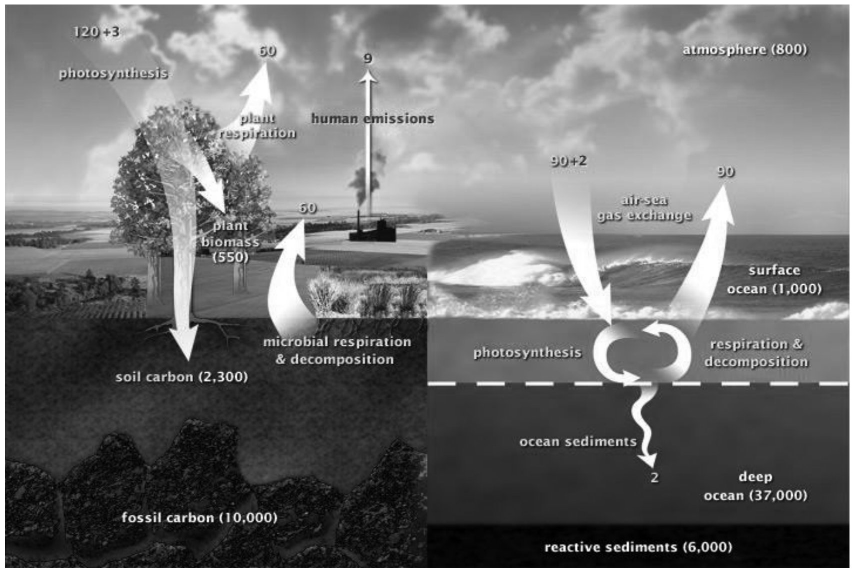
All told, technology is available today to store carbon or avoid future greenhouse gas emissions from agriculture in the U.S. equivalent to more than 30 GtC_{eq} by 2100. Farmers, ranchers, and landowners have shown a willingness to accept payments for implementing such practices. Financial incentives and Federal policies will need to be aligned with the sequestration practices described below in order to achieve this scale of increased sequestration.

Expert Opinion

1.0 Introduction

Carbon is one of the most abundant elements on Earth. Most of the carbon on Earth is stored in rocks. The rest of Earth's carbon is in our oceans, atmosphere, plants, soil, and fossil fuels. Earth's carbon cycle involves the flow of carbon between each of these carbon reservoirs (or sinks). Some of the flow is very slow and some is fast. When carbon moves out of one reservoir it enters another, as depicted in **Figure 1.**

Figure 1



This diagram of the fast carbon cycle shows the movement of carbon between land, atmosphere, and oceans. Yellow numbers are natural fluxes, and red are human contributions in gigatonnes of carbon (GtC) per year. White numbers indicate stored carbon (carbon locked in deep geological reservoirs is not included except for fossil fuel reserves that could be mined). The human contribution, though seemingly small, adds up to a large imbalance and consequent increase in atmospheric CO_2. (*https://earthobservatory.nasa.gov/Features/CarbonCycle/*)

The atmosphere's CO_2 content is largely determined by the balance between processes that remove CO_2 from the atmosphere, such as photosynthesis and CO_2 absorption by seawater, and processes that return CO_2 to the atmosphere, such as respiration and fossil fuel burning. About 50% of the CO_2 that humans add to the atmosphere each year by burning fossil fuels is removed annually by natural removal and storage processes; the remainder accumulates in the atmosphere.

CO_2 transferred from the fossil deposits reservoir to the atmosphere through the burning of fossil fuels results in rising temperatures on Earth, as predicted by theory in the 19th century. In order to restore the Earth's energy balance so that temperatures can stabilize at safe levels for humanity and our natural systems, the carbon content of the atmosphere must be reduced. Such reductions will happen naturally over millennia if carbon emissions from the fossil reservoir cease. However, to avoid unsafe temperature increases, CO_2 must be removed more quickly. Managing plant and soil reservoirs for greater carbon storage represents a way to reduce—or mitigate—atmospheric CO_2. Increasing the amount of carbon stored in these reservoirs is commonly referred to as carbon sequestration, carbon storage and removal, or negative emissions.

Decreasing the amount of carbon stored in the atmosphere is widely acknowledged to require removing and storing CO_2 in other carbon reservoirs (negative emissions) as well as curtailing CO_2 sources such as fossil fuel burning (decarbonization) and deforestation. Of almost 900 mitigation scenarios evaluated by the Intergovernmental Panel on Climate Change (IPCC) with integrated assessment models,[1] all of the 116 deemed effective involved curtailing sources of CO_2 and more than 100 also involved CO_2 removal.[2, 3] Both CO_2 source reduction *and* CO_2 removal are thus central to future climate mitigation efforts. Indeed, under any climate recovery scenario, negative CO_2 emissions (removal and storage) will be required starting immediately to bring atmospheric CO_2 concentrations back within safe limits for our biological and human systems.[4, 5]

Three types of CO_2 removal are most widely discussed today: (1) Improved land management, (2) Bioenergy with CO_2 capture and storage (referred to as BECCS), and (3) Direct air capture.[3, 6, 7] Improved land management entails managing ecosystems to sequester more carbon in living biomass such as long-lived trees and in dead biomass such as organic matter in soils and ocean sediments. Bioenergy with CO_2 capture and storage refers to extracting energy by burning biomass and storing the resulting CO_2 in geologic reservoirs. Direct carbon capture involves extracting CO_2 directly from the air via enhanced weathering of rocks and minerals or direct air capture, with subsequent geologic storage. BECCS and direct air capture are both theoretically possible but currently unproven at any meaningful scale, and thus are not further analyzed in this report. Enhanced rock weathering and ocean fertilization have also been proposed but are less widely discussed or tested.[7, 8] Of this group, improved land management represents the most mature, technically feasible, widely deployable, and lowest cost option currently available.[3, 7] We have known about this option and its environmental co-benefits for decades.

In addition to managing land for negative emissions, land management can also contribute to climate mitigation by avoiding further greenhouse gas emissions.[4, 9] This can be done, for example, by reducing deforestation, a practice responsible for ~10% of total global carbon emissions today,[10] almost all outside the U.S. But greenhouse gases are also emitted by other land management and agricultural practices. For example, nitrogen fertilizer emits CO_2 when manufactured and emits nitrous oxide when applied to soils. Methane is emitted by soils under rice cultivation. Land management practices that avoid or reduce greenhouse gas emissions thus represent an additional climate mitigation opportunity. Some management changes have the potential to both curtail CO_2 emissions and remove CO_2 from the atmosphere. For example, producing ethanol from perennial grasses instead of corn grain both consumes less fossil fuel (curtailing CO_2 emissions) and stores more soil carbon (enhancing CO_2 removal and storage).

In the pages that follow are current opportunities for improved land management practices in the U.S. that are feasible and currently available to mitigate climate change. I emphasize those land management practices most likely to produce significant negative emissions—those that remove and store CO_2 from the atmosphere—and as well those practices capable of reducing emissions of CO_2 and the other biogenic greenhouse gases nitrous oxide and methane, respectively responsible for 82%, 10% and 5% of total U.S. greenhouse gas emissions.[11]

2.0 Scale of the Problem

From pre-industrial times fossil fuels have added 327 GtC to the atmosphere (half of that just since the 1980s),[12] with another 156 GtC added by deforestation. In 2014 fossil fuel burning added 8.8 GtC to the atmosphere,[13] with the U.S. responsible for 1.5 GtC[11] or about 17% of the global total that year. In recent years global deforestation has added annually another 0.9 GtC,[10] none from the U.S.[11]

To avoid or deflect the most disruptive effects of climate change now underway—sea level rise, shifting climate zones, species extinctions, coral reef decline, climate extremes, expanded forest burning, and human health impacts—requires returning atmospheric CO_2 concentrations, currently above 400 parts per mission, to 350 parts per million or below.[5, 14] This CO_2 level would largely restore Earth's energy balance, keeping temperatures within the Holocene range to which human societies, agriculture, and other species are adapted. This could be achieved by limiting total cumulative fossil fuel emissions to 500 GtC coupled with cumulative negative emissions equivalent to 100 GtC by 2100.[4] Hansen, *et al.,*[4] identify two major ways that land management can achieve a 100 GtC drawdown this century: (1) negative emissions from forest and soil carbon storage including reforestation and improved agricultural practices, and (2) avoided emissions from ending deforestation and deriving bioenergy from dedicated energy crops that do not compete with food crops. I agree these strategies have the potential to produce that quantity of negative emissions and both are discussed in more detail, below.

Ocean and land sinks today remove from the atmosphere about half of the CO_2 emitted by anthropogenic activities, or ~4.9 GtC annually for the 1990–2000 period.[10] About ⅓ of the emitted CO_2, 2.6 GtC for this period, is removed by land sinks.[10] In the U.S., land sinks remove annually 0.2 GtC.11 Negative emissions as discussed here are in addition to these existing natural sinks.

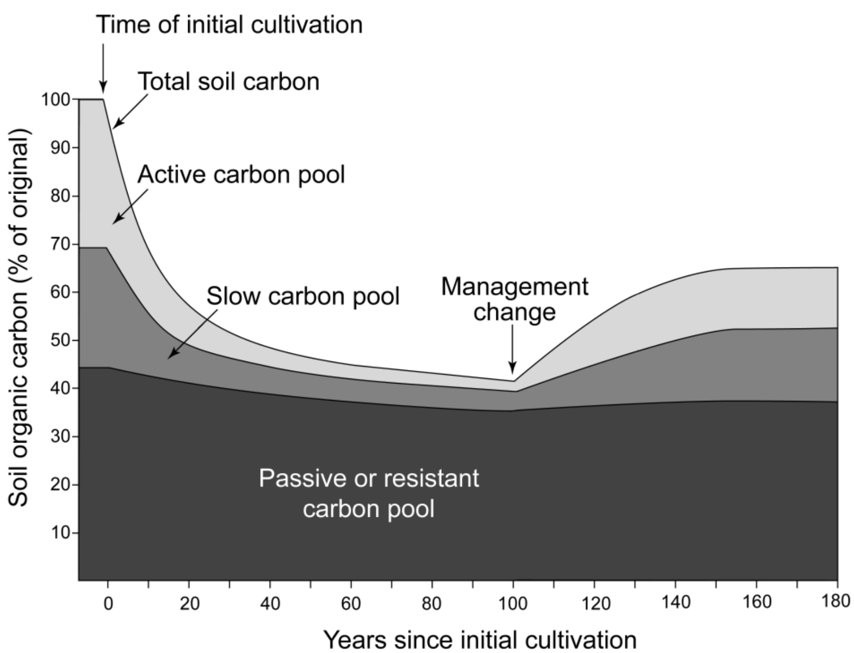
3.0 Soil Carbon Cycling and Storage

Carbon accumulates naturally during soil development as plants colonize new substrates such as sand and rock surfaces, transform atmospheric CO_2 to new biomass via photosynthesis, and then leave behind carbon-rich leaves, wood, roots, and other biomass that then decompose. Some plant parts decompose quickly, others more slowly. Wood, for example, is very resistant to microbial attack, and some of the natural carbon products that are highly resistant to microbes can persist for thousands of years. Soil organic carbon can also be trapped within soil aggregates, which are hardened clusters of soil particles (grains of sand, silt, and clay) wherein very low oxygen levels inhibit microbial activity. And some decomposition products, usually in the form of complex organic molecules, can be highly resistant to decay especially when bound to soil mineral surfaces.

Over time, most soils accumulate organic carbon to some equilibrium value that represents a few percent of total soil mass; in most soils this value is less than 5%. In waterlogged or cold soils such as those under bogs and tundra, decomposition occurs very slowly-microbial activity is suppressed by low oxygen or low temperatures or both—and in these locations, carbon can accumulate to very high proportions of soil mass.

Soil thus contains organic carbon of different ages and different susceptibilities to microbial decomposition. Soil disturbance—both natural and anthropogenic—can stimulate decomposition by altering the soil physiochemical environment. Clearing land for agriculture does exactly this: plowing the soil breaks apart aggregates and exposes protected carbon to microbial attack, and allowing soil to remain bare for much of the year causes it to be wetter and warmer—perfect conditions for microbes to convert soil organic carbon back to CO_2 in their quest for energy. Almost everywhere, conversion of native forest and grassland soils to agriculture results in a 30–50% loss of carbon from the top soil layers within just a decade or 2 (**Figure 2**),[15] a general pattern well-recognized since the 19th century.[16] Global estimates of this loss total 133 GtC, split nearly evenly between crop and grazing lands.[17]

Figure 2



Changes in soil organic matter fractions following cultivation of a soil profile undernative vegetation. Redrawn from Grandy and Robertson (2006).[26]

The basis for soil carbon gain is thus the net balance between photosynthesis, which fixes CO_2 into biomass carbon, and decomposition, which transforms biomass carbon back to CO_2. Thus the organic carbon content of soils is regulated by the balance between the rate of carbon added to soils from plant residues (both aboveground biomass and roots), plus, in agricultural soils, organic amendments such as compost and manure, and the rate of carbon lost from soil, mainly via decomposition, though soil erosion can be locally important.

3.1 Measuring Soil Carbon Storage

The total amount of organic carbon in a soil sample can be measured by a variety of techniques, most reliably by thermal oxidation.[18] Historically, carbon has been assessed by combusting a small soil sample at temperatures sufficient to convert organic carbon to CO_2. This generally entails placing a soil sample of known weight into a high-temperature furnace for several hours; the difference in mass on reweighing represents oxidized carbon and by difference, the carbon content of the soil prior to combustion. A variation on this technique uses a chemical oxidizing agent rather than direct heat to combust the carbon. Today soil carbon is most commonly analyzed by gas chromatography: an automated sampler drops a tiny amount of ground, well-mixed soil into an oxygen-infused chamber that is subsequently ignited; the CO_2 liberated is then measured by gas chromatography or infrared gas absorption analysis.[19] Data from samples so analyzed can be used with high confidence; identical samples typically vary no more than 5–10%.

Due to the natural variability of soil at even small scales, most field experiments to document the effects of a management practice on soil carbon typically compare practices for similar slope positions, and often in replicated small plots, in order to detect differences with statistical confidence. Even so, to dependably detect soil carbon change typically requires a decade or more[20] because change occurs slowly such that it is much easier to detect with confidence a 10% carbon change over 10 years that a 1% change over 1 year. Thus, both long-term sampling and experiments are important for assessing changes in soil carbon.

Soil carbon also varies with depth in the soil profile, so it is also necessary to design sampling programs to directly compare similar depths. Typically, the upper few cm of soil contain the most carbon, with concentrations falling rapidly in lower layers. Lower subsoil carbon concentrations plus its greater natural variability make it especially difficult to detect soil carbon change in lower horizons.[21] Thus, most of what we know about the effects of land management practices on soil carbon stores comes from changes in surface horizons,[22] typically the upper 25–30 cm where most root growth and biological activity occurs.

3.2 Soil Carbon Gain by Improved Land Management

Soils globally contain ~1,800 GtC to 1 m depth, comprising the largest terrestrial organic carbon pool and representing about twice the amount of carbon that is in the atmosphere (830 GtC). Soils of the conterminous U.S.† contain ~81 GtC to 1 m depth.[23] Thus a relatively small percentage increase in soil carbon represents a potentially strong climate change mitigation opportunity.[24]

Soil carbon stocks can be increased by increasing the rate of carbon additions to soil or by decreasing the rate of decomposition, or both. Croplands and grazing lands can be managed for enhanced carbon gain, but for each there are limits to the extent of gains possible. First, with changes to soil management that lead to carbon gain, soil carbon stocks tend towards a new equilibrium asymptotically, such that gains diminish as the new equilibrium level is approached, usually over a few decades (**Figure 2**).[25] Second, this equilibrium level is finite for a given soil at a given location: soils tend to have a saturation level above which no further soil carbon increase is likely possible.[26] Furthermore, if this equilibrium is reached because of high exogenous inputs such as compost or manure, cessation of these inputs will lead to a new, lower equilibrium.[27]

Nevertheless, almost all soils in the U.S. actively managed for agriculture, as well as those that have been abandoned from agriculture due to degraded fertility, have soil carbon levels well below saturation, providing significant opportunities to manage for additional carbon. Cropland surface soils of the central U.S. are believed to have lost ~50% of their pre-cultivation carbon stocks by 1950.[28]

A number of agricultural practices have the potential to increase soil carbon. In most cases these practices differ by management system: practices for croplands are different from practices for grazing lands and both are different from practices for managed forests. Nevertheless, the principles in all cases are the same, and some practices can be applied across systems. Practices below are grouped into three categories: those relevant to cropland and grazing lands management, wetlands restoration, and forest management.

In Section 5, below, the total potential impact for the U.S. (GtC) is estimated based on the average likely carbon gain ($GtC\ ha^{-1}\ yr^{-1}$) for a given practice multiplied by the areal extent (acreage) on which the practice could be implemented, and then again by the number of years between 2020 and 2100 that the average gain might persist. In some cases, multiple practices could be implemented on the same

† This includes soils on both Federal and private lands in the lower 48 United States.

lands—many cropland management practices, for example, such as no till adoption and diversified crop rotations. In other cases, practices are mutually exclusive—cropland management practices, for example, cannot be applied to set-aside cropland converted to perennial grasses. And some practices are already implemented to limited degrees.

Areal extents of potential practices are thus additional to any existing implementation, and are intentionally conservative in order to avoid the likelihood of double counting. The maximum extents possible are, of course, constrained by available land area; all private and public lands within the conterminous U.S. (the lower 48 states), on which Section 5 estimates are based, contains 159 Mha of cropland, 265 Mha of rangeland and pasture, and 256 Mha of forest lands.[29]

About 43% of total rangeland and pasture30 and 42% of total forest land[31] in the conterminous U.S. are owned by the Federal Government and thus practices could be implemented directly. On privately held lands practices can be encouraged through financial incentives such as tax abatements or direct payments, used since the 1930s to advance national conservation goals. In 2017, for example,[32] the USDA spent $2.0 billion for the Conservation Reserve program, which kept 9.4 Mha of environmentally sensitive land set aside from production, including 0.8 Mha of restored wetlands; $2.8 billion for the Environmental Quality Incentives Program and the Conservation Stewardship Program, which provide landowners conservation assistance to reduce soil erosion and enhance water, air, and wildlife resources on crop and grazing lands; and $0.5 billion for the Agricultural Conservation Easement Program, which helps to conserve grazing and wetlands in particular. Other than fire suppression, minor assistance was provided to private forest landowners, chiefly through the $0.02 billion Forest Stewardship program.

The duration of a given practice's carbon gain is likewise constrained by the average amount of time it takes the sink, whether soil or trees, to reach local equilibrium. For soils this will vary mainly by climate, management, and initial carbon content—for example, a degraded or long-cultivated soil will take longer to equilibrate than will a soil closer to its original carbon content. For trees this will vary mainly by location, species, and soil fertility—for example, trees in the Rocky Mountains grow more slowly than trees in the Pacific Northwest, and red pine grows faster than Douglas fir. On the other hand, the duration of avoided emissions is not constrained by biology—the emissions reductions will persist for as long as the practice persists.

3.2.1 Cropland Management

Cropland Management: Tillage

Farmers plow to control weeds, manage residues, and prepare the seed bed for planting. Plowing also causes carbon loss by mixing plant residues throughout the surface soil, bringing it into contact with microbes and other soil organisms like earthworms, and with moister soil more favorable to microbial activity. Plowing also breaks apart soil aggregates, especially the larger ones, exposing trapped organic carbon to aerobic microbes that readily respire it to CO_2.[33] In fact much of the early increase in atmospheric CO_2 starting in the 19th century was the result of pioneer cultivation,[34] which stimulated microbial activity and the conversion of soil organic matter to CO_2.

Modern advances in tillage technology provide many more options than traditional moldboard plowing, which inverts the upper 20–30 cm of soil. Contemporary lower-impact options, typically termed conservation tillage, range from chisel plowing, which avoids inverting the soil profile, to no till, which leaves the soil profile completely undisturbed. With no till, weeds are usually suppressed with herbicides or, at smaller scales, with cover crops and mechanical crimping, and seeds are planted with equipment that places seeds in slits cut through the preceding crop's residue, which is left to decompose on the soil surface rather than buried. Both of these practices can significantly increase the amount of carbon stored in the soil.

The primary impetus for the development of no-till and other conservation tillage techniques was erosion control.[35] Under no-till corn, for example, erosion can be reduced as much as 90%[36–39] by reducing the exposure of soil aggregates to raindrop impacts and to freeze-thaw and wet-dry cycles, allowing more to remain intact, protecting entrapped carbon from microbial oxidation to CO_2.[40] And plant residue, by remaining on the soil surface, decomposes more slowly.[41]

Carbon accumulation due to no-till has been documented in soils worldwide, including the U.S. since the 1950s.[35] Long-term field experiments comparing no-till to conventional tillage show typical no-till increases of 0.1–0.7 tC ha^{-1} yr^{-1}.[42, 43] West and Marland[44] estimated average rates of 0.3 tC ha^{-1} yr^{-1}, a rate consistent with other syntheses[45–48] including Eagle, *et al.*'s,[48] who included the impact of nitrous oxide emissions in their overall estimate. Where soil carbon is already high, no-till has less capacity to increase soil carbon; no till also has less capacity to increase soil carbon in cooler or wetter areas where it can sometimes reduce crop yield.[49] Other forms of conservation tillage can also build soil carbon but at lower rates and less consistently.[50]

Importantly, to achieve a long-term increase in soil carbon from no-till practices, the no-till practices must be implemented continuously. Stored soil carbon can be quickly oxidized to CO_2 when no-till soils are tilled,[15, 51] with much of the no-till carbon benefit lost after a single tillage event.[52] Thus, while no-till is practiced on as much as 36% of U.S. soils annually, because it is practiced at least 3 years in a row on less than 13% of U.S. cropland,[53] and almost certainly less on a permanent basis, there presently is little long-term climate benefit. Efforts to use no-till as a negative CO_2 emissions strategy must consider no-till longevity an important design component.

An exception to this continuous long-term no-till rule is the potential for burying surface soil carbon with a single inversion tillage. In humid climates with poorly drained soils, a one-time deep inversion tillage may promote soil carbon storage by moving high-carbon surface soils to >50 cm depth, where decomposition is slowed due to cooler, wetter conditions with less oxygen. At the same time, low carbon soil at depth is moved to the surface where it can accumulate more carbon. In one of the only long-term deep tillage experiments, Alcàntara, *et al.,*[54] found carbon accumulation rates equivalent to ~1 tC ha^{-1} yr^{-1} in Germany.

A further consideration is the potential for soil carbon to change at depths below the top soil horizon. Almost all quantitative assessments of no-till to date have assessed changes in soil carbon in the upper 25–30 cm of the soil where roots, soil organic matter, and microbes are most concentrated. However soil carbon also occurs at lower depths,[17] and there is the potential,[22, 55] but little quantitative evidence,[21, 56] for soil carbon changes at depth to counteract surface soil gains in some locations.

Although carbon savings associated with no-till also accrue from reduced fuel use due to fuel saved by not plowing, this saving is typically small (typically <0.05 tC ha^{-1} yr^{-1}),[44, 57] though permanent in that it is not subject to re-release like stored soil carbon.

Cropland Management: Summer Fallow and Winter Cover Crops

In most annual cropping systems soils are left bare for a substantial portion of the year. Without plants, soils lose carbon because there are fewer carbon inputs from roots and aboveground residues and because decomposition rates are higher—soils are wetter and warmer without plant transpiration and shading.[58] For most annual crops in the U.S. (*e.g.,* corn, soybean, cotton, sorghum, peanut, and vegetables) the fallow period occurs over winter, stretching from mid-fall to late-spring (5–7 months). For fall-planted crops like winter wheat and winter canola, the fallow period occurs over summer and lasts from the mid-summer harvest to at least late fall (~3 months), or, where followed by a summer crop, to the following spring (9–10 months). Thus for most U.S. cropland the soil is bare for much of the year. In semi-arid regions summer fallows are often used to conserve soil moisture for a following crop.

Eliminating summer fallow periods can, in the U.S., sequester up to 0.3 tC ha^{-1} yr^{-1} of soil carbon depending on climate and tillage method. Eagle, *et al.,*[48] estimated an average soil carbon gain of 0.16 tC ha^{-1} yr^{-1}. Less the CO_2 cost of the additional nitrogen fertilizer used reduces the net benefit to 0.09 tC ha^{-1} yr^{-1}. Where summer fallow is used for water conservation, summer fallow cannot likely be eliminated but could be used less frequently, such as every third or fourth year instead of every second or third year.[59, 60]

Winter cover crops include annual grasses such as rye and legumes such as clover that are typically planted in the fall following harvest of the preceding crop. Prior to winter the cover crop germinates and grows to a size that allows it to survive wintertime temperatures in a dormant state, after which it grows rapidly the following spring. Before planting the following summer crop, the cover crop is killed and then either left to decompose on the soil surface or, more commonly but not necessarily, buried with tillage. Adding winter cover crops to a rotation can add 0.03–0.55 tC ha^{-1} yr^{-1} of soil carbon,[61, 62] depending on climate, even when the cover crop is tilled under—providing in many cases a carbon gain equal to no-till.[63]

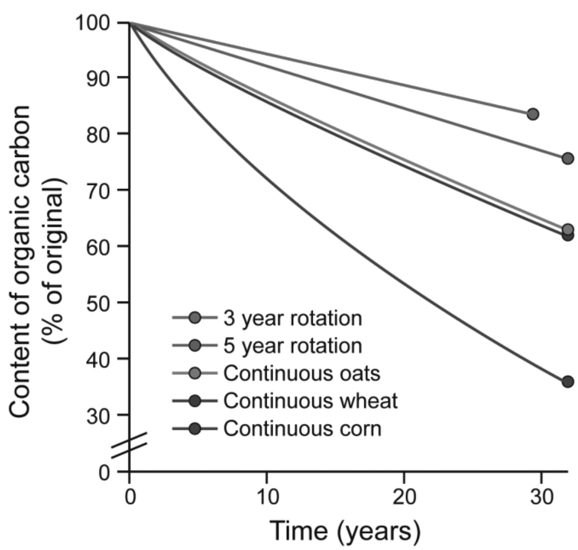
Winter cover crops provide the additional co-benefit of reducing the need for nitrogen fertilizer due to their ability to scavenge the previous crop's leftover soil nitrogen that would otherwise be leached to groundwater or emitted to the atmosphere, and, in the case of legume cover crops, the ability to capture or "fix" nitrogen from air. This captured or new nitrogen is then made available to the next crop, reducing the need to apply fossil fuel-derived nitrogen fertilizers, thereby creating additional carbon savings by avoiding one of the most significant sources of greenhouse gases in intensively managed field crops.[64]

A recent meta-analysis[65] estimates average carbon sequestration potentials for winter cover crops of 0.32 tC ha^{-1} yr^{-1} globally, with a number of studies reporting rates as high as 1 tC ha^{-1} yr^{-1}. Including fertilizer savings, Eagle, *et al.,*[48] estimate a net potential carbon benefit of 0.37 tC ha^{-1} yr^{-1} for winter cover crop use in the U.S., not including CO_2 and nitrous oxide savings from reduced nitrogen fertilizer use, which they estimate could add another 0.16 tC ha^{-1} yr^{-1} of carbon savings. Poeplau and Don's[65] analysis suggest a new soil carbon equilibrium is reached after 155 years;[9] the reduced CO_2 and nitrous oxide savings from reduced nitrogen fertilizer use, where it occurs, would last indefinitely. For a variety of reasons, including additional seed and labor expenses as well as the risk of not killing the cover crop in a timely manner, cover crops are planted today on only ~3% of U.S. cropland.[66]

Cropland Management: Diversifying Crop Rotations

Crop species vary in the amount of biomass they produce, in the proportion of biomass that goes unharvested, including roots, and in the resistance of unharvested residue to decomposition. Thus, diversifying crop rotations is a time-tested means to build and retain soil carbon. In the U.S. as early as 1933 Salter and Green[67] reported on a 31 year experiment in which more complex rotations retained more soil carbon. In central Ohio they found that continuous corn (corn planted year after year) lost three times more soil carbon than did a 3 year corn-wheat-oats rotation; continuous wheat and continuous oats similarly lost twice as much carbon as did the 3 year rotation (**Figure 3**).

Figure 3



Rotation effects on soil carbon maintenance over a 31 year experiment. Redrawn from Salter and Green (1933).[58]

Diversifying annual crop rotations can thus significantly increase carbon stores.[50, 60, 68] The addition of perennial species such as hay and alfalfa to annual crop rotations, because of the deep and persistent roots of perennial crops and their longer growing season, can boost soil carbon still further,[42] as can the inclusion of legumes such as clover.[69] Measurements of soil carbon change under more diverse annual cropping systems range from 0.02 to 1.1 tC ha^{-1} yr^{-1},[46, 50, 70, 71] but results are highly dependent on associated full-rotation changes in crop residues, tillage, and other factors that affect soil carbon stores. In consideration of these unknowns, Eagle, *et al.,*[48] estimate an average net carbon benefit of 0.05 tC ha^{-1} yr^{-1} for diversifying crop rotations to a sequence more complex than corn—soybean, mainly achieved by lower nitrous oxide emissions.

Cropland Management: Manure and Compost Addition

Organic materials such as compost and manure, when added to productive soils, tend to increase soil carbon stocks only as long as additions are sustained.[27] Added to less productive soils, however, benefits can persist because of their additional impact on soil water holding capacity, porosity, aeration, infiltration, and nutrient holding capacity. These soil fertility co-benefits can increase crop productivity and subsequent residue inputs. Thus, while the climate benefit of moving compost or manure from one part of the landscape to another must be considered,[72] where soil fertility is sufficiently improved to increase productivity the soil carbon gain is a legitimate and persistent climate benefit.

In one recent example, Ryals, *et al.,*[73, 74] added compost to rangeland, which, exclusive of carbon in the compost addition itself, appeared to increase soil carbon storage by 25–70% or 0.51–3.3 tC ha^{-1} 3 years after a single compost addition.[74] Where manure is derived from crop harvest, which is the case for most dairy and feed-lot cattle in the U.S., its return to soil can be considered another form of crop residue return and thus also a climate-legitimate carbon gain when compared to business-as-usual practices. Estimates of soil carbon gain from long-term applications of livestock manure to arable soils range from 0.2 to 0.53 tC ha^{-1} yr^{-1}.[75, 76] Eagle, *et al.,*[48] estimate a range of 0.05 to 1.4 for an average of 0.71 tC ha^{-1} yr^{-1} that does not include CO_2 savings from reduced nitrogen fertilizer use. Sequestration will likely continue for the duration of manure additions, in our case >80 years—the world's longest-running manure addition experiment has found soil carbon stocks still increasing after 120 years,[77] though stocks will equilibrate to some lower level upon cessation.[77, 78]

3.2.2 Cropland Conversion to Perennial Grasses

Cropland Conversion: Set-aside Highly Erodible Cropland

Converting degraded or highly erodible cropland to perennial grasslands has the potential to sequester soil carbon insofar as perennial grasses have greater root carbon stocks than annual crops and because they are grown without tillage. Nevertheless, such conversions must be planned carefully to result in a legitimate climate benefit: Converting annual cropland to perennial grassland has no climate benefit where equivalent food production must be made up by more intensive crop production elsewhere, especially if such displaced crop production causes deforestation.[79] Indirect land use change effects, while disputed by some,[80] are undoubtedly possible and can potentially exceed local carbon savings.[81]

Nevertheless, USDA conservation programs that pay farmers to convert privately-owned annual cropland with conservation value (*e.g.,* highly erodible land) to grasslands or trees can lead to significant soil carbon savings as a valuable co-benefit. For example, around 9 Mha are currently enrolled in the U.S. Conservation Reserve Program, down from a high of 15 Mha in 2007.[82] Sperow, *et al.,*[83] estimate that an additional 30 Mha could be added to the 9 Mha currently enrolled based on a USDA erodibility index.

Several recent reviews of soil carbon gain on conversion of annual grain to perennial grasses report average carbon sequestration potentials that range from 0.28–1.3 tC ha^{-1} yr^{-1}.[84–87] Including the upstream savings from reduced agronomic inputs and nitrous oxide emissions (but not fossil fuel carbon offsets), Eagle, *et al.,*[48] estimate an average carbon benefit of 0.97 tC ha^{-1} yr^{-1}.

Cropland Conversion: Cellulosic Bioenergy on Grain Ethanol Lands

Where annual crops are currently used for grain-based biofuel production, conversion to dedicated cellulosic feedstocks such as perennial grasses could likewise sequester soil carbon and in this case without potential indirect land use change effects. Cellulosic feedstocks would additionally provide greater life cycle carbon savings than the grain-based feedstocks they would replace.[88] In 2017 ~38% of total U.S. corn acreage, or 13 Mha, was used for grain ethanol production;[89] converting this cropland to a perennial cellulosic crop would result in carbon savings additional to those from no-till conversion (assuming conversion from no-till to avoid double counting the no-till and perennial conversion benefits).

The rate of soil carbon gain for annual cropland converted to perennial biofuel crops would be similar to that for set-aside cropland (0.97 tC ha^{-1} yr^{-1}). This assumes little of the converted annual cropland was under permanent no-till management (see Section 3.2.1, above).

Cropland Conversion: Cellulosic Bioenergy on Former Cropland

The potential for additional mitigation from planting marginal lands—former cropland now abandoned—to cellulosic biofuel crops is also significant. Additional to the fossil fuel offset benefit is the soil carbon gain, especially on soils abandoned due to low fertility. Again, placement of such crops would need to avoid land with significant standing carbon stocks such as forests and wetlands to achieve a short-term climate benefit. Robertson, *et al.,*[88] note that about 55 Mha of the 70–100 Mha of cropland abandoned since 1900 that is neither forest nor wetland would be needed to meet expected 2050 biofuel needs.[90] Planting these lands to higher productivity grass species would cause carbon accumulation additional to that already occurring in these lands.

The rate of soil carbon gain for former cropland converted to perennial biofuel crops would be similar to that for set-aside cropland but discounted by the carbon gain already occurring under existing unmanaged vegetation.[88] Assuming that the managed grasses are about twice as productive as the pre-existing vegetation, the discounted credit is likely to be ~50% of the grassland conversion credit of 0.97 tC ha^{-1} yr^{-1}, or 0.48 tC ha^{-1} yr^{-1}. This value does not include a fossil fuel offset credit.

3.2.3 Grazing Lands Management

Grazing Lands Management: Improved Animal Stocking Rates

Grazing lands, whether planted pastures as are typical in the eastern U.S., or extensive rangelands as are typical in the western U.S., are dominated by perennial grasses managed without annual tillage. Soil carbon stores can be improved significantly by increasing plant productivity via improved attention to livestock stocking rates.86 On rangelands, estimates of soil carbon increases resulting from improved stocking rates range from 0.07 to 0.31 tC ha^{-1} yr^{-1},[91, 92] with higher rates for the Rocky Mountains and Great Plains region. In a new meta-analysis of some 50 studies, Conant, *et al.,*[86] estimate an average soil carbon sequestration potential for improved stocking management on extensive rangelands of 0.28 tC ha^{-1} yr^{-1}. Because of a relatively low sequestration rate, time to equilibration will likely exceed 80 years.

On pasturelands, Eagle, *et al.,*[48] note the potential for intensive rotational grazing to improve soil carbon storage due to increased plant productivity and careful attention to stocking rates. The average sequestration rate for the few available published studies is 0.25 tC ha^{-1} yr^{-1}.

Grazing Lands Management: Improved Plant Species Composition

Grazing lands carbon sequestration can also be increased by improving grass species composition. Interseeding legumes such as alfalfa on rangeland[93] can increase long-term carbon accrual by 3.1 tC ha^{-1} yr^{-1}, and interseeding improved grass species can improve average soil C by similar amounts.[94] Eagle, *et al.,*[48] estimate an average soil carbon gain of 0.40 tC ha^{-1} yr^{-1} for improved species composition on rangelands. Henderson, *et al.,*[95] estimate an average gain of 0.56 tC ha^{-1} yr^{-1} for planting legumes in pastures, even after decrementing rates for increased nitrous oxide emissions.

3.2.4 Frontier Technologies

There are unconventional technologies also under study for increasing carbon removal and storage through agricultural land management practices, some more mature than others. While these practices may eventually prove to increase the carbon sequestration potential within the U.S., I do not include these technologies in my quantitative assessment of negative emissions because their feasibility and benefits are yet too uncertain. The technologies include, but are not limited to:

(1) Very high animal stocking rates on extensive rangeland for short periods of time, known by a number of names including intensive rotational grazing (as for pasturelands) and mob grazing, have shown promise for improving productivity and soil carbon stocks. In at least one study additional soil carbon accumulation was ~3 tC ha^{-1} yr^{-1} compared to continuous grazing.[96] These results are too early to generalize, however,[97] and recommendations await the results of further experimentation.

(2) Biochar additions to soils have shown, in many cases, a propensity to increase long-term soil stocks via direct carbon stock change and improved soil fertility that, like compost, can boost productivity in degraded or infertile soils. Biochar is charcoal: a pyrolysis byproduct of the thermochemical conversion of wood to other energy products such as biogas and liquid bio-oil.[98] Most biochar is highly resistant to microbial attack, and additions to a wide variety of soils have demonstrated its general tendency to persist-indeed, many soils of fire-prone ecosystems in the U.S. contain substantial amounts of natural biochar.[99]

But biochar additions can also enhance the decomposition of native soil organic matter,[100, 101] offsetting the soil carbon benefit of biochar itself, and as well biochar may be of greater mitigation value if converted directly to energy to offset fossil fuel use.[8] A biochar recommendation awaits further research to clarify both the long-term soil carbon gain in field studies and life cycle carbon analysis in comparison to alternative uses.

3.2.5 Wetlands Restoration

Wetlands Restoration: Histosols

Histosols are soils high in organic matter due to their formation under water-logged conditions that inhibit microbial activity. As wetland plants such as sphagnum moss produce biomass, a significant fraction accumulates as peat and high-carbon sediments. When drained for agriculture, histosols tend to be extremely productive, but once exposed to oxygen, microbial activity accelerates and histosols can lose carbon quickly at rates as high as 20 tC ha^{-1} yr^{-1}.[102] About 8% of histosol soils in the U.S. have been drained for agriculture, mostly in Florida, Michigan, Wisconsin, Minnesota, and California.

Carbon accumulation in these soils can be restored (carbon loss reversed) by taking them out of production and restoring the high water table. Although restoring wetland conditions will also restore methane production, the combination of reversed carbon loss and abated nitrous oxide emissions usually will exceed the additional methane loss, leading to a large net emissions reduction.[103] However, the area of cultivated histosols soils is relatively small in the U.S.—used mostly for vegetables and sugar cane production—so the overall mitigation potential is modest.[24] And as for cropland conversion to perennial grasslands, care must be taken to avoid indirect land use change effects. In 2017, the USDA paid farmers to maintain 0.8 Mha of restored wetlands[32] through the Farmable Wetlands Program (*https://www.fsa.usda.gov/programs-and-services/conservation-programs/farmable-wetlands*) within the Conservation Reserve Program (see Section 3.2); at least another 0.8 Mha is readily available.[48]

Estimates of carbon gain under restored histosols vary widely, from 0.6 to 20 tC ha^{-1} yr^{-1}.[48] An average value, considering other greenhouse gas impacts such as increased methane emissions, was estimated by Alm, *et al.,*[104] to be around 2.7 tC ha^{-1} yr^{-1} for Finnish peatlands; more recently Griscom, *et al.,*[9] suggest an average value from a global peatlands database of 3.65 tC ha^{-1} yr^{-1}.

Wetlands Restoration: Non-Histosols

A substantial fraction of non-histosol wetlands have been drained for agriculture in the U.S., and despite being below the threshold for definition as histosols, prior to agricultural conversion they generally had higher soil organic matter content than well-drained soils. About 80% of wetland drainage in the U.S. has been attributed to agriculture, or ~32 Mha since 1780. Estimates of soil carbon accumulation upon restoration are highly uncertain but in the range of 0.41 tC ha^{-1} yr^{-1},[105] much smaller than for histosol wetlands with their substantially greater soil carbon content, and in the range that could be offset by increased methane emissions. Thus it is not yet clear whether non-histosol wetland restoration is an effective carbon sequestration strategy.

3.2.6 Forest Management

Forests, like croplands and grazing lands, can be managed to enhance carbon sequestration via changes to forestry practices or by conserving standing forests. Generally forest management includes reforestation, which refers to the reestablishment of trees following forest harvest, but does not include *afforestation,* defined by IPCC[105] as the establishment of trees on lands that have been deforested for 50 years or more. In the U.S., afforestation largely comes at the expense of current crop and pasturelands[106] and thus will create indirect land use change effects elsewhere, likely resulting in little if any net climate benefit.[107, 108] About 42% of total forestland in the conterminous U.S. is publicly owned and managed by Federal agencies.

Forest Management: Improved Stand Management

Improved forest management designed to enhance carbon sequestration in tree biomass includes choices of tree species (fast *versus* slow growing), harvest age or rotation length, and the use of practices such as fertilization, controlled burning, and thinning to increase forest productivity and carbon storage. Delaying rotation increases carbon storage because carbon continues to accumulate as the trees grow;[109, 110] even relatively old growth forests continue to accumulate carbon in soil stocks, including carbon in slow-to-decay fallen trees on the forest floor.[111, 112] But even without additional carbon sequestration, preservation of an existing forest biomass stock keeps it from the atmosphere for the period delayed.

Rotation lengths differ regionally by tree species and ownership and can be managed readily. Softwoods and mixed species in nonindustrial private forests of the southern U.S. are typically managed on rotations of 25 to 35 years or longer, although rotations in commercial forestry may be half this length.[113] In the western U.S., commercial rotations tend to be 45–60 years because of longer-lived species.

Delaying harvest and converting unmanaged forests to faster-growing species to increase forest productivity can sequester, on average, 1.4–2.1 tC ha^{-1} yr^{-1}.[113, 114] Using an economic model, the U.S. Environmental Protection Agency (EPA)106 estimated that 7–105 MtC yr^{-1} (0.07–0.105 Gt C yr^{-1}) could be stored by all forests in the conterminous U.S. at carbon prices from $1 to $50 per tCO_2 for 100 years or more; at a conservative $15 per tCO_2,[8] this amounts to 60 MtC yr^{-1}. Their variable price economic model yields a 55 MtC yr^{-1} average by mid-century, which is consistent with Griscom, *et al.*'s,[9] U.S. projection of 18 MtC yr^{-1}, not including planted forests nor fire management, which they consider alone could avoid 11 tC ha^{-1} yr^{-1} of carbon loss in fire-prone forests such as those in the western U.S.

Reforestation, not considered here because of overlap with marginal lands included in cellulosic biofuel estimates (Sections 3.2.2 and 4.2.4), could also provide substantial negative emissions. Griscom, *et al.,* project potential sequestration of 98 MtC yr^{-1} were all once-forested U.S. pastureland, mostly east of the Missouri River and including lands currently grazed, reforested. Such a strategy, however, would require diet shifts away from meat to avoid indirect land use effects, whereby displaced food production results in conversion of natural areas (with its carbon loss) elsewhere, such as Amazonia. On the other hand, reforestation on marginal lands not used for grazing could provide carbon benefits similar to conversion to cellulosic biofuels once biofuels were no longer used for fossil fuel displacement.[115]

Forest Management: Improved Soil Management

Soil carbon stocks in U.S. forests are, in aggregate, substantial;[116] about 50% of the carbon in U.S. forests is in the soil and another 8% in detrital material on the forest floor.[117] Various activities can affect forest soil carbon storage: rotation length, harvest intensity, and fire management are among the most important. Kimble, *et al.,*[117] estimate that in total, U.S. forests managed for timber could sequester 25 to 103 MtC yr^{-1} (0.25–0.103 GtC yr^{-1}), for average sequestration rates of 0.12–0.51 tC ha^{-1} yr^{-1}, or a mean of 0.32 tC ha^{-1} yr^{-1}, a more conservative rate than earlier IPCC[105] estimates for temperate forests of 0.53 tC ha^{-1} yr^{-1}. This sequestration would be additional to the current U.S. forest soil background sink recently estimated[118] at 13–21 MtC yr^{-1}. Kimble, *et al.,*[119] further estimate that soils under agroforestry systems—*e.g.,* alleycrops, riparian buffers, windbreaks, and urban forests—could sequester nationally another 17–28 MtC yr^{-1}, or an average of 22.5 MtC yr^{-1}.

4.0 Agricultural Greenhouse Gas Abatement by Land Management

4.1 Measuring Nitrous Oxide and Methane Fluxes

Nitrous oxide and methane, like CO_2, are naturally occurring greenhouse gases. They are distinguished in part by their substantial global warming potentials, the degree to which they are responsible for radiative forcing of the atmosphere compared to CO_2. Over a 100 year time horizon, nitrous oxide has 265–300 times the global warming potential of CO_2, and methane 28–36.[10, 120] Another way of thinking about global warming potentials is that 1 Mt of avoided nitrous oxide emission is equivalent to 265–300 Mt of sequestered CO_2. Thus, though their atmospheric concentrations are substantially lower than those of CO_2, they pack significant punch and concentrations of each have risen by about 45% since 1970.[1] In order to directly compare the atmospheric impact of all three gases, emissions of nitrous oxide and methane are multiplied by 298 and 25, respectively,[102] and expressed as CO_2 or carbon equivalents (CO_{2eq} or Ceq).

Nitrous oxide is naturally emitted by bacteria in soils and other environments as a byproduct of their nitrogen metabolism. Some nitrous oxide is also emitted naturally from fires. Agriculture is responsible for 84% of anthropogenic nitrous oxide emissions,[121] and most agricultural emissions (62%) come from soils amended with nitrogen from fertilizers, manures, or legumes. Thus a major mitigation opportunity related to land management is improved nitrogen fertilizer efficiency.

Agricultural methane emissions come from enteric fermentation by livestock (52%), rice cultivation (22%), biomass burning (19%), and livestock manure handling (8%).[121] From the standpoint of land management, rice cultivation offers today a substantial cropland mitigation opportunity where rice is grown.

The non-CO_2 greenhouse gas exchanges with the atmosphere (fluxes) are not easily quantified. Most of what we know comes from thousands of gas flux measurements made from small chambers (often 25–30 cm diameter) placed on the soil surface. As gases accumulate in the chamber, over the course of an hour or 2 gas samples are withdrawn and analyzed for nitrous oxide or methane. The rates of gas accumulation are calculated from these samples and represent net emissions.[122]

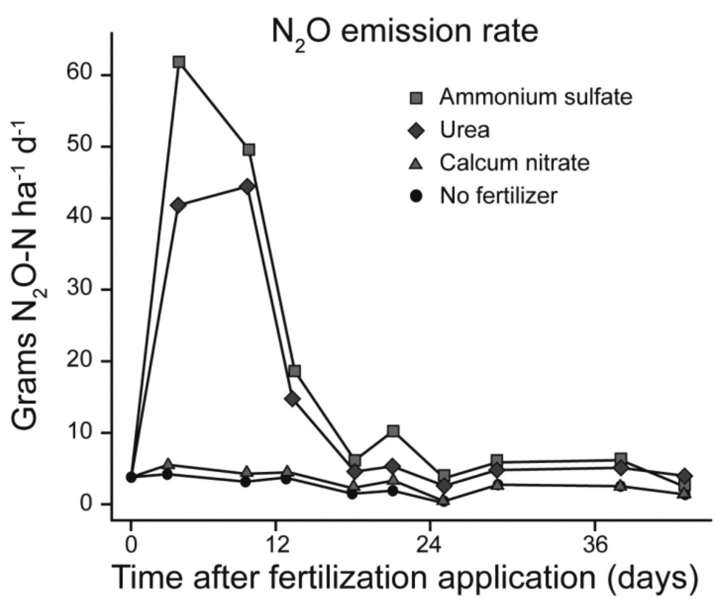
Like soil carbon, the spatial variability of fluxes from soil is very high. Consequently, evaluations of abatement by different agricultural practices are usually made in experimental plots to isolate the effect of the practice from natural soil variability. Such comparisons provide a high degree of confidence when they are made at appropriate times: unlike soil carbon stocks, gas fluxes are also highly variable in time. It's thus important to compare fluxes during periods of low fluxes and high fluxes, and sampling campaigns are expensive because of this need for frequent sampling. Nevertheless, nitrous oxide and methane fluxes have been measured in agricultural systems for over 40 years, and we have a reasonable understanding of the major factors that regulate fluxes and can identify a number of mitigation paths.

4.2 Avoided Emissions by Improved Land Management

4.2.1 Reduced Nitrous Oxide Emissions from Field Crops

About 50% of anthropogenic nitrous oxide emissions are from nitrogen-fertilized field crops such as corn and wheat, where natural soil bacteria that produce nitrous oxide are stimulated by more available soil nitrogen. While factors other than fertilizer can also accelerate nitrous oxide production, it has been known from field studies since the 1970s [123–125] that nitrogen fertilizers are responsible for most agricultural nitrous oxide emissions (*e.g.,* **Figure 4**). In fact, most IPCC national greenhouse gas inventories tally agricultural nitrous oxide emissions as a fixed percentage of nitrogen fertilizer use.[126, 127] Recent evidence that N_2O emissions increase exponentially with nitrogen fertilizer additions in excess of crop need [128, 129] places even more importance on fertilizer nitrogen rate as a predictor of agricultural emissions; this exponential increase is incorporated in both commercial greenhouse gas reduction protocols [130, 131] and in USDA protocols for quantifying farm-level emissions.[132] These protocols are now being built into the COMET-Farm tool that allows farmers and ranchers to calculate the greenhouse gas impacts of current and projected practices.[133]

Figure 4



Nitrous oxide (N_2O) emission response to nitrogen fertilizer. Redrawn from Brietenbeck, *et al.,* (1980).[111]

While other management interventions are also known to reduce nitrous oxide emissions at specific locations,[132] reducing nitrogen fertilizer inputs to the rate needed for optimum yields (called by agronomists the economically optimum rate) is the most reliable means to reduce nitrous oxide emissions from fertilized cropping systems.[134] Carbon equivalent savings for a 15–20% increase in fertilizer use efficiency (equivalent to a 15–20% reduction in average nitrogen fertilizer use) in rainfed crops range from 0.15 to 0.29 tC_{eq} ha^{-1} yr^{-1}.[103, 134–136]

Millar, *et al.,*[134] used an optimum fertilizer rate calculator to show that nitrogen fertilizer rates on corn could be reduced for seven Midwest states by at least 15% without affecting yields. A 15% reduction represents an average avoided nitrous oxide emission of 2.2 kg N_2O ha^{-1} yr^{-1}, equivalent to 0.18 tC_{eq} ha^{-1} yr^{-1} assuming a conservative emission factor of 0.017 kg of nitrous oxide nitrogen per kg of nitrogen fertilizer applied.[129] In 2014 the U.S. consumed 13.3 Mt of fertilizer N;[137] a 15% savings (2.0 Mt N) would additionally save 15% of the CO_2 cost of manufacture, equivalent to 2.2 MtC yr^{-1} (0.0022 GtC yr^{-1}) at a fertilizer production cost of 4 kg CO_2 per kg of nitrogen.[138]

At midcentury, others[139, 140] project a 50% increase in nitrogen fertilizer use efficiency, from 53% today to 75% in the future. If implemented immediately, this would lead to a 32% reduction in nitrogen fertilizer use,[9] for avoided nitrous oxide emissions of 0.36 tC_{eq} ha^{-1} yr^{-1} and avoided CO_2 from fertilizer production of 2.2 Mt C yr^{-1}. Cropland affected by this savings is assumed to be that planted to crops in 2012 (139 Mha) less the acreage in soybeans and peanuts,[141] major commodity crops that require no nitrogen fertilizer.

4.2.2 Rice Water Management for Methane

Rice in the U.S. grows in flooded soils that create the oxygen-depleted soil environment necessary for methane production. While rice is not a major cereal crop in the U.S., annual rice-related methane production is 3.1 GtC_{eq},[11] about 2% of 2015 U.S. methane emissions and about 2% of total worldwide methane production from rice.[142]

Methane from flooded rice is most readily controlled by periodic drainage. Sass, *et al.,*[143] documented a 50% reduction in emissions in Texas with a single mid-harvest drainage, and almost complete cessation with a 2 day drainage every 3 weeks. Others have found similar responses around the world, particularly in China.[144] Eagle, *et al.,*[145] suggest a U.S. rice methane mitigation potential of 0.54 tC_{eq} ha^{-1} yr^{-1} based on improved drainage practices. Additional mitigation can be achieved with new high-yielding rice cultivars that increase root zone porosity and consequent methane oxidation.[146]

4.2.3 Cellulosic Bioenergy Production on Grain Ethanol Lands

As noted earlier, about 44% of U.S. corn acreage is currently used for grain-based ethanol production. Were this acreage turned to biomass production for cellulose-based ethanol production, using technology that is currently in commercial use in the U.S., the climate benefit of ethanol production would be substantially improved because the production of cellulosic biomass crops like switchgrass require very few fossil fuel inputs, unlike the production of corn grain. Whereas grain-based ethanol avoids only 18% of the CO_{2eq} that would otherwise be emitted by gasoline, cellulosic ethanol avoids nearly 90%.[147, 148] Thus, substituting cellulosic feedstocks such as switchgrass on current corn grain ethanol cropland could provide a substantially greater fossil fuel offset than grain ethanol feedstocks, in addition to providing soil carbon sequestration as noted above in Section 3.2.

The additional climate benefit can be calculated from a standard life cycle analysis model such as GREET.[149, 150] Not including the soil carbon benefit already considered above, switchgrass with a conservative biomass yield of 8 Mg ha^{-1} yr^{-1} can provide 1.44 tC ha^{-1} yr^{-1} of fossil fuel CO_2 savings when converted to ethanol.[150, 151] The difference from corn grain (0.73 tC ha^{-1} yr^{-1} for a grain biomass yield of 11 Mg ha^{-1} yr^{-1}) represents a net avoided CO_2 emission benefit of 0.71 tC ha^{-1} yr^{-1}. The difference would be greater with a higher yielding cellulosic biomass crop.

4.2.4 Cellulosic Bioenergy Production on Marginal Lands

Cellulosic biofuels can also be grown on former agricultural lands, as noted earlier. To meet expected 2050 liquid transportation fuel demands requires ~55 Mha of the 70–100 Mha of crop and pastureland abandoned from agriculture since 1900, excluding urban, forest, and wetlands.[88] Planting this acreage to switchgrass with an avoided CO_2 emission benefit of 1.08 tC ha^{-1} yr^{-1} for an average 6 Mg ha^{-1} yr^{-1} yield[150, 151] would generate a significant avoided CO_2 emissions savings. This value does not include the soil carbon sequestration included as negative emissions. Note that this is not BECCS, insofar as the carbon in the fuel is not geologically sequestered as CO_2.

5.0 Total Mitigation Potentials

Several published studies have estimated a total biophysical potential for soil carbon sequestration globally and in the United States with land management technologies that are currently available. Before summarizing the U.S. carbon mitigation potential it is worth considering the global perspective.

5.1 Global Estimates of Potentials for Soil Carbon Gain

Recent global estimates of the biophysical potential for cropland and grazing land soils to sequester carbon range from $0.4^{-1.5}$ GtC yr^{-1} (**Table 1**).[24, 105, 152–156] Each of the estimates in **Table 1** assume adoption of some combination of improved cropland and grazing land management, agroforestry, and restoration of degraded lands and histosol wetlands. Note that they do not include other sequestration practices described above, including sequestration due to improved forest management and conversion of grain ethanol lands to cellulosic biofuel crops, nor savings from avoided emissions such as those from improved nitrogen fertilizer use. That these global estimates are similar to one another arises from considering the same types of practices and using similar well-constrained field estimates that are based on long-term experiments for major mitigation practices such as no-till.

To calculate the total century-long mitigation potential requires knowing for how long these rates are sustainable. As noted earlier, soil carbon accumulation tends to behave asymptotically—after some period maximum rates slow until a new equilibrium is reached (**Figure 2**). Although very long term experiments in agricultural systems are rare, it's clear that the applicable period likely differs among management practices, climate zones, and initial soil carbon levels. Many researchers assume conservatively that average maximum rates occur for at least 20 years with the rate of sequestration after then declining to a new steady state that occurs about 40 years post management change,[28, 44] although some (*e.g.,*[152]) assume >50 years persistence. A 30 year period at average sequestration rates seems a reasonable working value and is the value I have used for the calculations contained in this report.

Table 1

Year	Estimate (GtC_{eq} yr^{-1})	Improved cropland management	Improved grazing land management	Set-aside of erodible cropland to grassland	Restoration of degraded land	Agroforestry	Restored peat soils	Reference
1998	0.4–0.9	X		X	X			Paustian, *et al.*[152].
1999	0.5–0.6	X			X			Lal and Bruce [153].
2000	0.82	X	X	X		X	X	IPCC [105].
2004	0.4–1.2	X	X	X	X	X		Lal [154].
2008	1.4–1.5	X	X	X	X		X	Smith, *et al.*[103].
2014	0.7–1.4	X	X	X	X	X		Sommer and Bossio [156].
2016	0.3–1.5	X	X	X	X	X	X	Paustian, *et al.*[24].

Published estimates of global soil carbon sequestration potentials based on biophysical processes that could be enhanced by land management actions. Not included are sequestration potentials from forest management, cellulosic biofuel crops, or carbon additions such as compost or biochar, nor savings from avoided emissions such as those from avoided nitrogen fertilizer use.

If the average global sequestration rate of 1.2 GtC yr^{-1} for the three most recent analyses [24, 155, 156] is multiplied by a conservative 30 year sequestration period, then we can calculate an end-of-century value of ~36 GtC sequestered for this set of soil carbon practices.

Expanding the scope to include forests and coastal wetlands readily boosts global negative emissions potentials well past the 100 GtC end-of-century target for restoring a 350 ppm CO_2 atmosphere.[4] In one recent analysis Griscom, *et al.,*[9] consider at the global scale 20 conservation, restoration, and land management actions that, in aggregate, could sequester or avoid as much as 6.5 GtC yr^{-1} for at least a 25 year period. They include aggressive reforestation, forest management, coastal wetland and peatland restoration, and **Table 1** practices to yield 169 GtC of negative emissions by the year 2100 if implemented soon. If reforestation were to more reasonably include reforesting only 25% of the once-forested areas, rather than 100%, their estimate reduces to 148 GtC by 2100.

Avoided emissions, including stopping deforestation and wood fuel harvest, improved nitrogen fertilizer management, and avoided coastal wetland and peatland conversion provides another 128 GtC of savings, for a global end-of-century total of 276 GtC.

It is worth emphasizing that these practices are feasible and available for implementation today, and would provide land-based CO_2 mitigation additional to the existing 2.6 GtC yr^{-1} land sink (Section 2.0).

Including frontier technologies such as biochar additions and the development of microbiome-assisted carbon accrual could further increase soil carbon sequestration potentials, perhaps by as much as 1.8 fold.[24] Worth noting too is the French Government's "4 per mille" initiative announced at the time of the 2016 Paris climate accord,[157] which aims to increase global soil carbon stocks by 0.4% per year, an aspirational goal equivalent to sequestration rates of 3.4 GtC_{eq} yr^{-1} (272 GtC if sustained through 2100) that has attracted significant attention.[158–160] Many, myself included, feel this rate is overambitious in part because we don't know the saturation potentials for most soils, but the initiative has raised awareness and will likely spur further research to identify additional soil carbon management interventions.

5.2 U.S. Potentials for Negative and Avoided Emissions by Land Management Change

Table 2 presents a summary synthesis of the management practices identified in the sections above for the U.S. Negative emissions, including Cropland management (Section 3.2.1), Cropland conversion to perennial grasses (3.2.2), Grazing land management (3.2.3), Wetland histosols restoration (3.2.4), and Forest management (3.2.6), sum to a potential total carbon storage rate of 414 MtC_{eq} yr^{-1} (0.414 GtC_{eq} yr^{-1}).

This rate is similar to those calculated for other recent U.S. summaries[28, 83, 159, 161] when considering individual practices. While other syntheses estimate a lower range of 75–174 MtC_{eq} yr^{-1}, with an average rate of 85 MtC_{eq} yr^{-1}, they do not include carbon sequestered due to improved forest management or the establishment of cellulosic bioenergy crops. These alone add 198 MtC_{eq} yr^{-1}. A 2007 Congressional Budget Office analysis[162] that included forest management estimated a 2030 sequestration potential of 479 MtC_{eq} yr^{-1}. Thus the present analysis (summing to 414 MtC_{eq} yr^{-1} for negative emissions) is consistent with earlier analyses.

As noted earlier, the duration of individual sequestration rates by different practices differ. Sequestration rates for all practices could be sustained for at least 30 years, and some for 50–80 years or more as noted in Section 5.1. With these durations, total negative emissions sum to 20.9 GtC_{eq} through 2100 (**Table 2**).

Avoided emissions are also additional in the present analysis. These include (a) improved fertilizer efficiency (Section 4.2.1), (b) rice water management for methane (4.2.2), and (c) cellulosic bioenergy production (Sections 4.2.3 and 4.2.4). These provide additional mitigation potentials that themselves sum to an annual capacity of 122 MtC_{eq} yr^{-1} (0.122 GtC_{eq} yr^{-1}), totaling 9.7 GtC_{eq} through 2100 (**Table 2**). It is worth noting that the capacity of these activities is on-going and permanent, i.e. most of their carbon benefits are not subject to saturation as are biological carbon sinks, nor subject to re-emission upon management change or natural disturbance such as forest fires. It is also worth noting that, except for cellulosic biofuels, there is likely no overlap with decarbonization pathways for energy use. Should, however, energy analyses include cellulosic biofuel production at the magnitude noted here, then the avoided emissions here (72 MtC yr^{-1} or 5.7 GtC for 80 years) would be double counted so this total should be appropriately discounted. The negative emissions due to cellulosic biofuels—soil carbon capture—does not contribute to avoided fossil fuel use so should remain part of this total.

Table 2

Practice change	Local rate (tC_{eq} ha^{-1} yr^{-1})	Areal extent (Mha)	Annual total (MtC_{eq} yr^{-1})	Duration (yr)	Yr 2100 total (GtC_{eq})
Negative emissions					
Cropland management (3.2.1)					
No till adoption	0.40	[a] 94	37.6	30	1.13
Reduced summer fallow	0.09	[a] 20	1.8	30	0.05
Winter cover crops	0.52	[a] 66	34.3	80f	2.75
Diversified crop rotations	0.05	[a] 46	2.3	80	0.18
Manure & compost additions	0.71	[a] 8.5	6.0	80	0.48
Cropland conversion to perennial grasses (3.2.2)					
Set-aside highly erodible cropland	0.97	[b] 26	25.2	30	0.76
Cellulosic bioenergy on grain ethanol lands	0.97	[c] 13	12.6	30	0.38
Cellulosic bioenergy on marginal lands	0.48	[d] 55	26.4	30	0.79
Grazing land management (3.2.3)					
Improved stocking rates on rangeland	0.28	[e] 216	60.5	80	4.84
Improved species composition	0.56	[a] 80	44.8	30	1.34
Wetland histosol restoration (3.2.4)	3.65	[a] 0.8	2.9	80	0.23
Forest management (3.2.6)					
Improved soil management—timberland	0.32	[e] 256	81.9	50	4.10
Improved soil management—agroforestry			22.5	50	1.13
Improved stand management			55.0	50	2.75
Subtotal—Negative emissions			414		20.9

Table 2—Continued

Practice change	Local rate (tC_{eq} ha^{-1} yr^{-1})	Areal extent (Mha)	Annual total (MtC_{eq} yr^{-1})	Duration (yr)	Yr 2100 total (GtC_{eq})
Avoided emissions					
Improved fertilizer efficiency (4.2.1)					
Avoided nitrous oxide emissions	0.36	[c] 125	45.0	80	3.60
Avoided CO_2—fertilizer production			4.4	80	0.35
Rice water management for methane (4.2.2)	0.54	[a] 1.3	0.7	80	0.06
Cellulosic bioenergy production					
Production on grain ethanol lands (4.2.3)	0.71	[c] 17	12.1	80	0.97
Production on marginal lands (4.2.4)	1.08	[d] 55	59.4	80	4.75
Subtotal—Avoided emissions			122		9.7
Total potential			535		30.6

Potential sources and magnitude of U.S. greenhouse gas mitigation from changes in land management practices that lead to negative emissions (carbon storage) and avoided emissions for the period 2020–2100. Numbers in parentheses refer to sections in text for local sequestration values.
[a] Eagle, *et al.*[48, 145].
[b] Sperow, *et al.*83.
[c] ERS[89].
[d] Robertson, *et al.*[88].
[e] Bigelow and Borchers[29].
[f] Poeplau and Don[65].
[g] USDA[163].

Assuming no overlap, and over an 80 year end-of-century lifetime, then, these avoided emissions practices sum to 9.7 GtC_{eq} through 2100.

Altogether, then, I conclude that U.S. potentials for mitigating greenhouse gas emissions through negative emissions due to land management practices on forest, range and crop lands in the conterminous U.S. sum to 20.9 GtC_{eq} for the period 2020–2100. This represents more than 20% of the global natural sequestration target needed to bring CO_2 concentrations to 350 ppm.[4] Including avoided emissions due to land management practices brings the sum to 30.6 GtC_{eq} for the period 2020–2100, or >30% of the total needed.

That the Federal Government manages 43% of rangeland and 44% of forests in the conterminous U.S. (see Section 3.2) allows an estimate of the sequestration potential on public grazing and forest lands of 115 MtC_{eq} yr^{-1}, or 6.2 GtC_{eq} through 2100. About 56% of this total is sequestration on forest lands, the remainder on rangelands.

In its annual inventory of greenhouse gas emissions and sinks for the U.S., the USEPA[11] estimates for U.S. land management a background sink of 212 MtC_{eq} yr^{-1} (0.212 GtC_{eq} yr^{-1}) for 2015. The primary drivers of these sinks in 2015 were forest growth (181 MtC_{eq} yr^{-1}) and forestland expansion (21 MtC_{eq} yr^{-1}), with urban tree growth and landfills (9 MtC_{eq} yr^{-1}) contributing most of the remaining sink. Decrementing this by concomitant changes in methane and nitrous oxide emissions brought the net land management sink to 207 MtC_{eq} yr^{-1}. The 535 MtC_{eq} yr^{-1} potential land management sink noted in **Table 2** (both negative and avoided emissions) is additional to this existing background sink. Were the strategies in this report fully implemented, a future USEPA inventory might tally a net U.S. sink close to 750 MtC_{eq} yr^{-1} (0.750 GtC_{eq} yr^{-1}).

5.3 Barriers that Prevent Optimized Biotic Greenhouse Gas Mitigation in the U.S.

The principal barriers to adopting management practice changes to mitigate greenhouse gas emissions in the U.S. are neither knowledge-based nor technical. There is ample evidence, detailed and summarized above, that land management changes can achieve real and verifiable negative and avoided emissions with high confidence. The values in **Table 2** are, in general, conservative—they include values from field observations and experiments conducted throughout the U.S. and similar ecoregions, *i.e.,* they are empirically-based, representative estimates from farm, rangeland, and forest systems typical of the U.S. Further research will lead to their refinement, but it seems unlikely that average values will change more than 20–30%, and, importantly, the values are in any case as likely to increase in magnitude as to decrease. Further, as noted earlier, not all possible practices to drive negative or avoided emissions are included.

Research and experience show that farmers, ranchers, and forest managers who own and manage non-Federal lands are willing to accept payments for providing ecosystem services such as soil organic matter accrual, nitrate leaching avoidance, wetland protection, and greenhouse gas avoidance.[164, 165] For example, in 2017, USDA and its partners worked with 680,000 land managers to fund the development of conservation plans for 27 million acres of working lands.[166] Both research[164, 165, 167–169] and over-subscribed USDA conservation programs point to farmers' and other landowners' openness to accepting conservation and other ecosystem service payments through a variety of mechanisms, including auctions. Thus, the principal barrier for engaging landowners and managers is not feasibility or lack of interest, but lack of policy support and financial incentive.

How much financial incentive is necessary? The success of USDA conservation programs show that farmers and ranchers are willing to accept relatively low payments for changing specific practices, sometimes as low as a few dollars per acre. In many cases the payments depend on cobenefits. Building soil carbon, for example, benefits soil fertility, water holding capacity, and drainage, and experimental auctions have shown lower payments would be required than, for example, reducing nitrous oxide emissions, which are considered by farmers to have fewer cobenefits.[165, 170] Practices with higher management costs—cover crops, for example—would likewise require higher payments. That said, most analyses to date that include economic costs conclude that many practices could be implemented at costs as low as \$10 per $MtCO_2$ (\$2.70 per MtC). Griscom, *et al.,*[9] for example, state that ⅓ of the potentials they consider could be provided at this cost, with the remainder requiring no more than \$100 per $MtCO_2$, which is consistent with the expected avoided cost of holding warming to below 2 °C by 2100.[171] USEPA modeling[106] concludes that some forest and agricultural management practices could be incentivized at carbon prices as low as \$1 per $MtCO_2$, with full implementation at \$50.

Various voluntary efforts such as the USDA Building Blocks for Climate Smart Agriculture and Forestry (*https://www.usda.gov/oce/climate—change/buildingblocks.html*)[172] provide frameworks for farmers, ranchers, and landowners to respond to climate change. For example, the Building Blocks program provides a series of measures intended to assist a wide variety of land management stakeholders to increase carbon storage and reduce greenhouse gas emissions; ten categories of activities range from soil health and nitrogen stewardship to grazing and pastureland management. The program provides case studies to inspire users and provides technical assistance through NRCS and other USDA professionals to help individual land managers meet personal greenhouse gas reduction goals. Only 3 years old, the effectiveness of the Building Blocks initiative is largely untested but it provides an evidence-based framework for engaging landowners and managers in the sorts of meaningful activities identified herein. The Building Blocks framework is an important start, but the quantitative goal it contains (33 MtC_{eq} yr^{-1} by 2025) is far below the 535 MtC_{eq} yr^{-1} identified in the present analysis, and because the initiative is strictly voluntary with no incentives, it is unlikely to meet even this goal.

More useful is the on-line COMET-Farm tool (*http://cometfarm.nrel.colostate.edu*)[133] that allows farmers and ranchers to calculate the greenhouse gas impacts of current and projected land management practices. Calculations are based on the USDA's methods for quantifying farm-level emissions (*https://www.usda.gov/oce/climate_change/estimation.htm*).[132] Calculations are specific to individual fields as identified by aerial and satellite imagery, and cover most of the crop and grazing land practices in Sections 3.2 and 4.2, including avoided emissions from improved nitrogen fertilizer management, all of which make comparisons between business-as-usual and alternative practices straightforward and directly relevant to the land being managed.

Likewise, national carbon registries offer a framework to provide landowners and carbon markets detailed evidence-based protocols for voluntarily quantifying the carbon captured or emissions avoided by specific land management practices. Both the American Carbon Registry (*www.americancarbonregistry.org*) and the Verified Carbon Standard (www.verra.org), for example, provide protocols for awarding carbon credits based on avoided nitrous oxide emissions by improved nitrogen fertilizer management[130, 131] as well as avoided methane emissions from improved rice management and wetland restoration.[173]

That said, scaling up sequestration nationwide on the order discussed in the present report will require revisiting the many Federal policies and incentives that influence agricultural, grazing, and forestry practices on both private and public lands of the U.S. Without supportive Federal policies and payments sufficient to cover costs, farmers, ranchers, and forest owners are unlikely to participate in sufficient numbers to effect meaningful change.

6.0 Concluding Opinions

Based upon a review of the literature, my own research, and in consultation with other experts in the field, it is my expert opinion that through improved land management practices, at a combined peak rate of 535 MtC_{eq} yr^{-1} (0.535 GtC_{eq} yr^{-1}), about 31 GtC_{eq} of additional emissions could be sequestered and avoided by land management changes on U.S. forestland, rangelands, and farms between 2020 and

2100. Some 21 GtC could be provided by negative emissions, *i.e.,* natural carbon removal and storage by practices such as improved cropland and rangeland management. Another 10 GtC could be provided by avoided emissions from practices such as improved nitrogen management and cellulosic bioenergy production. We have known for decades the potential for most of these practices to contribute to negative or avoided emissions. Sequestration on this scale would meet the scientific prescription for sequestration set forth by Hansen, *et al.*[4, 174, 175]

Signed this 13th day of April, 2018 in Cambridge, UK.

G. PHILIP ROBERTSON.

Exhibit D: Government Climate and Energy Actions, Plans, and Policies Must Be Based on a Maximum Target of 350 ppm Atmospheric CO_2 and 1 °C by 2100 to Protect Young People and Future Generations

Introduction

Human laws can adapt to nature's laws, but the laws of nature will not bend for human laws. Government climate and energy policies **must** be based on the best available climate science to protect our climate system and vital natural resources on which human survival and welfare depend, and to ensure that young people's and future generations' fundamental and inalienable human rights are protected.

Because carbon dioxide (CO_2) is the primary driver of climate destabilization and ocean warming and acidification, all government policies regarding CO_2 pollution and CO_2 sequestration should be aimed at reducing global CO_2 concentrations below **350 parts per million (ppm)** by 2100. Global atmospheric CO_2 levels, as of 2019, are approximately 407 ppm and rising.[1] An emission reductions and sequestration pathway back to 350 ppm could limit peak warming to approximately 1.3 °C this century and stabilize long-term heating at 1 °C above pre-industrial temperatures.

As explained in more detail below, there are numerous scientific bases and lines of evidence supporting setting 350 ppm and 1 °C by 2100 as the uppermost safe limit for atmospheric CO_2 concentrations and global warming. Beyond 2100, atmospheric CO_2 may need to return to below 300 ppm to prevent the complete melting of Earth's ice sheets and protect coastal cities from sea level rise. Fortunately, it is still not only technically and economically feasible to return to those levels, but transitioning to renewable energy sources will provide significant economic and public health benefits and improve quality-of-life.

Why 350 ppm And 1 °C Long-Term Warming?

Three lines of robust and conclusive scientific evidence, based on the paleo-climate record and realworld observations show that above an atmospheric CO_2 concentration of 350 ppm there is: (1) significant global energy imbalance; (2) massive ice sheet destabilization and sea level rise; and (3) ocean warming and acidification resulting in the bleaching death of coral reefs and other marine life.

(1) Energy Balance

Earth's energy flow is out of balance. Because of a buildup of CO_2 in our atmosphere, due to human activities, primarily the burning of fossil fuels and deforestation,[2] more solar energy is retained in our atmosphere and less energy is released back into space.[3] The energy imbalance of the Earth is roughly equivalent to 2500 Camp Creek[4] fires **per day** burning around the world.[5] Returning CO_2 concentrations to below 350 ppm would restore the energy balance of Earth by allowing as much heat to escape into space as Earth retains, an important historic balance that has kept our planet in the sweet spot for the past 10,000 years, supporting stable sea levels, enabling productive agriculture, and allowing humans and other species to thrive.[6] The paleo-climate record shows that CO_2 levels, temperature, and sea

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[1] Ed Dlugokencky & Pieter Tans, NOAA/ESRL, *www.esrl.noaa.gov/gmd/ccgg/trends/*.

[2] Intergovernmental Panel on Climate Change, *Summary for Policymakers, Climate Change 2014: Impacts, Adaptation, and Vulnerability* 5 (2014).

[3] James Hansen, *et al., Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature,* PLOS ONE 8:12 (2013) [hereinafter *Assessing "Dangerous Climate Change"*].

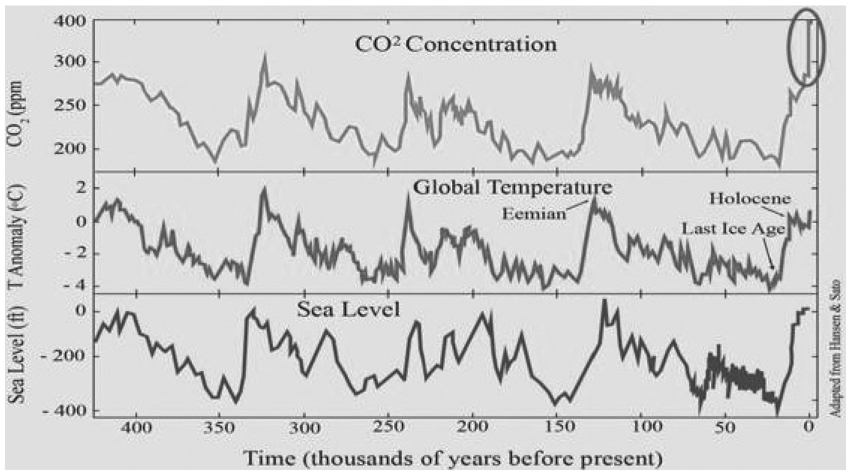
[4] The Camp Creek fire was the 2018 California fire, the deadliest and most destructive in the state's history, that burned over 150,000 acres (almost 240 square miles).

[5] Steven W. Running, *Declaration in Support of Plaintiffs,* ***Juliana*** *v.* ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-12-Running-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–12 (9th Cir. Feb. 7, 2019).

[6] James Hansen, *Storms of My Grandchildren* 166 (2009).

level all move together (see *Figure 1*). Humans have caused CO_2 levels to shoot off the chart (circled in red), rising to levels unprecedented over the past 3 million years, and causing the energy imbalance.[7]

Figure 1



Evidence from the paleo-climate record showing the relationship between CO_2 concentration, global temperature, and sea level.

(2) Ice Sheets and Sea Level Rise

The last time the ice sheets appeared stable in the modern era was in the 1980s when the atmospheric CO_2 concentration was below 350 ppm. The consequences of >350 ppm and 1 °C of warming are already visible, significant, and dangerous for humanity. With just 1 °C of warming, glaciers in all regions of the world are shrinking, and the rate at which they are melting is accelerating.[8] Large parts of the Greenland and Antarctic ice sheets, which required millennia to grow, are teetering on the edge of irreversible disintegration, a point that if reached, would lock-in major ice sheet mass loss, sea level rise of many meters, and worldwide loss of coastal cities—a consequence that would be irreversible on any timescale relevant to humanity (see *Figure 2*).[9] Greenland's ice sheet melt is currently occurring faster than anytime during the last 3½ centuries, with a 33% increase alone since the 20th century.[10] The paleo-climate record shows the last time atmospheric CO_2 levels were over 400 ppm, the seas were **70′ higher** than they are today and that heating consistent with CO_2 concentrations as low as 450 ppm may have been enough to melt almost all of Antarctica.[11] While many experts are predicting multi-meter sea

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[7] Willeit, *et al., Mid-Pleistocene transition in glacial cycles explained by declining CO_2 and regolith removal.* SCIENCE ADVANCES (2019).

[8] Zemp, *et al., Global glacier mass changes and their contributions to sea-level rise from 1961–2016.* NATURE (2019); B. Menounos, *Heterogeneous Changes in Western North American Glaciers Linked to Decadal Variability in Zonal Wind Strength,* GEOPHYSICAL RESEARCH LETTERS (2018).

[9] Hansen, *Assessing "Dangerous Climate Change,"* at 13; see also James Hansen, *et al., Ice Melt, Sea Level Rise and Superstorms; Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations that 2 °C Global Warming Could be Dangerous,* ATMOS. CHEM. & PHYS. 16, 3761 (2016) [hereinafter *Ice Melt, Sea Level Rise and Superstorms*].

[10] Trusel, L.D., *et al., Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming,* NATURE (2018).

[11] Dec. of Dr. James E. Hansen, *Juliana,, et al.,* v. *United States, et al.,* No. 6:15–cv–01517–TC, 14 (D. Or. Aug. 12, 2015); Intergovernmental Panel on Climate Change: 2007 Working Group I: *The Physical Science Basis, Chapter 6.3.2, What Does the Record of the Mid-Pliocene Show?;* Dowsett & Cronin, *High eustatic sea level during the middle Pliocene: Evidence from the southeastern U.S. Atlantic Coastal Plain,* GEOLOGY (1990); Shackleton, *et al., Pliocene stable isotope stratigraphy of ODP Site 846,* PROCEEDINGS OF THE OCEAN DRILLING PROGRAM, SCIENTIFIC RESULTS (1995).

level rise this century, even NOAA's modest estimate of 3–6′ by 2100 would impact between 4 and 13 million Americans (see *Figure 3*).[12]

Figure 2

Antarctic melt water from the Nansen ice shelf.

Most climate models represent sea level rise as a gradual linear response to melting ice sheets, but the historic climate record shows something very different. In reality, seas do not rise slowly and predictably but rather in quick pulses as ice sheets destabilize.[13] Scientists believe we have a chance to preserve the large ice sheets of Greenland and Antarctica and most of our shorelines and ecosystems if we limit long-term warming by the end of the century to no more than 1 °C above pre-industrial levels (short-term warming will inevitably exceed 1 °C but must not exceed 1 °C for more than a short amount of time).

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[12] NOAA, *Examining Sea Level Rise Exposure for Future Populations, https://coast.noaa.gov/digitalcoast/stories/population-risk.*

[13] Wanless, H.R., *et al., Dynamics and Historical Evolution of the Mangrove/Marsh Fringe Belt of Southwest Florida, in Response to Sea-level History, Biogenic Processes, Storm Influences and Climatic Fluctuations.* Semi-annual Research Report (June 1993 to February 1994); Hansen, *Ice Melt, Sea Level Rise and Superstorms,* at 3761; Hansen, *Assessing "Dangerous Climate Change,"* at 20.

Figure 3

South Florida, including Miami, will face significant inundation with 6′ of sea level rise.

(3) Ocean Warming and Acidification

Our oceans have absorbed 93% of the excess heat in the atmosphere trapped by greenhouse gases (see *Figure 4*) as well as approximately 30% of CO_2 emitted into the atmosphere, causing ocean temperatures to surge and the ocean to become more acidic.[14] Indeed, our oceans are warming much more rapidly than previously-thought.[15] Many marine ecosystems, and particularly coral reef ecosystems, cannot tolerate the increased warning and acidity of ocean waters that result from increased CO_2 levels.[16] At today's CO_2 concentration, around 407 ppm,[17] critically important ocean ecosystems, such as coral reefs, are rapidly declining and will be irreversibly damaged from high ocean temperatures and repeated mass bleaching events if we do not quickly curtail emissions (see *Figures 5* and *6*).[18] According to the Intergovernmental Panel on Climate Change, bleaching events are occurring more frequently than the IPCC previously projected and 70–90% of the world's coral reefs could disappear as soon as 2030 (the IPCC also predicts 99% of coral reefs will die with 2 °C warming).[19] Even the recent National Climate Assessment acknowledged that coral reefs in Florida, Hawaii, Puerto Rico, and the U.S. Virgin Islands have been harmed by mass bleaching and coral diseases and could disappear by

[14] Hansen, *Assessing "Dangerous Climate Change,"* at 1; Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013); Cheng, *et al., How fast are the oceans warming?* 363 SCIENCE 128 (2019); National Oceanic and Atmospheric Administration, *What is Ocean Acidification?, https://oceanservice.noaa.gov/facts/acidification.html.*

[15] Cheng, L., *et al., How fast are the oceans warming?,* 363 SCIENCE 128 (2019).

[16] Hughes, *et al., Global warming impairs stock-recruitment dynamics of corals,* NATURE (2019).

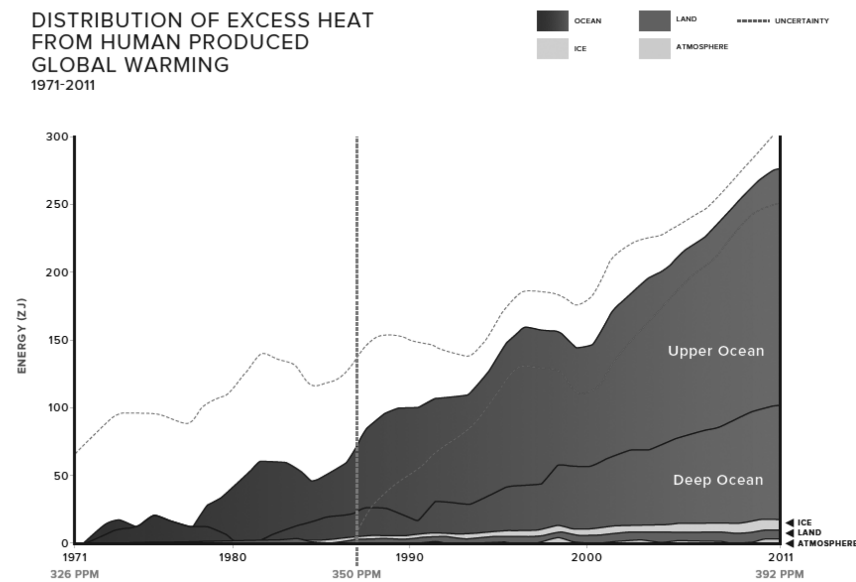
[17] Ed Dlugokencky and Pieter Tans, NOAA/ESRL, *www.esrl.noaa.gov/gmd/ccgg/trends/*.

[18] Frieler, K., *et al., Limiting global warming to 2 degrees C is unlikely to save most coral reefs.* NATURE CLIMATE CHANGE 3: 165–170. (2013); Veron, J.,, *et al; The coral reef crisis: The critical importance of <350ppm CO_2.* MARINE POLLUTION BULLETIN 58: 1428–1436 (2009); Hughes, T., *et al., Spatial and temporal patterns of mass bleaching of corals in the Anthropocene,* SCIENCE 359: 80–83 (2018); Hughes, T., *et al. Global warming impairs stock-recruitment dynamics of corals,* NATURE (2019).

[19] Hoegh-Guldberg, Ove, *et al., Impacts of 1.5 °C Global Warming on Natural and Human Systems.* In *Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* at pp. 225–226 (2018); IPCC, *Summary for Policymakers of IPCC Special Report on Global Warming of 1.5 °C Approved by Governments* (2018).

mid-century as a result of warming waters.[20] Scientists believe we can protect marine life and prevent massive bleaching and die-off of coral reefs only by rapidly returning CO_2 levels to below 350 ppm.[21]

Figure 4



Over 90% of the excess energy from human caused climate change has been absorbed by the oceans, adding energy to storms and harming coral reefs around the globe.

No scientific institution, including the IPCC, has ever concluded that 2 °C warming or 450 ppm would be safe for ocean life. According to Dr. Ove Hoegh-Guldberg, one of the world's leading experts on ocean warming and acidification, and a Coordinating Lead Author on the "Oceans" chapter of the IPCC's Fifth Assessment Report and on the "Impacts of 1.5 °C global warming on natural and human systems" of the IPCC's Special Report on 1.5 °C:

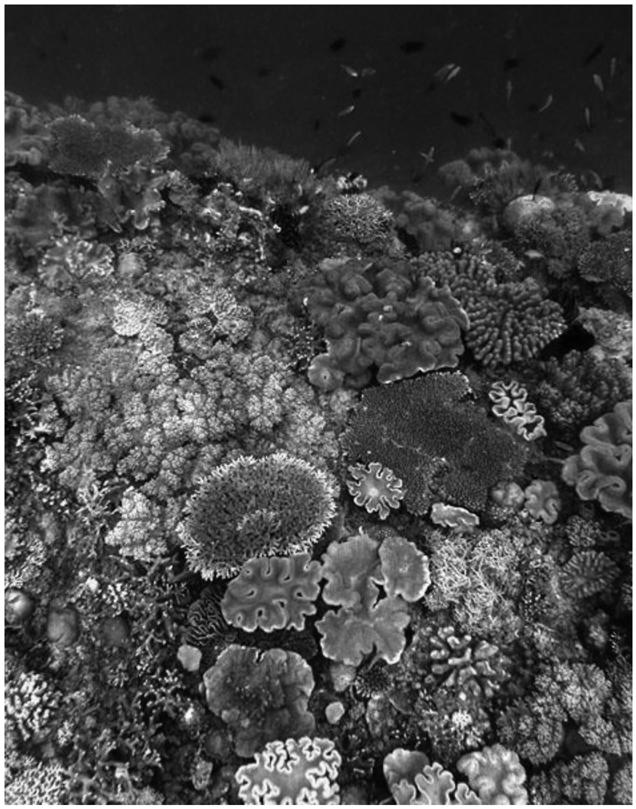
> *"Allowing a temperature rise of up to 2 °C would seriously jeopardize ocean life, and the income and livelihoods of those who depend on healthy marine ecosystems. Indeed, the best science available suggests that coral dominated reefs will completely disappear if carbon dioxide concentrations exceed much more than today's concentrations. Failing to restrict further increases in atmospheric carbon dioxide will eliminate coral reefs as we know them and will deny future generations of children from enjoying these wonderful ecosystems."*[22]

[20] Pershing, A.J., *et al., Oceans and Marine Resources.* In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II,* USGCRP (2018)[.]

[21] Veron, J., *et al., The coral reef crisis: The critical importance of <350 ppm CO_2,* 58 MARINE POLLUTION BULLETIN 1428 (2009).

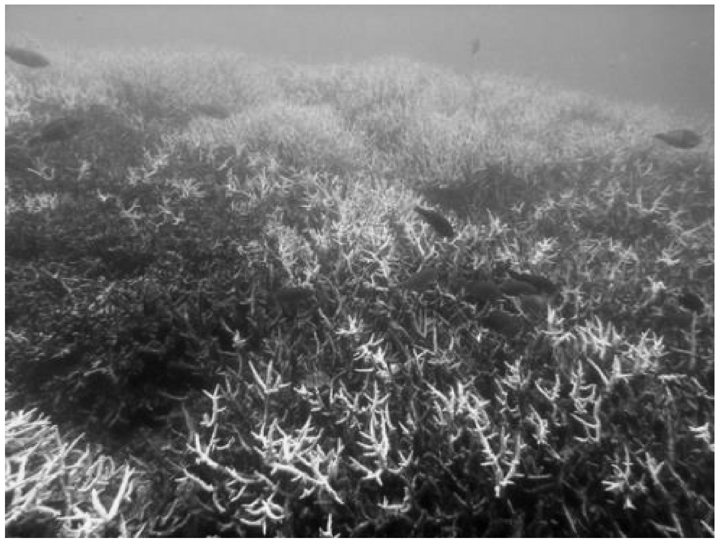
[22] *Id.*

Figure 5



Healthy coral like this are already gravely threatened and will likely die with warming of 1.5 °C.

Figure 6



Bleached coral from warmer ocean temperatures.

Additional Observations Illustrate the Dangers of Increased Warming

In addition to the evidence discussed above which illustrates the necessity of ensuring that the atmospheric CO_2 concentration returns to no more than 350 ppm, based on present day observations about climate impacts occurring **now,** it is clear that the present level of 1 °C is already causing significant climate impacts and additional warming will exacerbate these already dangerous impacts. Climate impacts that are already being experienced today include:

- Declining snowpack and rising temperatures are increasing the length and severity of drought conditions, especially in the western United States and Southwest, causing problems for agriculture users, forcing some people to relocate, and leading to water restrictions.[23]
- In the western United States, the wildfire season is now almost 3 months longer (87 days) than it was in the 1980s.[24]
- Extreme weather events, such as intense rainfall events that cause flooding, are increasing in frequency and severity because a warmer atmosphere holds more moisture.[25] What are supposedly 1-in-1,000-year rainfall events are now occurring with alarming frequency—in 2018 there were at least five such events.[26]
- Tropical storms and hurricanes are increasing in intensity, both in terms of rainfall and windspeed, as warmer oceans provide more energy for the storms (we saw this with Hurricanes Harvey, Irma, and Maria in 2017) (*Figure 7*).[27]

[23] Steven W. Running, *Declaration in Support of Plaintiffs,* ***Juliana*** *v.* ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-12-Running-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–12 (9th Cir. Feb. 7, 2019).

[24] Steven W. Running, *Declaration in Support of Plaintiffs,* ***Juliana*** *v.* ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-12-Running-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–12 (9th Cir. Feb. 7, 2019).

[25] Kevin E. Trenberth, *Declaration in Support of Plaintiffs,* ***Juliana*** *v.* ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-3-Trenberth-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–3 (9th Cir. Feb. 7, 2019).

[26] Belles, F., *America's 'One-in-1,000-Year' Rainfall Events in 2018,* The Weather Channel (Sept. 27, 2018).

[27] Kevin E. Trenberth, *Declaration in Support of Plaintiffs,* ***Juliana*** *v.* ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-3-Trenberth-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–3 (9th Cir. Feb. 7, 2019).

Figure 7

Flooding in Port Arthur, Texas on August 13, 2018 after Hurricane Harvey.

- Terrestrial ecosystems are experiencing compositional and structural changes, with major adverse consequences for ecosystem services.[28]
- Terrestrial, freshwater, and marine species are experiencing a significant decrease in population size and geographic range, with some going extinct and others are facing the very real prospect of extinction—the rapid rate of extinctions has been called the 6th mass extinction.[29]
- Human health and well-being are already being affected by heat waves, floods, droughts, and extreme events; infectious diseases; quality of air, food, and water.[30] Doctors and leading medical institutions are calling climate change a "health emergency."[31] Children are being uniquely impacted by climate change.[32]
- In addition to physical harm, climate change is causing mental health impacts, ranging from stress to suicide, due to exposure to climate impacts, displacement, loss of income, chronic stress, and other impacts of climate change.[33]
- As Congress has recognized, "climate change is a direct threat to the national security of the United States and is impacting stability in areas of the world both where the United States Armed Forces are operating today, and where

[28] Nolan, *et al., Past and future global transformation of terrestrial ecosystems under climate change,* SCIENCE (2018).

[29] G. Ceballos, *et al., Accelerated modern human-induced species losses: Entering the sixth mass extinction,* SCIENCE Advances (2015); Steven W. Running, *Expert Report, **Juliana** v. **United States*** (*https://www.ourchildrenstrust.org/s/Doc-264-1-Running-Expert-Report.pdf*), No. 6:15–cv–01517–TC, Doc. 264–1 (D. Or. June 28, 2018).

[30] Ebi, K. L., *et al., Human Health.* In IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II, USGCRP (2018).

[31] Solomon, C.G. & LaRocque R.C., *Climate Change—A Health Emergency,* N. ENGL. J. MED. 380:3 (2019).

[32] May, C., *et al., Northwest.* In IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II, USGCRP (2018); Watts, N., *et al., The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come,* LANCET, Vol. 392 at 2482 (2018); *Brief of Amici Curiae Public Health Experts, Public Health Organizations, and Doctors in Support of Plaintiffs* (*https://www.ourchildrenstrust.org/s/DktEntry-47-Amicus-of-Public-Health-Experts-ISO-Pls.pdf*), No. 18–36082, Doc. 47 (9th Cir. Mar. 1, 2019).

[33] Lise Van Susteren, *Expert Report, **Juliana** v. **United States*** (*https://www.ourchildrenstrust.org/s/Doc-271-1-Van-Susteren-Expert-Report.pdf*), No. 6:15–cv–01517–TC, Doc. 271–1 (D. Or. June 28, 2018).

strategic implications for future conflict exist."[34] Senior military leaders have called climate change "*the* most serious national security threat facing our Nation today,"[35] a conclusion similarly recognized by our nation's intelligence community.[36] Climate change is increasing food and water shortages, pandemic disease, conflicts over refugees and resources, and destruction to homes, land, infrastructure, and military assets, directly threatening our military personnel and the "Department of Defense's ability to defend the Nation" (see *Figure 8*).[37]

Figure 8

Offutt Air Force Base was impacted by flood waters during flooding in Nebraska during spring 2019.

- Climate change is already causing vast economic harm in the United States. Since 1980 the United States has experienced 246 climate and weather disasters that each caused damages in excess of $1 billion, for a total cost of $1.6 trillion.[38] In 2018 alone, Congress appropriated more than $130 billion for weather and climate related disasters.[39]

These already serious impacts will grow in severity and will impact increasingly large numbers of people and parts of the world if CO_2 concentrations continue to rise. If we want our children and grandchildren to have a safe planet to live on, full of health and biodiversity rather than chaos and conflict, we must follow the best scientific prescription to restore Earth's energy balance and avoid the destruction of our planet's atmosphere, climate, and oceans.

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[34] *National Defense Authorization Act for Fiscal Year 2018,* Pub. L. No. 115–91, 131 Stat. 1358.

[35] Vice Admiral Lee Gunn, USN (Ret.), *Declaration in Support of Plaintiffs,* ***Juliana*** v. ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-17-Gunn-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–17 (9th Cir. Feb. 7, 2019) (emphasis in original); see also CNA Military Advisory Board, *National Security and the Accelerating Risks of Climate Change* (2014), *https://www.cna.org/cna_files/pdf/MAB_5-8-14.pdf*.

[36] National Intelligence Council, *Implications for U.S. National Security of Anticipated Climate Change* (Sept. 2016), *https://www.dni.gov/files/documents/Newsroom/Reports and Pubs/Implications_for_US_National_Security_of_Anticipated_Climate_Change.pdf*.

[37] U.S. Dep't of Defense, *2014 Climate Change Adaptation Roadmap* (2014), *https://www.acq.osd.mil/eie/downloads/CCARprint_wForward_e.pdf*.

[38] NOAA, *Billion Dollar U.S. Weather/Climate Disasters 1980–2019* (2019), *http://www.ncdc.noaa.gov/billions/events.pdf*.

[39] U.S. House of Representatives Committee on the Budget, *The Budgetary Impact of Climate Change* 2 (Nov. 27, 2018).

International Political Targets of 1.5 °C Or 2 °C Are Not Science-Based and Are Not Safe

International, politically-recognized targets like 1.5 °C or "well below" 2 °C—which are commonlyassociated with long-term atmospheric CO_2 concentrations of 425 and 450 ppm, respectively—have not been and are not presently considered safe or scientifically-sound targets for present or future generations.

Importantly, the Intergovernmental Panel on Climate Change ("IPCC") has never established nor endorsed a target of 1.5 °C or 2 °C warming as a limit below which the climate system will be stable.[40] It is beyond the IPCC's declared mandate to endorse a particular threshold of warming as "safe" or "dangerous." As the IPCC makes clear, "each major IPCC assessment has examined the impacts of [a] multiplicity of temperature changes but has left [it to the] political processes to make decisions on which thresholds may be appropriate."[41]

Neither 1.5 °C nor 2 °C warming above pre-industrial levels has ever been considered "safe" from either a political or scientific point of view. The 2 °C figure was originally adopted in the political arena "from a set of heuristics," and it has retained predominantly political character ever since.[42] It has recently been all-but-abandoned as a credible policy goal, in light of the findings in IPCC's 1.5 °C Special Report, and the mounting evidence leading up to its publication, that 2 °C would be catastrophic relative to lower, still-achievable levels of warming.[43]

On the other hand, the idea of a 1.5 °C target was first raised by the Association of Small Island States (AOSIS) in the negotiations leading up to the ill-fated 2009 UNFCCC Conference of Parties in Copenhagen.[44] AOSIS, however, was explicitly advocating a *well below* 1.5 °C and well below 1 °C target, on the basis of the research of Dr. James Hansen and his colleagues.[45] Political compromise on this science-based target then led to the adoption of a goal of "pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" in Article 2 of the Paris Agreement. Yet the 2018 IPCC Special Report on 1.5 °C has made clear that allowing a temperature rise of 1.5 °C:

> is **not considered 'safe'** for most nations, communities, ecosystems, and sectors and poses significant risks to natural and human systems as compared to current warming of 1 °C (*high confidence*) . . . .[46]

Dr. James Hansen warns that "distinctions between pathways aimed at 1 °C and 2 °C warming are much greater and more fundamental than the numbers 1 °C and 2 °C themselves might suggest. These fundamental distinctions make scenarios with

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[40] Dec. of Dr. James E. Hansen, *Juliana, et al.,* v. *United States, et al.,* No. 6:15–cv–01517–TC, 5 (D. Or. Aug. 12, 2015).

[41] IPCC, *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report,* 125 (2014), *http://report.mitigation2014.org/report/ipcc_wg3_ar5_chapter1.pdf*.

[42] Randalls, S. *History of the 2 °C Temperature Target. 1.* WIREs CLIMATE CHANGE 598, 603 (2010); Jaeger, C. and J. Jaeger, *Three views of two degrees.* 11 (Suppl. 1) REGIONAL ENVIRONMENTAL CHANGE S15 (2011).

[43] IPCC, *Summary for policymakers at 13–14, Climate Change 2014: Impacts, Adaptation, and Vulnerability* (2014), *http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf;* UNFCCC, Report on the structured expert dialogue on the 2013–2015 review, 18 (2015), *http://unfccc.int/resource/docs/2015/sb/eng/inf01.pdf;* Petra Tschakert, *1.5* °C or *2* °C*: a conduit's view from the science-policy interface at COP20 in Lima, Peru,* CLIMATE CHANGE RESPONSES 8 (2015), *http://www.climatechangeresponses.com/content/2/1/3;* IPCC, *Global warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5* °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018), *https://www.ipcc.ch/sr15/*.

[44] See Webster, R. *A brief history of the 1.5C target.* CLIMATE CHANGE NEWS (December 10, 2015), *http://www.climatechangenews.com/2015/12/10/a-brief-history-of-the-1-5c-target/; Submission from Grenada on behalf of AOISIS to the Ad Hoc Working Group on Further Commitments for Annex I Parties Under the Kyoto Protocol, U.N.* Doc. FCCC/KP/AWG/2009/MISC.1/Add.1 (25 March 2009), *https://unfccc.int/sites/default/files/resource/docs/2009/awg7/eng/misc01a01.pdf*.

[45] *Submission from Grenada on behalf of AOISIS to the Ad Hoc Working Group on Further Commitments for Annex I Parties Under the Kyoto Protocol, U.N.* Doc. FCCC/KP/AWG/2009/MISC.1/Add.1 (25 March 2009), *https://unfccc.int/sites/default/files/resource/docs/2009/awg7/eng/misc01a01.pdf*, citing Hansen, J., *et al., Target Atmospheric CO_2: Where Should Humanity Aim?* 2 THE OPEN ATMOSPHERIC SCIENCE JOURNAL 217 (2008).

[46] Roy, J., *et al., Sustainable Development, Poverty Eradication and Reducing Inequalities.* In GLOBAL WARMING OF 1.5°C. AN IPCC SPECIAL REPORT ON THE IMPACTS OF GLOBAL WARMING OF 1.5°C ABOVE PRE-INDUSTRIAL LEVELS AND RELATED GLOBAL GREENHOUSE GAS EMISSION PATHWAYS, IN THE CONTEXT OF STRENGTHENING THE GLOBAL RESPONSE TO THE THREAT OF CLIMATE CHANGE, SUSTAINABLE DEVELOPMENT, AND EFFORTS TO ERADICATE POVERTY at 447 (2018) (emphasis added)

2 °C or more global warming far more dangerous; so dangerous, we [James Hansen, *et al.*] suggest, that aiming for the 2 °C pathway would be foolhardy."[47] This target is at best the equivalent of "flip[ping] a coin in the hopes that future generations are not left with few choices beyond mere survival. This is not risk management, it is recklessness and we must do better."[48]

Tellingly, more than 45 eminent scientists from over 40 different institutions have published in peer-reviewed journals finding that the maximum level of atmospheric CO_2 consistent with protecting humanity and other species is 350 ppm, and no one, including the IPCC, has published any scientific evidence to counter that 350 is the maximum safe concentration of CO_2.[49]

A 1.5° Or 2 °C Target Risks Locking-In Dangerous Feedbacks

The longer the length of time atmospheric CO_2 concentrations remain at dangerous levels (*i.e.,* above 350 ppm) and there is an energy imbalance in the atmosphere, the risk of triggering, and locking-in, dangerous warming-driven feedback loops increases. The 1.5 °C or 2 °C target reduces the likelihood that the biosphere will be able to sequester CO_2 due to carbon cycle feedbacks and shifting climate zones.[50] As temperatures warm, forests burn and soils warm, releasing their carbon. These natural carbon "sinks" become carbon "sources" and a portion of the natural carbon sequestration necessary to drawdown excess CO_2 simply disappear. Another dangerous feedback includes the release of methane, a potent greenhouse gas, as the global tundra thaws.[51] These feedbacks might show little change in the short-term, but can hit a point of no return, even at a 1.5 °C or 2 °C temperature increase, which will trigger accelerated heating and sudden *and irreversible* catastrophic impacts. Moreover, an emission reduction target aimed at 2 °C would "yield a larger eventual warming because of slow feedbacks, probably at least 3 °C."[52] Once a temperature increase of 2 °C is reached, there will already be "additional climate change 'in the pipeline' even without further change of atmospheric composition."[53]

It Is Technologically and Economically Feasible To Reduce CO_2 Levels to 350 ppm by 2100

There are two steps to reducing CO_2 levels to 350 ppm by the end of the century: (1) reducing CO_2 emissions; and (2) sequestering excess CO_2 already in the atmosphere. Carbon dioxide emission reductions of approximately 80% by 2030 and close to 100% by 2050 (in addition to the requisite CO_2 sequestration) are necessary to keep long-term warming to 1 °C and the atmospheric CO_2 concentration to 350 ppm. Emission reduction targets that seek to reduce CO_2 emissions by 80% by 2050 are consistent with long-term warming of 2 °C and an atmospheric CO_2 concentration of 450 ppm, which, as described above, would result in catastrophic and irreversible impacts for the climate system and oceans. Importantly, it is economically and technologically feasible to transition the entire U.S. energy system to a zero-CO_2 energy system by 2050 and to drawdown the excess CO_2 in the atmosphere through reforestation and carbon sequestration in soils.[54]

Deep Decarbonization Pathways Project and Evolved Energy Research recently completed research and very sophisticated modeling describing a nearly complete phase out of fossil fuels in the U.S. by 2050.[55] They describe six different technologically feasible pathways to drastically, and quickly, cut our reliance on fossil fuels

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[47] *Id.* at 15.

[48] Matt Vespa, *Why 350? Climate Policy Must Aim to Stabilize Greenhouse Gases at the Level Necessary to Minimize the Risk of Catastrophic Outcomes,* 36 ECOLOGY LAW CURRENTS 185, 186 (2009), *http://www.biologicaldiversity.org/publications/papers/Why_350.pdf*.

[49] James Hansen, *et al., Target Atmospheric CO_2: Where Should Humanity Aim?* (2008); James Hansen, *et al., Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature* (2013); James Hansen, *et al., Ice Melt, Sea Level Rise and Superstorms: Evidence From Paleoclimate Data, Climate Modeling, and Modern Observations That 2 °C Global Warming Could Be Dangerous* (2016); James Hansen, *et al., Young People's Burden: Requirement of Negative CO_2 Emissions* (2017); Veron, J., *et al., The Coral Reef Crisis: The Critical Importance of <350 ppm CO_2* (2009); Frieler, K., *et al., Limiting global warming to 2 °C is unlikely to save most coral reefs* (2012).

[50] *Id.* at 15, 20.

[51] *Id.*

[52] Hansen, *Assessing "Dangerous Climate Change,"* at 15.

[53] *Id.* at 19.

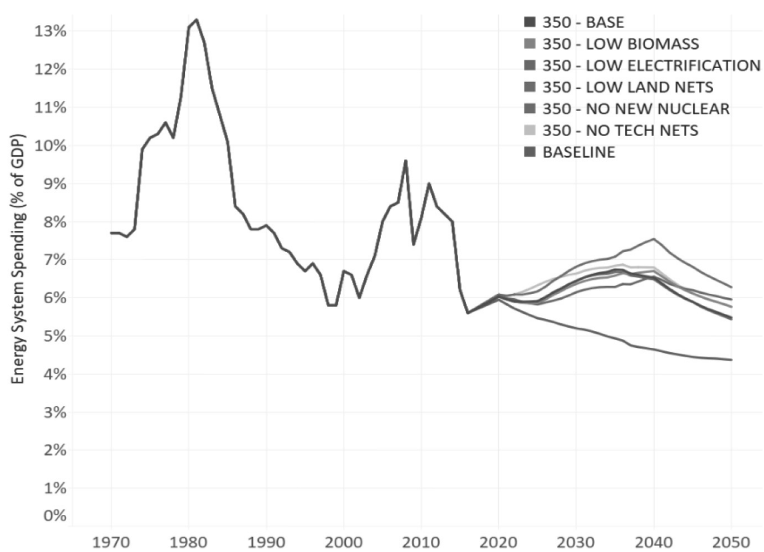
[54] *See* Mark Z. Jacobson, *et al., 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States*, 8 ENERGY & ENVTL. SCI. 2093 (2015) (for plans on how the United States and over 100 other countries can transition to a 100% renewable energy economy see *www.thesolutionsproject.org*); see also Arjun Makhijani, *Carbon-Free, Nuclear-Free: A Roadmap for U.S. Energy Policy* (2007); B. Haley, *et al., 350 ppm pathways for the United States* (2019).

[55] B. Haley, *et al.,* 350 ppm pathways for the United States (2019).

and achieve the requisite level of emissions reductions in the U.S. while meeting our nation's forecasted energy needs. All of the 350 ppm pathways rely on four pillars of action: (a) investment in energy efficiency; (b) electrification of everything that can be electrified; (c) shifting to very low-carbon and primarily renewable electricity generation; and (d) carbon dioxide capture as fossil fuels are phased out. The six scenarios are used to evaluate the ability to meet the targets even absent one key technology. For example, one scenario describes a route to 350 absent construction of new nuclear facilities; another illustrates getting to 350 with extremely limited biomass technology; still another describes a way to 350 without any carbon capture and storage. Even absent a key technology, each of these six routes are viable and cost effective.

The study also concludes that the cost of the energy system transition is affordable. The total cost of supplying and using energy in the U.S. in 2016 was about 5.6% of GDP (see *Figure 9*).[56] A transition from fossil fuels to low carbon energy sources is expected to increase those costs by no more than an additional two to three percent of GDP. Even with this small and temporary added expense, the cost would still be well below the 9.5% of GDP spent on the energy system in 2009 (not to mention well below the harm to the economy caused by climate change). Once the transition is complete, the cost of energy will remain low and stable because we will no longer be dependent on volatile global fossil fuel markets for our energy supplies. As Nobel Laureate Economist Dr. Joseph Stiglitz has stated: "[t]he benefits of making choices today that limit the economic costs of climate change far outweigh any economic costs associated with limiting our use of fossil fuels."[57]

Figure 9



Historic and Projected Costs of Energy in the U.S.

Other experts have already prepared plans for all 50 U.S. states as well as for over 139 countries that demonstrate the technological and economic feasibility of transitioning off of fossil fuels toward 100% of energy, for all energy sectors, from clean and renewable energy sources: wind, water, and sunlight by 2050 (with 80% reductions in fossil fuels by 2030).[58]

Products already exist that enable new construction or retrofits that result in zero greenhouse gas buildings. We have the technology to meet all electricity needs with

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[56] B. Haley, *et al.,* 350 ppm pathways for the United States (2019).

[57] Joseph E. Stiglitz, Ph.D., *Declaration in Support of Plaintiffs,* ***Juliana*** *v.* ***United States*** (*https://www.ourchildrenstrust.org/s/DktEntry-21-14-Stiglitz-Dec-ISO-Urgent-Motion-for-Preliminary-Injunction.pdf*), No. 18–36082, Doc. 21–14 (9th Cir. Feb. 7, 2019).

[58] Mark Z. Jacobson, *et al., 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States,* 8 ENERGY & ENVTL. SCI. 2093 (2015). For a graphic depicting the overview of the plan for the United States see: *https://thesolutionsproject.org/why-clean-energy/#/map/countries/location/USA*.

zero-emission electric generation. We know how to achieve zero-emission transportation, including aviation. These actions result in other benefits, such as improved health, job creation, and savings on energy costs.

The amount of natural carbon sequestration required is also proven to be feasible. Researchers have evaluated the potential to drawdown excess carbon dioxide in the atmosphere by increasing the carbon stored in forests, soils, and wetlands, and have found significant potential for these natural systems to support a return to 350 ppm by the end of the century.[59] We know the agricultural, rangeland, wetland, and forest management practices that decrease greenhouse gas emissions and increase sequestration.

There is no scientific, technological, or economic reason to *not* adopt a 350 ppm and 1 °C by 2100 target. There are abundant reasons for doing so, not the least of which is to do our best through human laws to respect the laws of nature and create a safe and healthy world for children and future generations who will walk this Earth.

Exhibit E.1: 350 PPM Pathways for the United States (2019), Executive Summary, Evolved Energy Research

May 8, 2019

Prepared by BEN HALEY, RYAN JONES, GABE KWOK, JEREMY HARGREAVES & JAMIL FARBES, *Evolved Energy Research*

JAMES H. WILLIAMS, *University of San Francisco, Sustainable Development Solutions Network*

Executive Summary

This report describes the changes in the U.S. energy system required to reduce carbon dioxide (CO_2) emissions to a level consistent with returning atmospheric concentrations to 350 parts per million (350 ppm) in 2100, achieving net negative CO_2 emissions by mid-century, and limiting end-of-century global warming to 1 °C above pre-industrial levels. The main finding is that 350 ppm pathways that meet all current and forecast U.S. energy needs are technically feasible using existing technology, and that multiple alternative pathways can meet these objectives in the case of limits on some key decarbonization strategies. These pathways are economically viable, with a net increase in the cost of supplying and using energy equivalent to about 2% of GDP, up to a maximum of 3% of GDP, relative to the cost of a business-as-usual baseline. These figures are for energy costs only and do not count the economic benefits of avoided climate change and other energy-related environmental and public health impacts, which have been described elsewhere.[1]

This study builds on previous work, *Pathways to Deep Decarbonization in the United States* (2014) and *Policy Implications of Deep Decarbonization in the United States* (2015), which examined the requirements for reducing GHG emissions by 80% below 1990 levels by 2050 ("80 x 50").[2] These studies found that an 80% reduction by mid-century is technically feasible and economically affordable, and attainable using different technological approaches. The main requirement of the transition is the construction of a low carbon infrastructure characterized by high energy efficiency, low-carbon electricity, and replacement of fossil fuel combustion with decarbonized electricity and other fuels, along with the policies needed to achieve this transformation. The findings of the present study are similar but reflect both a more stringent emissions limit and the consequences of 5 intervening years without aggressive emissions reductions in the U.S. or globally.

The 80 x 50 analysis was developed in concert with similar studies for other high-emitting countries by the country research teams of the Deep Decarbonization Pathways Project, with an agreed objective of limiting global warming to 2 °C above pre-industrial levels.[3] However, new studies of climate change have led to a growing consensus that even a 2 °C increase may be too high to avoid dangerous impacts. Some scientists assert that staying well below 1.5 °C, with a return to 1 °C or less by the end of the century, will be necessary to avoid irreversible feedbacks to the climate system.[4] A recent report by the IPCC indicates that keeping warming below

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[59] Benson W. Griscom, *et al., Natural Climate Solutions,* PROCEEDINGS OF THE NATIONAL ACADEMIES OF SCIENCES (2017); Joseph E. Fargione, *et al., Natural Climate Solutions for the United States,* SCIENCE ADVANCES (2018).

[1] S*ee e.g., Risky Business: The Bottom Line on Climate Change,* available at *https://riskybusiness.org/*.

[2] Available at *http://usddpp.org/*.

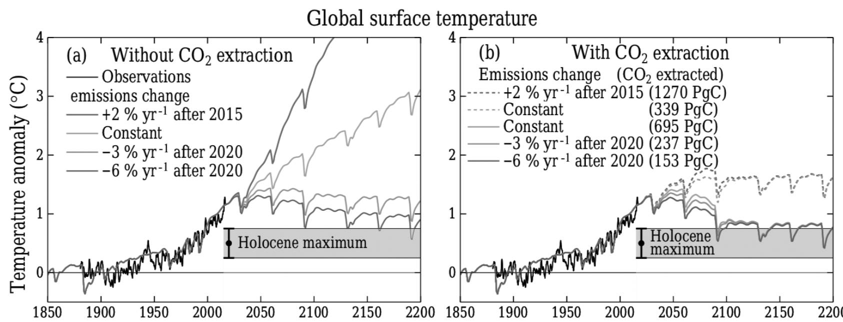
[3] Available at *http://deepdecarbonization.org/countries/*.

[4] James Hansen, *et al.,* (2017) "Young people's burden: requirement of negative CO_2 emissions," *Earth System Dynamics, https://www.earth-syst-dynam.net/8/577/2017/esd-8-577-2017.html*.

1.5 °C will likely require reaching net-zero emissions of CO_2 globally by mid-century or earlier.[5] A number of jurisdictions around the world have accordingly announced more aggressive emissions targets, for example California's recent executive order calling for the state to achieve carbon neutrality by 2045 and net negative emissions thereafter.[6]

In this study we have modeled the pathways—the sequence of technology and infrastructure changes—consistent with net negative CO_2 emissions before mid-century and with keeping peak warming below 1.5 °C. We model these pathways for the U.S. for each year from 2020 to 2050, following a global emissions trajectory that would return atmospheric CO_2 to 350 ppm by 2100, causing warming to peak well below 1.5 °C and not exceed 1.0 °C by century's end.[7] The cases modeled are a 6% per year and a 12% per year reduction in net fossil fuel CO_2 emissions after 2020. These equate to a cumulative emissions limit for the U.S. during the 2020 to 2050 period of 74 billion metric tons of CO_2 in the 6% case and 47 billion metric tons in the 12% case. (For comparison, current U.S. CO_2 emissions are about 5 billion metric tons per year.) The emissions in both cases must be accompanied by increased extraction of CO_2 from the atmosphere using land-based negative emissions technologies ("land NETs"), such as reforestation, with greater extraction required in the 6% case.

Figure ES1



Global surface temperature and CO_2 emissions trajectories. Hansen, *et al.,* 2017.

We studied six different scenarios: five that follow the 6% per year reduction path and one that follows the 12% path. All reach net negative CO_2 by mid-century while providing the same energy services for daily life and industrial production as the Annual Energy Outlook (AEO), the Department of Energy's long-term forecast. The scenarios explore the effects of limits on key decarbonization strategies: bioenergy, nuclear power, electrification, land NETs, and technological negative emissions technologies ("tech NETs"), such as carbon capture and storage (CCS) and direct air capture (DAC).

Table ES1. Scenarios Developed in this Study

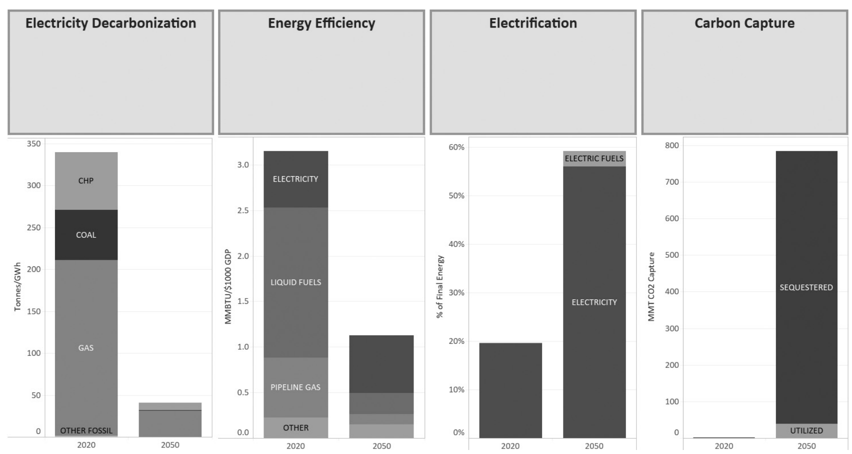
Scenario	Average annual rate of CO_2 emission reduction	2020–2050 maximum cumulative fossil fuel CO_2 (million metric tons)	Year 2050 maximum net fossil fuel CO_2 (million metric tons)	Year 2050 maximum net CO_2 with 50% increase in land sink (million metric tons)
Base	6%	73,900	830	−250
Low Biomass	6%	73,900	830	−250
Low Electrification	6%	73,900	830	−250
No New Nuclear	6%	73,900	830	−250
No Tech NETS	6%	73,900	830	−250
Low Land NETS	12%	57,000	−200	−450

[5] Available at *https://www.ipcc.ch/sr15/*.
[6] Available at *https://www.gov.ca.gov/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf*.
[7] Hansen, *et al.,* (2017).

The scenarios were modeled using two new analysis tools developed for this purpose, EnergyPATHWAYS and RIO. As extensively described in the *Appendix,** these are sophisticated models with a high level of sectoral, temporal, and geographic detail, which ensure that the scenarios account for such things as the inertia of infrastructure stocks and the hour-to-hour dynamics of the electricity system, separately in each of fourteen electric grid regions of the U.S. The changes in energy mix, emissions, and costs for the six scenarios were calculated relative to a high-carbon baseline also drawn from the AEO.

Relative to 80 x 50 trajectories, a 350 ppm trajectory that achieves net negative CO_2 by midcentury requires more rapid decarbonization of energy plus more rapid removal of CO_2 from the atmosphere. For this analysis, an enhanced land sink 50% larger than the current annual sink of approximately 700 million metric tons was assumed.[8] This would require additional sequestration of 25–30 billion metric tons of CO_2 from 2020 to 2100. The present study does not address the cost or technical feasibility of this assumption but stipulates it as a plausible value for calculating an overall CO_2 budget, based on consideration of the scientific literature in this area.[9]

Figure ES2



Four pillars of deep decarbonization—Base case.

Energy decarbonization rests on the four principal strategies ("four pillars") shown in *Figure ES2:* (1) electricity decarbonization, the reduction in emissions intensity of electricity generation by about 90% below today's level by 2050; (2) energy efficiency, the reduction in energy required to provide energy services such as heating and transportation, by about 60% below today's level; (3) electrification, converting end-uses like transportation and heating from fossils fuels to low-carbon electricity, so that electricity triples its share from 20% of current end uses to 60% in 2050; and (4) carbon capture, the capture of otherwise CO_2 that would otherwise be emitted from power plants and industrial facilities, plus direct air capture, rising from nearly zero today to as much as 800 million metric tons in 2050 in some scenarios. The captured carbon may be sequestered or may be utilized in making synthetic renewable fuels.

Achieving this transformation by mid-century requires an aggressive deployment of low-carbon technologies. Key actions include retiring all existing coal power generation, approximately doubling electricity generation primarily with solar and wind power and electrifying virtually all passenger vehicles and natural gas uses in build-

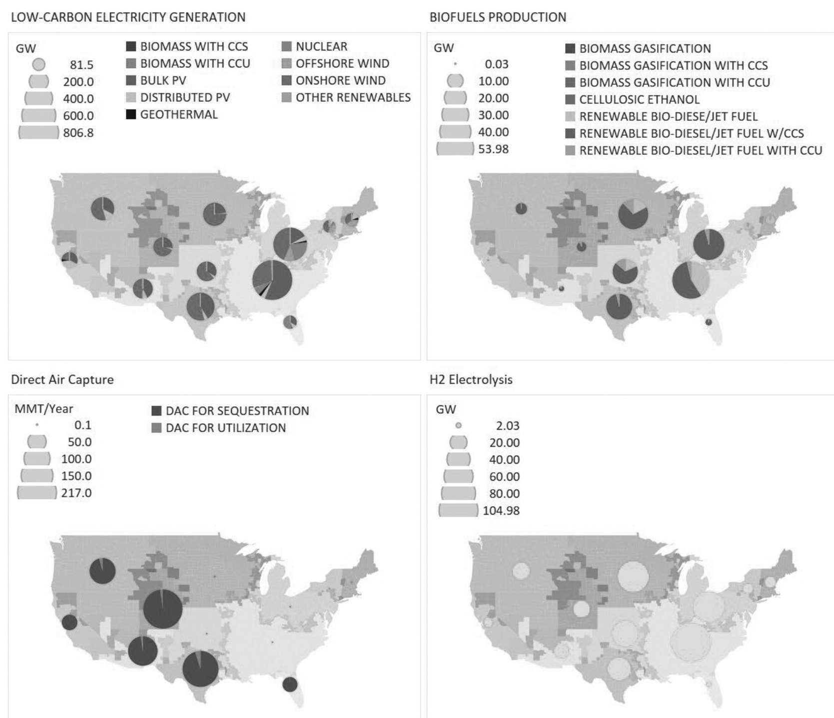
* **Editor's note:** the Our Children's Trust submission for the record for this hearing ***does not*** include **Appendix.** It has been reproduced, as submitted, herein. The full report (which includes the *Appendix*) is retained in Committee file and is available at: *https://docs.wixstatic.com/ugd/294abc_95dfdf602afe4e11a184ee65ba565e60.pdf.*

[8] U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2016,* available at *https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016.*

[9] Griscom, Bronson W., *et al.,* (2017) "Natural climate solutions." *Proceedings of the National Academy of Sciences* 114.44 (2017): 11645–11650; Fargione, Joseph E., *et al.,* (2018) "Natural climate solutions for the United States." *Science Advances* 4.11: eaat1869.

ings. It also includes creating new types of infrastructure, namely large-scale industrial facilities for carbon capture and storage, direct air capture of CO_2, the production of gaseous and liquid biofuels with zero net lifecycle CO_2, and the production of hydrogen from water electrolysis using excess renewable electricity. The scale of the infrastructure buildout by region is indicated in *Figure ES3*.

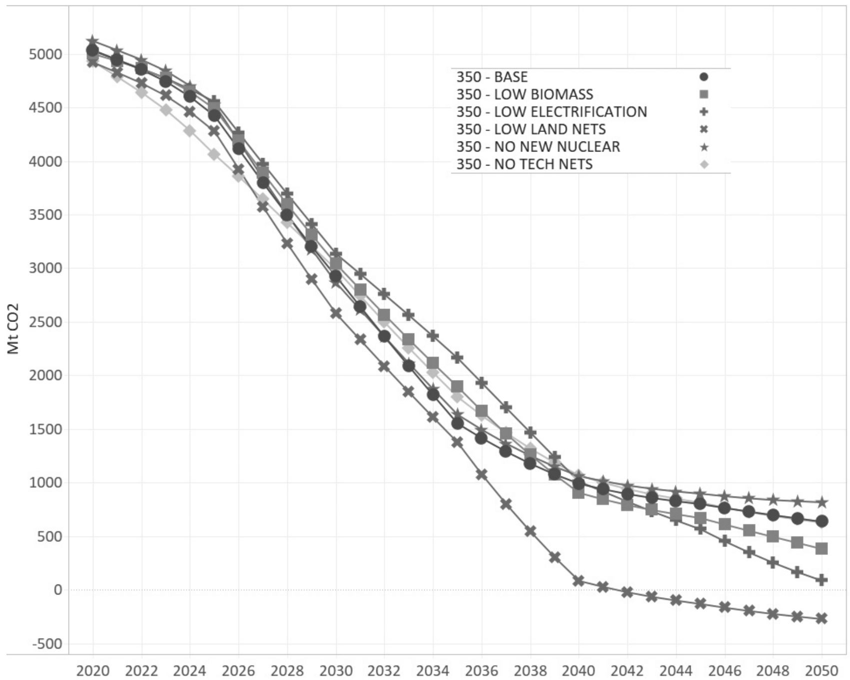
Figure ES3



Regional infrastructure requirements (Low Land NETS scenario).

Figure ES4 shows that all scenarios achieve the steep reductions in net fossil fuel CO_2 emissions to reach net negative emissions by the 2040s, given a 50% increase in the land sink, including five that are limited in one key area. This indicates that the feasibility of reaching the emissions goals is robust due to the ability to substitute strategies. At same time, the more limited scenarios are, the more difficult and/or costly they are relative to the base case with all options available. Severe limits in two or more areas were not studied here but would make the emissions goals more difficult to achieve in the mid-century time frame.

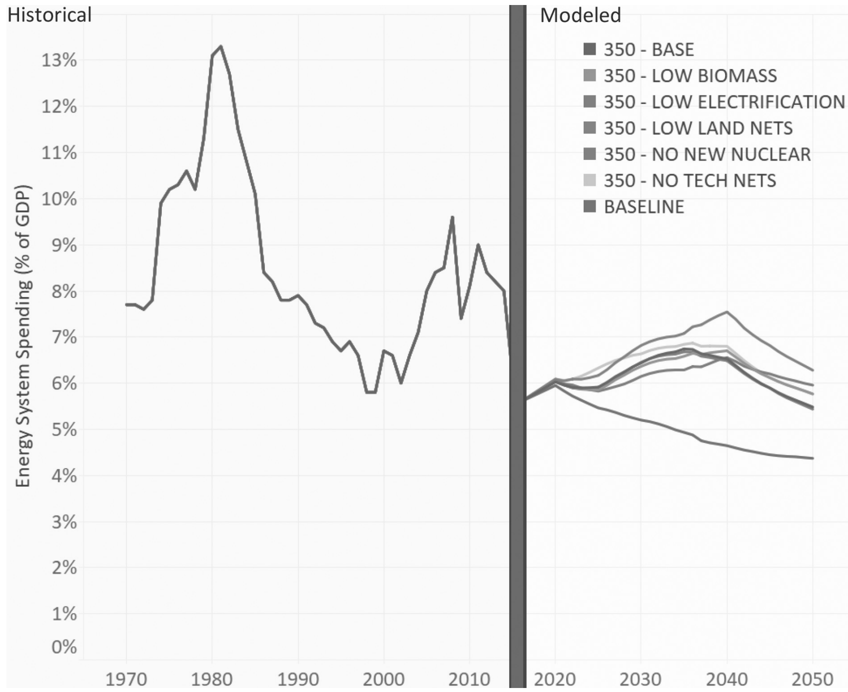
Figure ES4



2020–2050 CO_2 emissions for the scenarios in this study.

Figure ES5 shows U.S. energy system costs as a share of GDP for the baseline case and six 350 ppm scenarios in comparison to historical energy system costs. While the 350 ppm scenarios have a net cost of 2–3% of GDP more than the business as usual baseline, these costs are not out of line with historical energy costs in the U.S. The highest cost case is the Low Land NETs scenario, which requires a 12% per year reduction in net fossil fuel CO_2 emissions. By comparison, the 6% per year reduction cases are more closely clustered. The lowest increase is the Base scenario, which incorporates all the key decarbonization strategies. These costs do not include any potential economic benefits of avoided climate change or pollution, which could equal or exceed the net costs shown here.

Figure ES5



Total energy system costs as percentage of GDP, modeled (R.) and historical (L.).

A key finding of this study is the potentially important future role of "the circular carbon economy." This refers to the economic complementarity of hydrogen production, direct air capture of CO_2, and fuel synthesis, in combination with an electricity system with very high levels of intermittent renewable generation. If these facilities operate flexibly to take advantage of periods of excess generation, the production of hydrogen and CO_2 feedstocks can provide an economic use for otherwise curtailed energy that is difficult to utilize with electric energy storage technologies of limited duration. These hydrogen and CO_2 feedstocks can be combined as alternatives for gaseous and liquid fuel end-uses that are difficult to electrify directly like freight applications and air travel. While the CO_2 is eventually emitted to the atmosphere, the overall process is carbon neutral as it was extracted from the air and not emitted from fossil reserves. A related finding of this work is that bioenergy with carbon capture and storage (BECCS) for power plants appears uneconomic, while BECCS for bio-refineries appears highly economic and can be used as an alternative source of CO_2 feedstocks in a low-carbon economy.

There are several areas outside the scope of this study that are important to provide a full picture of a low greenhouse gas transition. One important area is better understanding of the potential and cost of land-based NETs, both globally and in the U.S. Another is the potential and cost of reductions in non-CO_2 climate pollutants such as methane, nitrous oxide, and black carbon. Finally, there is the question of the prospects for significant reductions in energy service demand, due to lifestyle choices such as bicycling over cars, structural changes such as increased transit and use of ride-sharing, or the development of less-energy intensive industry, perhaps based on new types of materials.

"Key Actions by Decade" below provides a blueprint for the physical transformation of the energy system. From a policy perspective, this provides a list of the things that policy needs to accomplish, for example the deployment of large amounts of low carbon generation, rapid electrification of vehicles, buildings, and industry, and building extensive carbon capture, biofuel, hydrogen, and synthetic fuel synthesis capacity.

Some of the policy challenges that must be managed include: land use tradeoffs related to carbon storage in ecosystems and siting of low carbon generation and transmission; electricity market designs that maintain natural gas generation capacity for reliability while running it very infrequently; electricity market designs that reward demand side flexibility in high-renewables electricity system and encourage the development of complementary carbon capture and fuel synthesis industries; coordination of planning and policy across sectors that previously had little interaction but will require much more in a low carbon future, such as transportation and electricity; coordination of planning and policy across jurisdictions, both vertically from local to state to Federal levels, and horizontally across neighbors and trading partners at the same level; mobilizing investment for a rapid low carbon transition, while ensuring that new investments in long-lived infrastructure are made with full awareness of what they imply for long-term carbon commitment; and investing in ongoing modeling, analysis, and data collection that informs both public and private decision-making. These topics are discussed in more detail in *Policy Implications of Deep Decarbonization in the United States.*

Key Actions by Decade

This study identifies key actions that are required in each decade from now to mid-century in order to achieve net negative CO_2 emissions by mid-century, at least cost, while delivering the energy services projected in the Annual Energy Outlook. Such a list inherently relies on current knowledge and forecasts of unknowable future costs, capabilities, and events, yet a long-term blueprint remains essential because of the long lifetimes of infrastructure in the energy system and the carbon consequences of investment decisions made today. As events unfold, technology improves, energy service projections change, and understanding of climate science evolves, energy system analysis and blueprints of this type must be frequently updated.

2020s

- Begin large-scale electrification in transportation and buildings.
- Switch from coal to gas in electricity system dispatch.
- Ramp up construction of renewable generation and reinforce transmission.
- Allow new natural gas power plants to be built to replace retiring plants.
- Start electricity market reforms to prepare for a changing load and resource mix.
- Maintain existing nuclear fleet.
- Pilot new technologies that will need to be deployed at scale after 2030.
- Stop developing new infrastructure to transport fossil fuels.
- Begin building carbon capture for large industrial facilities.

2030s

- Maximum build-out of renewable generation.
- Attain near 100% sales share for key electrified technologies (*e.g.,* EVs).
- Begin large-scale production of biodiesel and bio-jet fuel.
- Large scale carbon capture on industrial facilities.
- Build out of electrical energy storage.
- Deploy fossil power plants capable of 100% carbon capture if they exist.

[•] Maintain existing nuclear fleet.

2040s

- Complete electrification process for key technologies, achieve 100% stock penetration.
- Deploy circular carbon economy using DAC and hydrogen to produce synthetic fuels.
- Use synthetic fuel production to balance and expand renewable generation.
- Replace nuclear at the end of existing plant lifetime with new generation technologies.
- Fully deploy biofuel production with carbon capture.

Exhibit E.2: 350 PPM Pathways for Florida (2020), Executive Summary and U.S. data from the Technical Supplement, Evolved Energy Research

October 6, 2020

Prepared by BEN HALEY, GABE KWOK, AND RYAN JONES, *Evolved Energy Research*

Executive Summary

This study evaluates multiple scenarios to radically reduce the greenhouse gas emissions that result from Florida's energy system, and can serve as a tool to inform statewide energy system decisions.

We detail five technically and economically feasible pathways to reduce carbon dioxide emissions and remain within a small enough "carbon budget" to enable a return to 350 parts per million of carbon dioxide in the atmosphere by 2100, a level identified by scientists as a safe limit necessary to preserve a stable climate. These scenarios limit emissions while providing the same energy services for daily life and industrial production as the Department of Energy's long-term forecast.

This study builds upon the research conducted by Evolved Energy Research and the Sustainability Development Solutions Network (SDSN) and published on May 8, 2019, titled *350 PPM Pathways for the United States.*

Scenarios

This study evaluates five energy decarbonization [1] scenarios for the energy system of Florida:

Central: The least constrained scenario, this uses all options to decarbonize the energy system.

Low Biomass: This scenario reduces the development of new biomass feedstocks [2] by 50%.

Low Electrification: This scenario assesses the impact of a delayed adoption of electric vehicles and heat pumps.

100% Renewable Primary: This scenario describes an energy system based solely on biomass, wind, solar, hydro, and geothermal sources by 2050.

No New Regional Transmission (TX): This scenario limits the development of new electricity transmission lines between regions within the U.S.

Florida Energy System Results

Energy decarbonization in Florida relies on four principal strategies: (1) **Electricity decarbonization** requires reducing the amount of fossil fuels used for electricity generation, thereby reducing the amount of greenhouse gas emissions from every unit of electricity delivered by about 95% by 2050; (2) **Energy efficiency** is the reduction in energy required to provide energy services such as heating and transportation, and energy use per unit GDP is reduced by about 50% below today's level; (3) **Electrification** involves switching energy uses including transportation and building heating off of fossils fuels and onto low-carbon electricity, and (4) **Capturing carbon** that would otherwise be emitted from power plants and industrial facilities—with the captured carbon either stored permanently (sequestered) or used to create fuels like synthetic natural gas or synthetic diesel, by combining the carbon with renewably-generated hydrogen.

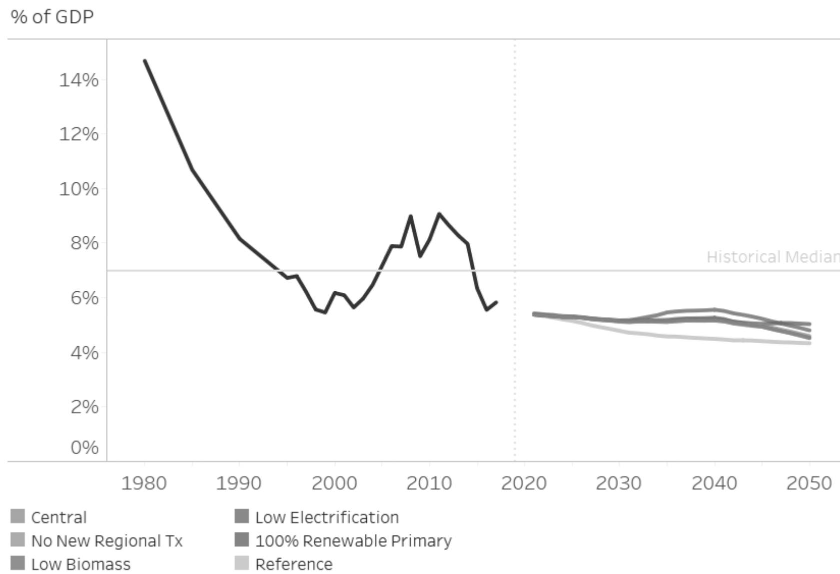
Figure 1 shows historical and projected energy system costs as a share of State Gross Domestic Product (GDP). All scenarios evaluated in this study are in line with historical energy costs in Florida and, even with decarbonization, energy system costs are anticipated to decline as a share of GDP. The highest cost scenario is the 100% Renewable Primary pathway due to the emphasis on displacing *all* fossil fuels by 2050, rather than continuing to use some small amount of the lowest-cost fossil fuels and capturing and storing the associated carbon. The lowest cost scenario is the Central scenario, which allows for the most flexibility in terms of key decarbonization strategies.

Note that the costs within this chart do not reflect any of the macroeconomic benefits of transitioning off of fossil fuels, including improved air quality, avoided climate impacts (like avoided sea level rise), reduced energy price volatility, and energy independence, which could equal or exceed the net costs shown here.

[1] "Decarbonization" is the process of removing sources of carbon dioxide (and other greenhouse gases) from a system—in this case, removing fossil fuel emissions from Florida's energy system.

[2] Biomass feedstocks are plant-based and animal-based sources of fuel, like trees, grasses, or animal fats, for example.

Figure 1



Total energy system costs as percentage of GDP, historical and projected for Florida.

Key Actions by Decade

Achieving the transition described above is not expensive but requires significant changes in public policy. Some of the **key policy challenges** that must be managed in all scenarios include: (a) managing tradeoffs between using land for low carbon electricity generation (like wind farms and solar arrays) and improving natural carbon storage in forests and soils; (b) electricity market designs that maintain natural gas generation capacity for reliability while using gas generators very infrequently; (c) developing electricity rates that incentivize customers to flex their energy use to better match periods of electricity surplus and shortage that come with intermittent renewables like wind and solar; (d) encourage the development of carbon capture industries that can leverage periods of excess electricity generation; (e) coordination of planning and policy across sectors that previously had little interaction, such as transportation and electricity; (f) coordination of planning and policy across jurisdictions; (g) mobilizing investment for a rapid low carbon transition; and [h]) investing in ongoing modeling, analysis, and data collection that informs both public and private decision-making. These topics are discussed in more detail in *Policy Implications of Deep Decarbonization in the United States.*

Achieving this transformation in Florida by mid-century at lowest cost requires an **aggressive deployment of low-carbon technologies,** including:

2020s

- Begin large-scale transition to electric technologies in key sectors; moving to electric light duty vehicles and electric heat pumps.
- Use coal fired power plants only when absolutely necessary, prioritizing all other sources of electricity generation first. Begin retiring coal assets.
- Ramp up construction of renewable electricity generation and upgrade electricity transmission where needed.
- Allow strategic replacement of natural gas power plants to support rapid deployment of low-carbon generation. These power plants must be financed with the understanding that they will run very infrequently to provide capacity, not as they are operated today.
- Maintain existing nuclear power plants.
- Pilot new technologies that will need to be deployed at scale after 2030.
- Stop developing new infrastructure to transport and process fossil fuels.

- Begin building carbon capture for large industrial facilities.

2030s

- Maximum build-out of renewable electricity generation.
- Nearly 100% of new vehicle sales and new building heating systems using electric technologies.
- Begin large-scale production of biodiesel and bio-jet fuel.
- Large scale carbon capture on industrial facilities.
- Build out electrical energy storage.
- Deploy new natural gas power plants capable of 100% carbon capture if they exist.
- Maintain existing nuclear power plants.
- Continue to reduce generation from gas-fired power plants.

2040s

- Complete the transition to electric technologies for key sectors; virtually 100% of light duty vehicles and building heating systems run on electricity.
- Produce large volumes of hydrogen for use in freight trucks and fuel production.
- Use synthetic fuel production to balance and expand renewable generation.
- Fully deploy biofuel production with carbon capture.
- Further limit gas generation to infrequent periods when needed for system reliability.

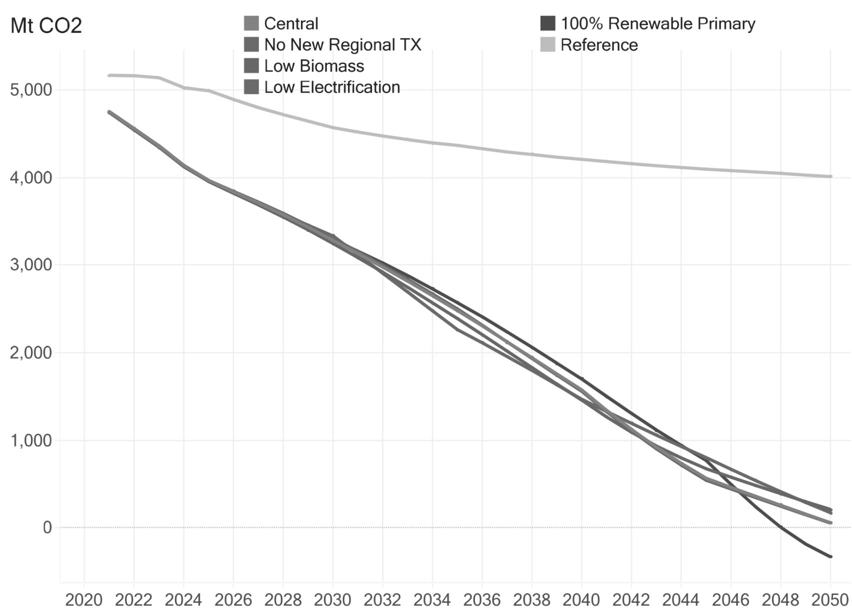
* * * * *

Technical Supplement

The following technical supplement shows results for the U.S. as a whole as well as scenario figures not shown in the body of the main report for Florida.

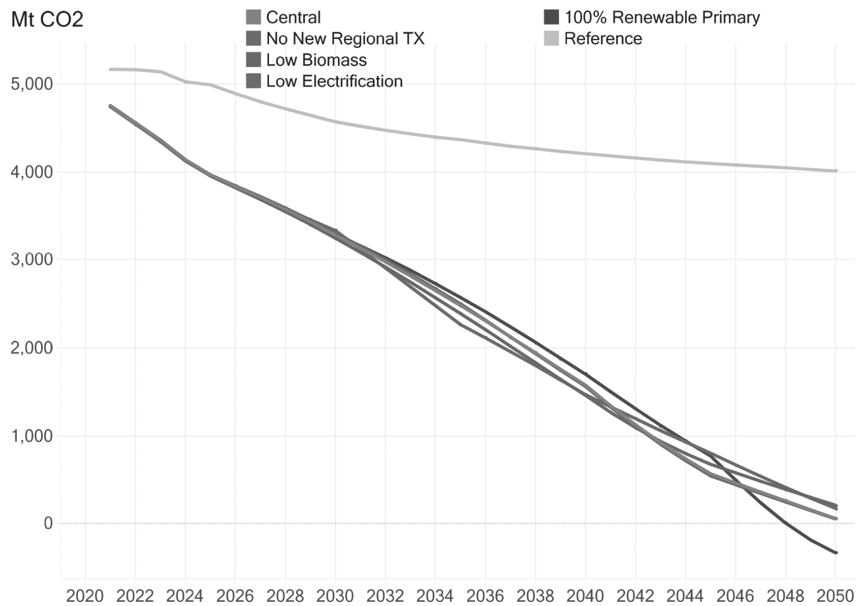
U.S. Results

Figure 30



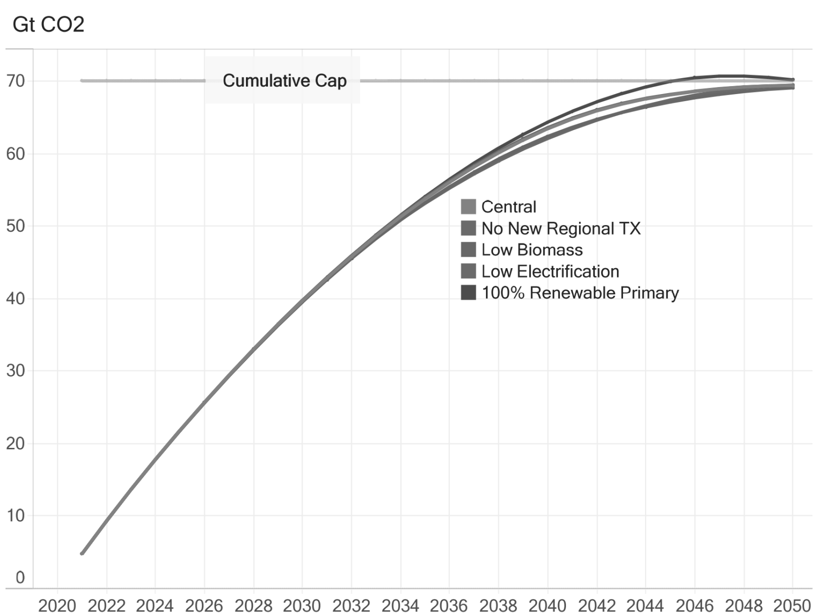
E&I CO_2 emissions trajectories—U.S.

Figure 31



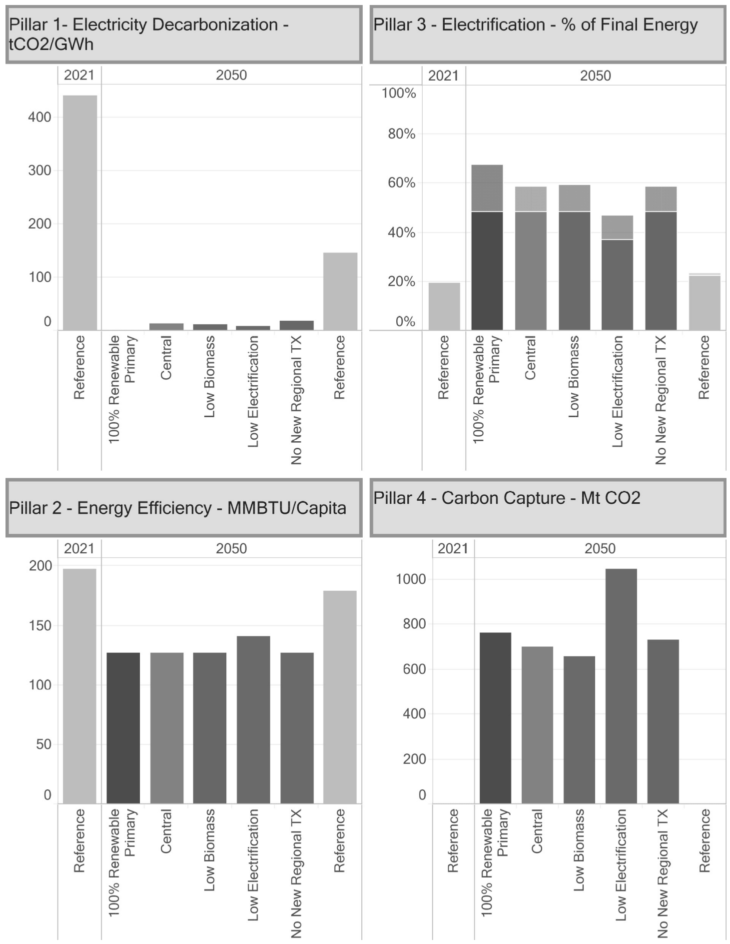
CO_2 emissions by final energy/emissions category.

Figure 32



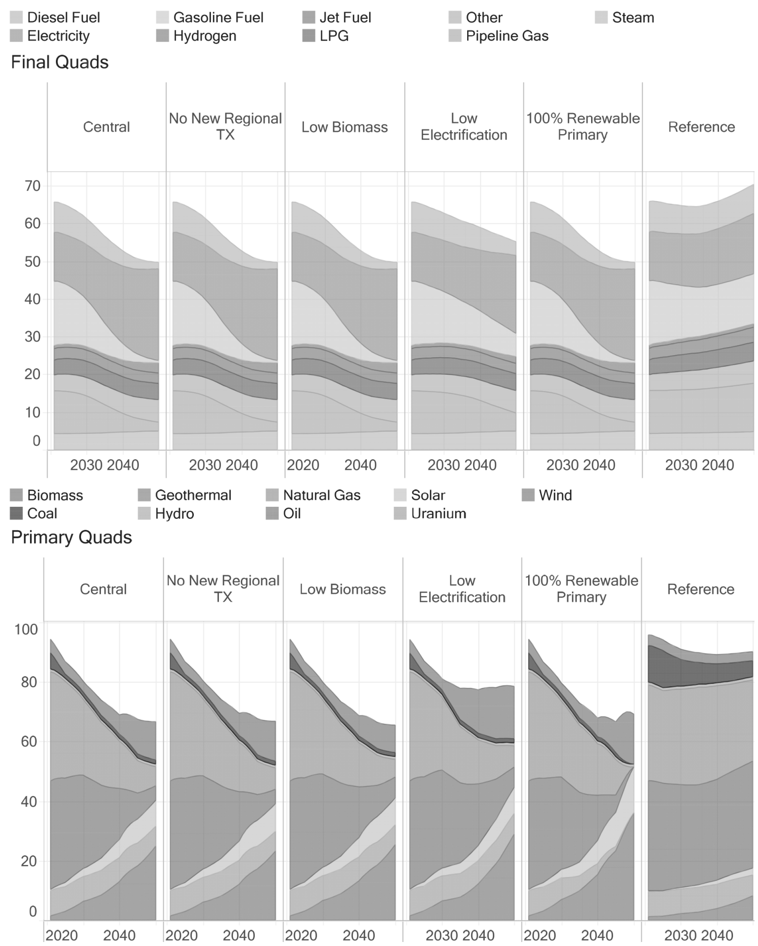
Cumulative E&I CO_2 emissions trajectories.

Figure 33



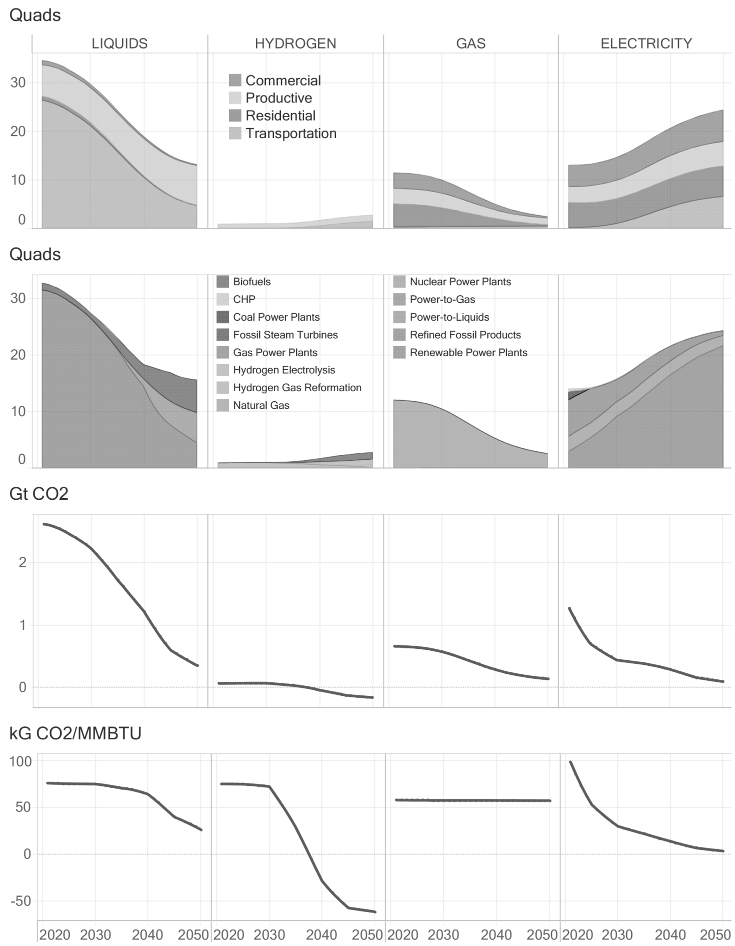
Four pillars of deep decarbonization—U.S.

Figure 34



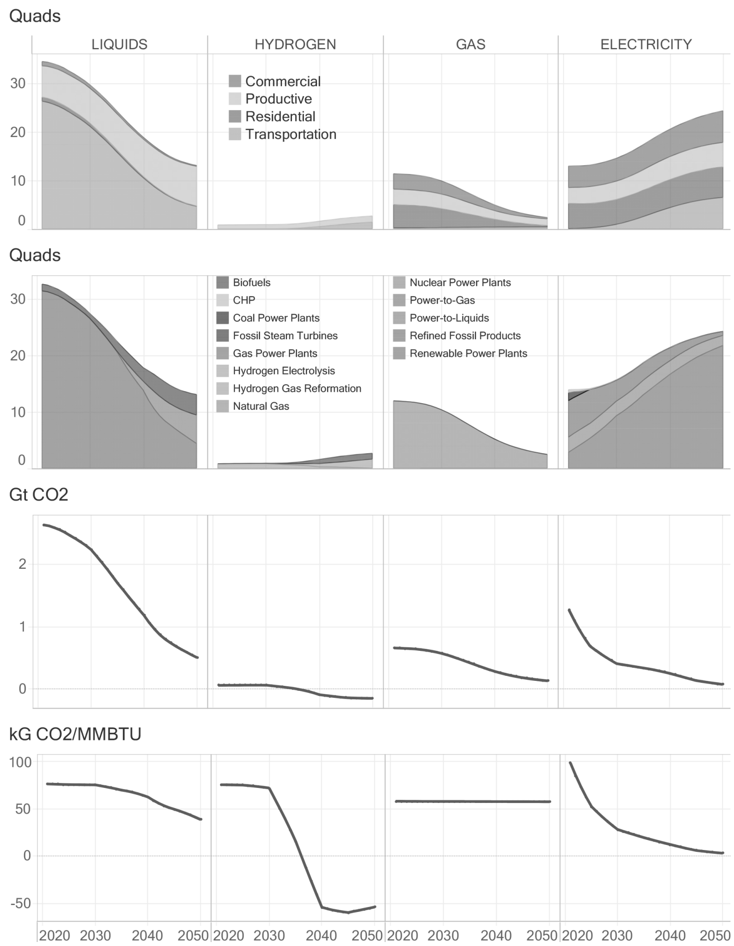
Final and primary energy demand for all scenarios from 2021–2050—U.S.

Figure 35



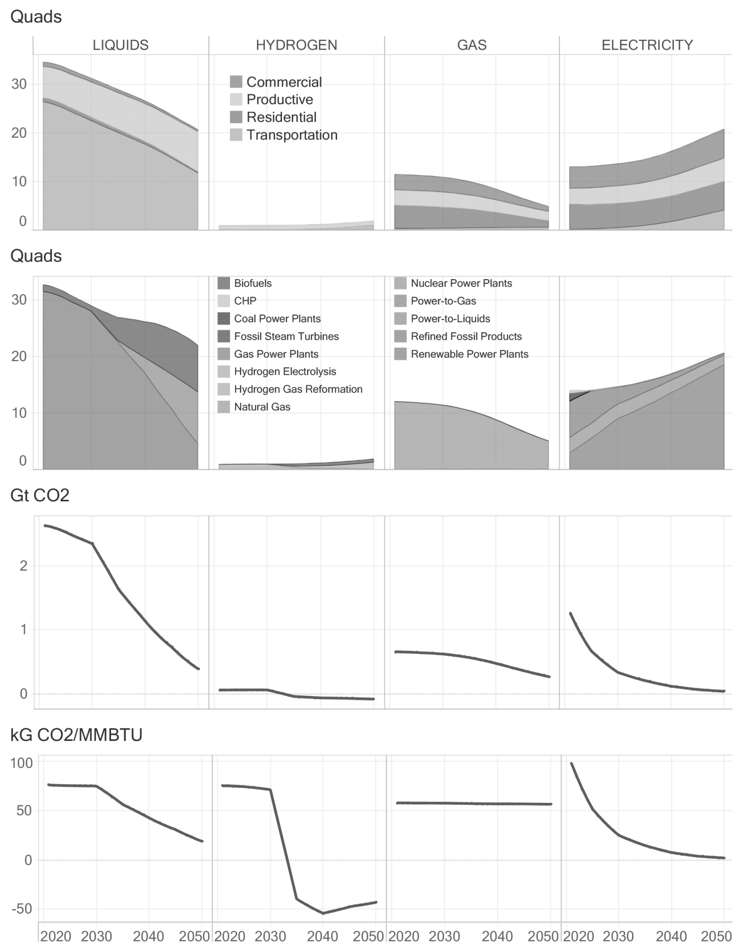
Components of emissions reductions in the Central scenario—U.S.

Figure 36



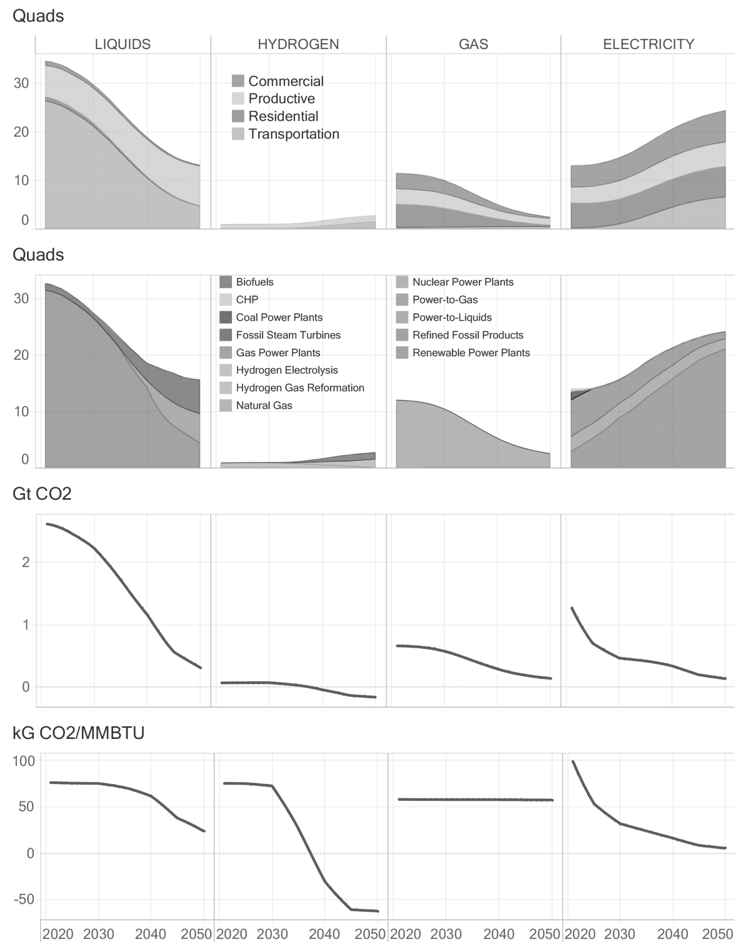
Components of emissions reductions in the Low Biomass scenario—U.S.

Figure 37



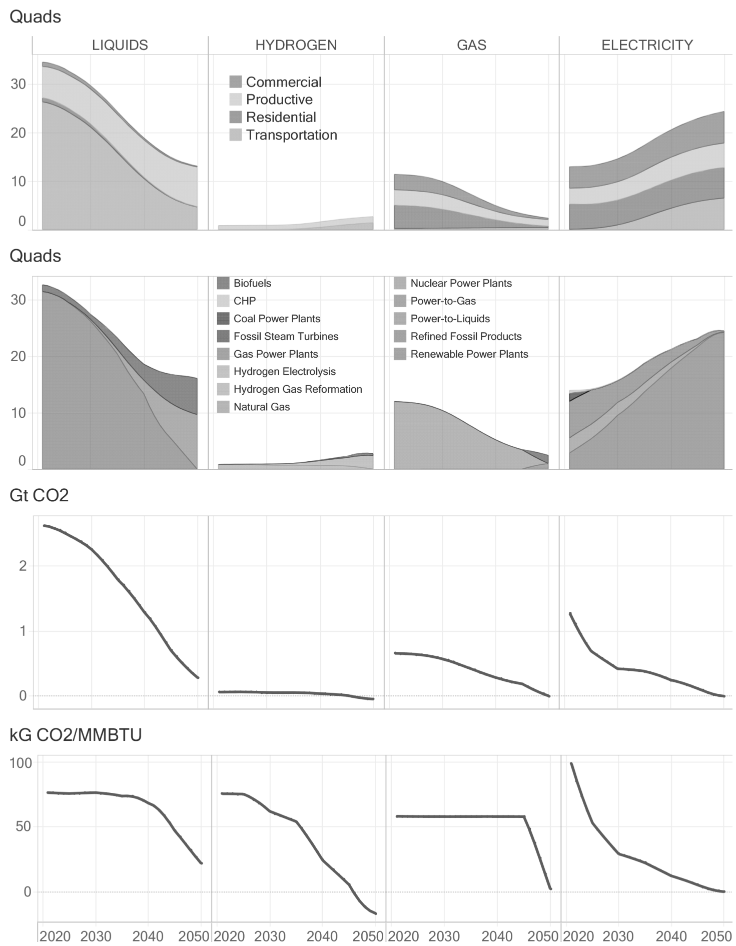
Components of emissions reductions in the Low Electrification scenario—U.S.

Figure 38



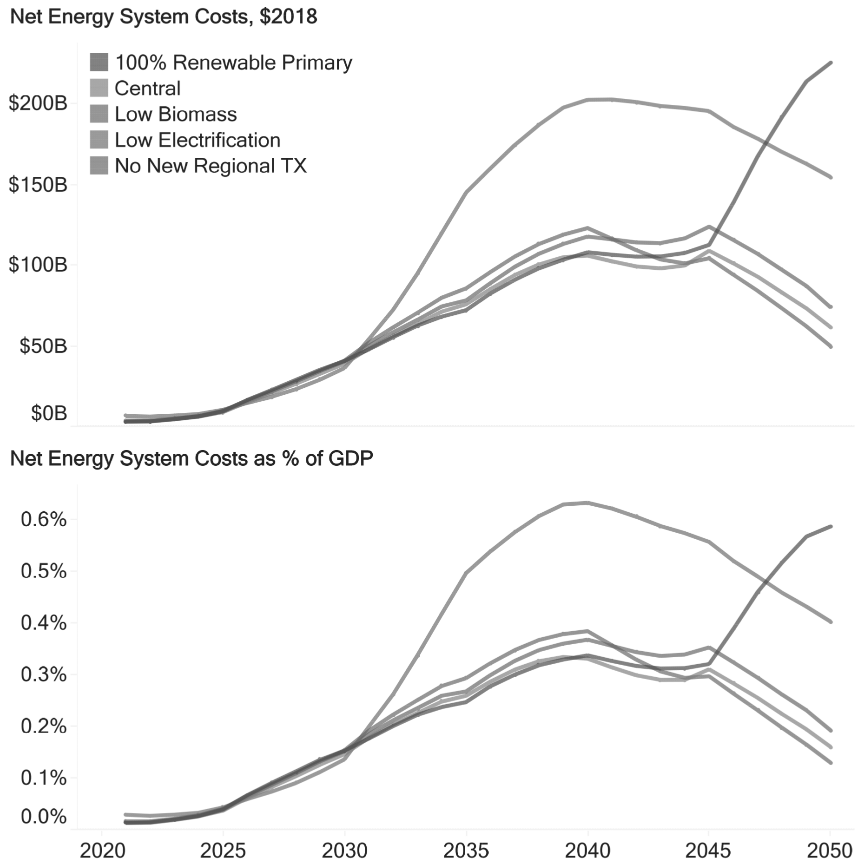
Components of emissions reductions in the No New Regional TX scenario—U.S.

Figure 39



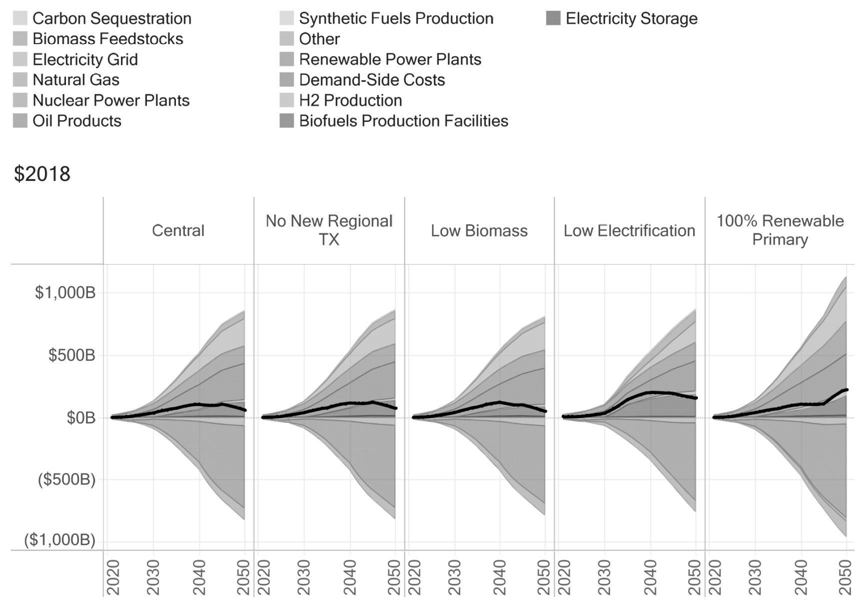
Components of emissions reductions in the 100% Renewable Primary scenario—U.S.

Figure 40



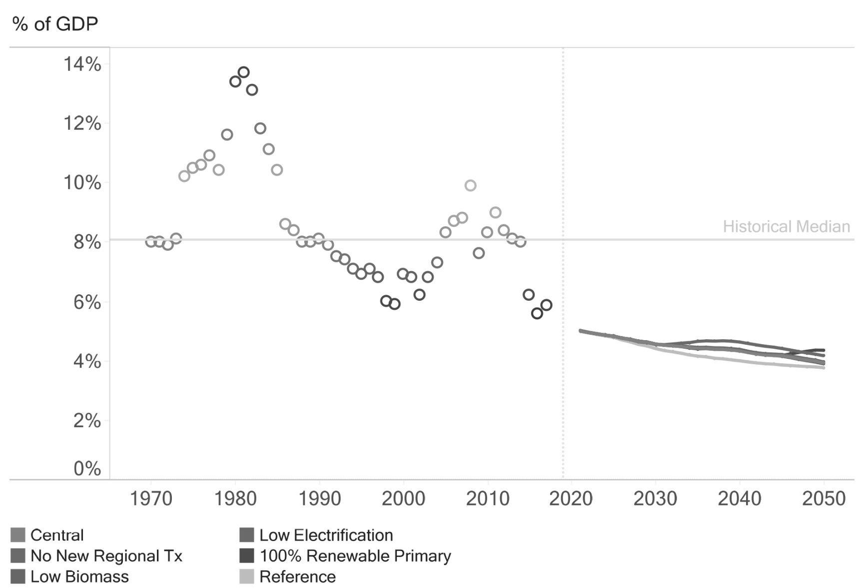
Annual net system cost premium above baseline in $2018 and as % of GDP—U.S.

Figure 41



Net Change in E&I System Spending—U.S.

Figure 42



Total energy system costs as % of GDP—historical and projected—U.S.

LETTER 4

ON BEHALF OF AGRICULTURAL RETAILERS ASSOCIATION, *et al.*

Hon. DAVID SCOTT, Hon. GLENN THOMPSON,

Chairman,
House Committee on Agriculture,
Washington, D.C.;

Ranking Minority Member,
House Committee on Agriculture,
Washington, D.C.

The farmers, cooperatives, researchers, retailers, seed producers, scientists and technology developers represented by the organizations signed below appreciate the opportunity to provide a statement for the record for the House Agriculture Committee hearing on February 25, 2021 addressing "Climate Change and the U.S. Agriculture and Forestry Sectors." We commend the Committee for addressing this important and complex issue. As organizations who embrace the use of crop varieties improved through biotechnology and recognize the many benefits this has enabled American agriculture to achieve, we want to specifically highlight the fact that agricultural biotechnology needs to be a part of any climate change discussion. Agriculture has achieved notable and well documented environmental improvements through the adoption of crop varieties improved through biotechnology that have enabled improved tillage practices, improved soil health and greatly reduced greenhouse gas (GHG) emissions, to name just a few. We are proud of the accomplishments achieved to date but are even more excited about the potential environmental benefits and climate change mitigation that could be possible through the continued development and adoption of new crop varieties improved with the help of innovative breeding methods such as gene editing, marker assisted selection, genomic selection and genetic engineering; new crop varieties that can produce more with less—less water, less land, less inputs.

We support the ongoing public and private investment in the research and development of new breeding methods which have the potential to enhance the sustainability of agriculture, the environment, and our global food system. In order for U.S. agriculture to lead in the future, we must have access to every tool available to address pressing challenges caused by climate change such as severe weather events and rapidly evolving pests and diseases. We must do this while meeting societal expectations for reductions in the use of crop inputs and increasing new varieties of healthy and affordable food and fiber options. Technology will be helpful in confronting these challenges but we believe that biotechnology has demonstrated a unique ability to meet these demands.

Our associations strongly support a regulatory system which fosters innovation, values the environmental benefits that crops improved using biotechnology enable, and recognizes the long and safe track record of plant breeding, and the overwhelming evidence of the safe use of genetic engineered plants. Congress should continue to encourage Federal agencies to broadly communicate how their policy decisions related to new plant varieties enable agriculture and forestry to further contribute to climate solutions. In 2020, the United States Department of Agriculture called for public input on the Agriculture Innovation Agenda to help "stimulate innovation so that American agriculture can achieve the goal of increasing U.S. agricultural production by 40 percent while cutting the environmental footprint of U.S. agriculture in half by 2050."[1] In a summary of the key findings from all of the feedback received, USDA published the "*Agriculture Innovation Agenda: Scorecard Report*." A key finding of that report was that a primary driver of productivity growth is "improvements in animal and crop genetics."[2] Biotechnology is a critical tool in plant breeding to enhance the efficiency and efficacy of improvements in genetics that will maintain American agriculture as the world leader in efficiency and sustainability.

The men and women represented by our associations believe in the vital contributions that our agriculture community can make to mitigate climate change and build toward a more sustainable and equitable food system. We believe in science and evidence-based solutions. We must acknowledge that scientific innovations, such as agricultural biotechnology, have resulted in environmental and societal benefits; and must continue to be a part of the comprehensive strategy on climate change and U.S. agriculture.

Thank you again for the opportunity to provide this statement for the record.

Sincerely,

Agricultural Retailers Association
American Farm Bureau Federation
American Seed Trade Association

National Association of Wheat Growers
National Corn Growers Association
National Cotton Council

[1] *https://www.usda.gov/aia.*

[2] Agriculture Innovation Agenda: Scorecard Report, *https://www.usda.gov/sites/default/files/documents/aia-scoreboard-report.pdf*, page 4.

Editor's note: the report referred to is also retained in Committee file.

American Soybean Association
American Sugarbeet Growers Association
Beet Sugar Development Foundation
Biotechnology Innovation Organization
Crop Science Society of America
National Council of Farmer Cooperatives
National Sorghum Producers
Produce Marketing Association
Syngenta
U.S. Canola Association

LETTER 5

ON BEHALF OF AMERICAN SOCIETY OF AGRONOMY, *ET AL.*

March 3, 2021

Hon. DAVID SCOTT,
Chairman,
House Committee on Agriculture,
Washington, D.C.;

Hon. GLENN THOMPSON,
Ranking Minority Member,
House Committee on Agriculture,
Washington, D.C.

RE: Climate Change and the U.S. Agriculture and Forestry Sectors, Outside Witness Testimony

Dear Chair Scott and Ranking Member Thompson:

The American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA) represent more than 8,000 scientists in academia, industry, and government, 12,500 Certified Crop Advisers (CCA), and 781 Certified Professional Soil Scientists (CPSS). We are the largest coalition of professionals dedicated to the agronomic, crop and soil science disciplines in the United States.

The House Agriculture Committee's timely hearing on Climate Change demonstrates what the Societies also know—that agriculture and forestry are the linchpins of America's fight against climate change. Agricultural and forest soils have the potential to sequester enough carbon to make America carbon neutral, if not a carbon sink. American agriculture represents about ten percent of the country's greenhouse gas emissions, and agriculture accounts for nearly twenty-five percent of emissions globally.[1] It does not need to be this way. Farmed soils have between 25 and 75 percent less carbon than undisturbed soils, which means that agriculture has the potential to be a significant carbon sink,[2] providing as much as 0.2 Gt CO_2 equivalents per year by 2050.[3] American farmers can become globally recognized climate heroes by sequestering more than ⅕ of U.S. carbon emissions, all without interfering with food production.[4] Forest activities, such as reforestation, improved forest management, and reduced deforestation have the potential for even greater carbon sequestration. The technical potential for carbon uptake by forest measures is estimated to be from 0.5 to 1.5 Gt CO_2 equivalents per year by 2050. Forest managers and agroforestry producers along with farmers and rangers are poised to deliver enormous emissions reductions and offsets from elsewhere in the economy.

Rural Americans have a strong voice in Congress through this Committee, but the fact that many rural Americans see environmental protection as destructive to their very livelihoods and way of life is an existential liability for the planet. We urge the Committee to quickly implement science-based policies that curb and mitigate climate change's effects while empowering producers with new tools, new sources of income, and the pride that comes from global recognition of their efforts.

Put Carbon Into Soil

Carbon-Rich Farms Are Healthy Farms

Sequestering carbon on farmland is critical to maintaining a healthy planet for generations to come. Sustainable agriculture that focuses on a broad, systems approach that returns carbon to the soil and builds soil organic matter has the double

[1] *https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector*

[2] Lal, Rattan. "Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security." † *BioScience* 60.9 (2010): 708–721.

Editor's note: entries annotated with † are retained in Committee file.

[3] E. Larson, *et al.* "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report." † Princeton University, Princeton, NJ. December 15, 2020.

[4] Fargione, Joseph E., *et al.* "Natural climate solutions for the United States." † *Science Advances* 4.11 (2018): eaat1869.

effect of pulling carbon out of the atmosphere and building healthier soils.[5] Soils with more organic matter absorb and retain more moisture, reducing the need for irrigation and increasing a farm's resilience to the damage associated with droughts or flooding.[6] More specifically, farms with high soil organic matter require fewer additional fertilizers and can produce healthier crops and higher yields.[7]

Awareness of Best Practices Is Key

Practices to sequester carbon include: no or low tillage; cover crops; diverse crop rotations, sometimes including grazing animals; land applications of manure, biosolids or urban compost; and precision agriculture.[8] These techniques are based in science, but widespread adoption in the United States is hampered by a variety of factors, one of which is awareness. The U.S. Department of Agriculture (USDA) and universities use Extension agents on a county level to deliver knowledge discovered through research to the farmers who can directly apply it on their land, but funding for Extension in real dollars has declined, as has the number of Extension agents available to farmers. Congress should triple the funds for conservation technical assistance to empower a new Climate Conservation Corps, with NRCS, Certified Crop Advisors, and university Extension employees serving as the boots-on-the-ground to help farmers transition to a new carbon economy.

Make Sure Techniques Are Cost-Effective

Concern over potential extra costs associated with switching to new, unfamiliar systems can be alleviated by USDA programs. For example, USDA could be funded to develop a cloud-based cover crop support tool that is easy to use, freely available nationally, and locally specific. The tool would give detailed recommendations for which crops to plant, seeding rates, and more. It would also provide long-term economic data for transitions to demonstrate a producer's likely return on investment, and, given adherence to its recommendations, USDA could offer loans that cover extra costs and potential lost income for the first 5 years to promote implementation. Once a transition is achieved, USDA could reduce insurance rates for the farm's now less risky, more resilient system. Crop insurance subsidies that are more generous and flexible to producers engaging in sustainable practices will encourage these practices and, subsequently, reduce risk.[9] So as not to disadvantage producers who have already made investments in cover crops, for farmers who have already have a 5 year or longer history of successful cover crop management experience, insurance premiums can be reduced to offset a portion of their investment and to not leave these pioneering early adopters behind. Important to note, these interventions become exponentially more effective with access to broadband, making rural connectivity a key driver to enabling sustainable practices.

Carbon Markets Require Scientific Legitimacy

Congress should consider policies that facilitate ecosystem services markets for producers to earn money directly from sequestering carbon, reducing emissions, preventing erosion, enhancing water quality, and improving the viability of carbon land sinks in both agricultural and forested lands. Such a market needs to be created and maintained with the most up-to-date science. Science is always moving forward—new information is constantly discovered, but this must not impede a market from forming now, nor should such a market be prevented from incorporating new findings as they come. Investments in ecosystems science, which includes, for example, soil science, agronomy, forestry, and data science working together, will inform a trusted market that accurately measures and values ecosystem services. Importantly, a lack of science underpinning such a market will greatly degrade trust in its value. This would lead not only to the system's demise but it could also doom future plans to pay producers for ecosystem services, even if subsequent ideas are defensible.

Hundreds of millions of dollars per year in soil and forestry research are needed over the next decade to establish ecosystem health benchmarks so that best prac-

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[5] Lal, Rattan. "Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands." *Land Degradation & Development* 17.2 (2006): 197–209.

[6] Basche, Andrea. "Turning Soils Into Sponges: How Farmers Can Fight Floods and Droughts." † *UCS, editor* Washington, DC (2017): 1–18.

[7] Lal, Rattan. "Soil carbon sequestration impacts on global climate change and food security." † *Science* 304.5677 (2004): 1623–1627.

[8] Montgomery, D.R. (2017). *Growing a revolution: bringing our soil back to life.* WW Norton & Company.

[9] Pan, William L., *et al.* "Integrating Historic Agronomic and Policy Lessons with New Technologies to Drive Farmer Decisions for Farm and Climate: The Case of Inland Pacific Northwestern U.S." † *Frontiers in Environmental Science* 5 (2017): 76.

tices can be developed for producers over wide geographic ranges. There are proven means of management-based soil carbon sequestration,[10–12] but which practices have the largest impact, and where these practices can be optimized, is essential information for valuing ecosystem credits. Also necessary are rapid soil tests that validate these benchmarks. USDA's National Institute of Food and Agriculture (NIFA) should carve out funding for research on soil and forest health and the sustainable, systems-based approaches that return carbon to the soil and build soil organic matter. Congress should fully fund AgARDA with a mandate to invest in high-risk and complex, systems-level research for improving carbon land sinks.

Invest in Conservation

Expand Conservation Programs Like the Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP)

Congress has decided that for some lands, the ecological impacts of farming outweigh the potential economic benefit to the producer. The Conservation Reserve Program (CRP) is an option Congress gives producers that pays them to take this land out of production and to restore forests and grasslands. But producers may decide that the potential profit made by planting crops could outweigh the CRP payments, compelling producers to plant on land better suited to conservation. Congress should adjust CRP guidelines to incentivize conservation under a variety of economic circumstances. The guidelines should also be amended to focus primarily on the marginal lands the program was intended to protect, while lands better suited to production should be channeled to the Environmental Quality Incentives Program (EQIP). EQIP is an excellent way to provide funding for conservation practices on working lands, but it is oversubscribed. Congress should allocate more funding for this program.

Water and Irrigation Research Helps Producers and Preserves Natural Ecosystems

Agriculture accounts for approximately 80 percent of freshwater use in the United States[13] because irrigation can double or even triple grain yields in managed agriculture.[14] But even as irrigation helps producers grow more food on less land, extreme weather events and increased development put pressure on freshwater resources. Research on improved regional irrigation strategies and on crops that require less water is key. This research has the combined benefit of helping producers withstand droughts and floods while preserving more freshwater for natural ecosystems and human consumption.[15]

Diverse Crops And Markets Make Resilient Farms

As new weather patterns change which crops producers can grow, science needs to step in with new options to keep farms resilient. Research is needed to help current commodity crops adapt, but producers and their lands will benefit from a new generation of climate-resilient crops that are better at carbon sequestration and nitrogen use efficiency and more tolerant of droughts and floods. USDA can partner with universities and industry to breed these desperately needed crops. AQUAmax corn and perennial grain crops, for example, are promising new options. Research and partnerships to produce these crops rely on the USDA National Plant Germplasm System and USDA gene banks, which preserve and develop plant genetic resources, such as seeds.[16–17] The genetic resources contained in USDA gene

[10] Poeplau, Christopher, and Axel Don. "Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis." *Agriculture, Ecosystems & Environment* 200 (2015): 33–41.

[11] Luo, Zhongkui, Enli Wang, and Osbert J. Sun. "Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments." † *Agriculture, Ecosystems & Environment* 139.1–2 (2010): 224–231.

[12] McDaniel, M.D., L.K. Tiemann, and A.S. Grandy. "Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis." † *Ecological Applications* 24.3 (2014): 560–570.

[13] *https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/*.

[14] Kukal, Meetpal, and Suat Irmak. "Irrigation-limited yield gaps: trends and variability in the United States post-1950." † *Environmental Research Communications* (2019).

[15] Basche, Andrea D., and Marcia S. DeLonge. "Comparing infiltration rates in soils managed with conventional and alternative farming methods: a meta-analysis." † *BioRxiv* (2019): 603696.

[16] Gepts P. (2006) *Plant genetic resources conservation and utilization: The accomplishments and future of a societal insurance policy.*† CROP SCIENCE 46: 2278–2292 doi: 10.2135/cropsci2006.03.0169gas.

[17] Byrne P.F., Volk G.M., Gardner C., Gore M.A., Simon P.W., Smith S. (2018) *Sustaining the future of plant breeding: the critical role of the USDA–ARS National Plant Germplasm System.*† CROP SCIENCE 58: 451–468 doi: 10.2135/cropsci2017.05.0303.

banks will be utilized more intensively, both for adapting existing crops and for introducing new crop species or crop uses to changing and more variable environments.

Crop diversification will require expanded markets and market diversification, enabling producers to weather crop price fluctuations, and diverse crop rotations are a tenant of a soil health-centered agriculture—a win-win for both producers and climate.[18] Agronomic research should widen to include a multitude of crops, agroecoforestry, and the investments needed in economics, marketing, and outreach to prepare for commercial production and expand their markets. Perennial crops, such as perennial grain crops, for example, have the potential to sequester carbon year after year while saving producers money in seeds and planting and enhancing biodiversity,[19] but market infrastructure is key to ensuring profitability at comparable levels to current commodities.

Expand On-Farm Energy Production Through Biofuel Systems

Biofuels play an important role in meeting global energy demands, but many crops traditionally used for bioethanol production, such as corn (maize), sugarcane, and sugar beets, are more valuable as food and feed sources. Because the priorities of energy and food are in constant competition, these types of biofuel crops will not be able to meet rising global energy demands. Instead, investments are needed to research and deploy biofuel systems that use agricultural residues and food waste while promoting sustainable land use.[20]

Nitrogen Management Research Benefits the Planet and the Producer's Bottom Line

The use of industrially produced nitrogen fertilizers on farms has saved billions from starvation and substantially reduced the amount of land that would have been cleared for agriculture. But applied nitrogen that a crop does not use immediately can lead to contaminated waterways, causing "dead zones" and "do not drink" water advisories. Excess nitrogen in the soil also converts to the potent greenhouse gas nitrous oxide,[21–22] which causes three hundred times more global warming than carbon dioxide.

Researchers are discovering new ways to reduce nitrogen applications without compromising yields. Precision agriculture, for example, is a promising technology powered by artificial intelligence that requires rural broadband for high-speed wireless connectivity. It combines best practices with on-farm data and digitally enabled equipment so that fertilizers can be applied according to variabilities across a field. This represents a major paradigm shift from managing an entire field the same way. Meanwhile, management techniques take advantage of rotations with crops that produce, or "fix," their own nitrogen from the air, and a recent discovery of nitrogen fixation in a corn (maize) landrace represents a huge potential for reducing nitrogen applications worldwide,[23] should researchers harness its potential in commercial varieties.

Research and Extension Are Vital

Agricultural producers need healthy soils that sequester carbon, resist flooding, and retain moisture; they need Extension experts and Certified Crop Advisors who can rapidly bring them up to speed on the latest best practices; they need cost-effective policies that incentivize conservation and follow the latest science; and they need resilient crops and robust markets for them. Each of these needs can be met with increased investments in Extension and agricultural and forestry research on soil and ecosystem health, agricultural and forestry best practices, and a diversity of crops. Resilient, sustainable farms, forests, and ranches of the future must be our legacy.

Thank you for your consideration. For additional information or to learn more about the ASA, CSSA, and SSSA please contact Karl Anderson, Director of Govern-

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[18] Pan, William L., *et al.* "Integrating Historic Agronomic and Policy Lessons with New Technologies to Drive Farmer Decisions for Farm and Climate: The Case of Inland Pacific Northwestern U.S." † *Frontiers in Environmental Science* 5 (2017): 76.

[19] Glover, Jerry D., *et al.* "Increased food and ecosystem security via perennial grains." † *Science* 328.5986 (2010): 1638–1639.

[20] Gupta, Anubhuti, and Jay Prakash Verma. "Sustainable bio-ethanol production from agro-residues: a review." *Renewable and Sustainable Energy Reviews* 41 (2015): 550–567.

[21] Canfield, Donald E., Alexander N. Glazer, and Paul G. Falkowski. "The evolution and future of Earth's nitrogen cycle." † *Science* 330.6001 (2010): 192–196.

[22] Snyder, C.S., *et al.* "Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions." † *Current Opinion in Environmental Sustainability* 9 (2014): 46–54.

[23] Van Deynze, Allen, *et al.* "Nitrogen fixation in a landrace of maize is supported by a mucilage-associated diazotrophic microbiota." † *PLoS Biology* 16.8 (2018): e2006352.

ment Relations, **Redacted** or **Redacted**. We look forward to hearing from the Committee on how our membership's expertise can help farmers become climate heroes.

Cc: Members of the House Agriculture Committee.

LETTER 6

BIOTECHNOLOGY INNOVATION ORGANIZATION

February 25, 2021

Hon. DAVID SCOTT,
Chairman,
House Committee on Agriculture,
Washington, D.C.;

Hon. GLENN THOMPSON,
Ranking Minority Member,
House Committee on Agriculture,
Washington, D.C.

Dear Chairman Scott, Ranking Member Thompson, and Members of the Committee:

The Biotechnology Innovation Organization (BIO) is pleased to submit a statement for the record to the to the United States House of Representatives Committee on Agriculture hearing entitled, "Climate Change and the U.S. Agriculture and Forestry Sectors."

Introduction

BIO[1] represents 1,000 members in a biotech ecosystem with a central mission— to advance public policy that supports a wide range of companies and academic research centers that are working to apply biology and technology in the energy, agriculture, manufacturing, and health sectors to improve the lives of people and the health of the planet. BIO is committed to speaking up for the millions of families around the globe who depend upon our success. We will drive a revolution that aims to cure patients, protect our climate, and nourish humanity.

Fighting Climate Change Through Biotechnology Innovation

BIO applauds the Committee for putting its immediate focus on the climate crisis. As we outline in our attached "100 Days of Innovation" Blueprint[2] (*Appendix I*), our nation is at a critical juncture. The start of the new administration and new Congress presents a unique opportunity to come together to galvanize our nation's scientific and entrepreneurial capacity, to mobilize new waves of homegrown innovation and American ingenuity to tackle the climate crisis, end the pandemic, and get more Americans back to work.

COVID–19 has also exposed the vulnerabilities and inequalities in how communities are disproportionately impacted, our capacity to respond to crisis, our ability to maintain our supply chains, and to withstand an economic downturn. These challenges will only grow more prevalent and damaging because of climate change.

To meet the challenge of climate change, it is crucial to lead with science and U.S. innovation. We must incentivize the adoption of innovative, sustainable technologies and practices; and streamline and expedite regulatory pathways for breakthrough technology solutions. Investment and deployment of cutting-edge technologies will be crucial to ensure farmers, ranchers, sustainable fuel producers, and manufacturers are able to respond to climate change and maintain the U.S.'s global leadership in agriculture. This includes removing barriers and assisting beginning and socially disadvantaged farmers and ranchers to access and utilize these technologies, so all producers can adapt to the challenges ahead. By accelerating and deploying innovation, American agriculture can be resilient, self-sustaining, and drive our economic recovery.

BIO supports legislative action on climate change that catalyzes resilient and sustainable biobased economies. Federal climate policy should use science-based targets to increase the use of biobased manufacturing, low-carbon fuels, and sustainable agricultural solutions. Science-based policy will promote resilient and sustainable supply chains across economic sectors including translating sustainability to best practices to all bioindustries. If done right, climate legislation will create market pull incentives for investment in and use of innovative technologies and products that

[1] *https://www.bio.org/.*
[2] *https://archive.bio.org/sites/default/files/docs/toolkit/BIO_100_Days_of_Innovation.pdf.*

fight climate change.[3] This will enable U.S. agriculture to combat climate change while producing enough food, feed, fuel, and fiber for a growing world.

Biotech Achievements

The adoption of biotechnology in agriculture and the development of biobased technologies has already contributed to food security, sustainability, and climate change solutions. The acceptance of biotechnology has enabled large shifts in agronomic practices that have led to significant and widespread environmental benefits. Some biotech climate solutions include:

- Biotech crops, such as those that require no-tilling, have saved 27.1 billion kg of carbon dioxide, equivalent to taking 16.7 million cars off the road.[4]
- Synthetic biology enables farmers to enhance soil health to grow more food on less land, manufacturers to create new food ingredients and alternative proteins, and industrial biotech companies to revolutionize manufacturing by optimizing processes for producing sustainable chemicals, biobased products, and biofuels.[5]
- The use of feed additives for ruminant livestock, has been demonstrated to reduce methane levels produced by ruminants by up to 30 percent[6] while the addition of enzymes[7] to chicken feed promotes better protein digestibility, which helps reduce residual nitrogen emissions from manure.
- New research[8] shows emissions from sustainable fuels made from corn are 46 percent lower than gasoline. Advanced and cellulosic biofuel technologies can reduce emissions from 101 to 115 percent.[9]
- Renewable chemicals and biobased products removed 12.7 million metric tons of CO_2 from the manufacturing sector in 2016 alone, and can continue to green our supply chains, reduce plastic pollution, and provide sustainable alternatives to fossil-based products.[10]

To learn more about these technologies and the innovative breakthroughs that can reduce greenhouse gas emissions throughout agricultural supply chains, please see BIO's attached comments[11] (*Appendix II*) to the U.S. Department of Agriculture's (USDA) Solicitation of Input from Stakeholders on Agricultural Innovations.[12]

Policy Recommendations

As the Committee and Congress examine policies to combat climate change, while also aiming to strengthen the economy and create jobs, BIO recommends the following policy approaches:

- ***Incentivize Modern Ag Techniques.*** Enable America's farmers, ranchers, and foresters to combat climate change by incentivizing the adoption of modern agricultural techniques and innovative technologies, including carbon sequestration, enhancing animal feed with enzymes, microbes to reduce emissions from livestock, precision plant breeding, and biostimulants and microbial inoculants—which boost production by building up soil carbon and using less fertilizer. This also includes:
  - ○ Helping producers solve the technical entry barriers to participating in carbon credit markets as proposed in the *Growing Climate Solutions Act.*
  - ○ Incentivizing farm management decisions that have large impact on reducing GHG emissions and increasing soil organic carbon, such as expanding section 45Q of the Tax Code to credit.

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[3] *https://www.bio.org/strategic-vision.*
[4] *https://www.isaaa.org/resources/publications/briefs/54/executivesummary/default.asp.*†
Editor's note: entries annotated with are retained in Committee file.
[5] *https://www.bio.org/blogs/synthetic-biology-sustain-agriculture-and-transform-food-system.*†
[6] *https://newfoodeconomy.org/feed-additive-methane-cow-burps/.*†
[7] *https://www.novozymes.com/en/news/news-archive/2017/03/more-from-one-acre-new-report.*†
[8] *https://iopscience.iop.org/article/10.1088/1748-9326/abde08.*†
[9] *https://www.eesi.org/articles/view/biofuels-versus-gasoline-the-emissions-gap-iswidening#:~:targetText=Argonne%20researchers%20show%20that%20compared, for%20the%20RFS%20from%202010.*†
[10] *https://www.biopreferred.gov/BPResources/files/BiobasedProductsEconomicAnalysis2018.pdf.*†
[11] *https://www.bio.org/letters-testimony-comments/bio-submits-comments-usda-ag-innovation.*
[12] *https://www.govinfo.gov/content/pkg/FR-2020-04-01/pdf/2020-06825.pdf.*†

- ◦ Bolster U.S. Department of Agriculture (USDA) conservation programs to promote improved soil health and carbon sequestration.

- ***Certify Sustainable Ag Practices.*** Create a certification program at USDA to allow producers to participate in carbon credit markets which will enable the manufacturers of biobased fuels, chemicals, plastics, food, animal feed, veterinary products, and everyday materials to reliably demonstrate their true environmental benefit—from farm to consumer.
- ***Promote Animal Biotechnology Innovations.*** Genetic innovation in animals can help prevent and respond to future infectious diseases. These technologies hold enormous potential to address numerous agricultural, environmental, humanitarian, and public health challenges associated with climate change by enabling animal agriculture to produce more protein with fewer animals and adapting livestock to a warming world. We need to streamline oversight of animal biotechnology to create a clear, timely, and science-based regulatory approval process that provides a viable path to market for these critical new innovations.
- ***Streamline Approval Process for Innovative Feed Additives.*** Feed additives are key for promoting robustness and resilience in livestock through improved nutrition. Furthermore, they improve the return on investment for farmers and reduce greenhouse gas emissions. Unfortunately, many of these new innovative products lack a suitable regulatory product category to ensure timely approval nationwide. An improved regulatory process is necessary to bring these innovative technologies to market to address climate change.
- ***Modernize Evaluation of Veterinary Products.*** Disruptive innovations and advances in veterinary products can increase protein production while decreasing emissions from livestock. To better account for these environmental benefits, the U.S. Food and Drug Administration and USDA's methods to evaluate the efficacy of these technologies must also evolve to properly measure the climate and sustainability improvements they provide.
- ***Boost Access to Nutrition.*** Utilize technology to boost the nutrient levels of fruits and vegetables. Biotech enables crops to maintain yields in the face of drought and less water, which has a direct bearing on improved food security and poverty alleviation. Increased production from biotechnology crops can help combat global hunger and malnutrition by increasing the vitamin and mineral contents of plants.
- ***Eliminate Food Deserts and Reduce Food Waste.*** Incentivize the use of biotech in specialty crops to address the lack of fresh fruits and vegetables in food deserts in urban and rural communities. Biotech advancements allow for fewer blemishes, such as bruises, that lead to more sellable crops for farmers requiring less acreage. These technologies can also extend the shelf life of produce, cutting down on food waste, which creates eight percent of all global emissions.* [1] Ensure biotech products are used to achieve the U.S. Environmental Protection Agency (EPA) and USDA's Food Loss and Waste Reduction Goal in alignment with Target 12.3 of the UN Sustainable Development Goal to reduce food waste by 50 percent by 2030. Additionally, support the development of bioplastics from sustainable chemicals that can be recyclable, biodegradable, or compostable to divert food packaging waste from landfills.
- ***Ensure Regulatory and Government Support Keep Pace with Technology Advancements.*** Innovations like synthetic biology, gene editing, cell culturing, and fermentation hold tremendous potential to solve urgent challenges throughout the agricultural supply chain which will only be compounded by climate change. Producers and developers will need access to these innovative technologies to increase production while cutting down on their environmental footprint. Enabling regulatory systems to keep pace with advancements in biology is essential if society is expected to fully benefit from food, health, and industrial products developed using the very latest cutting-edge platform technologies. Furthermore, domestic regulatory pathways must provide for more expedient approval timelines to ensure the economics of new product development are not a deterrent to bringing new products to market. In the absence of a predictable and well-designed regulatory product approval system developers may choose to invest in more mature markets with better approval timelines. Invest-

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* **Editor's note:** the footnote reference in the document as submitted is [1]. This is an endnote reference format, the extraneous formatting is retained herein.

[1] *http://www.fao.org/fileadmin/templates/nr/sustainability_pathways/docs/FWF_and_climate_change.pdf*†

ments by the government in next generation of biotechnologies and genomics will also be critical to meet the challenge of climate change.

- ***Support Federal Biobased Procurement and Sustainability Programs to Buy "Green".*** Enhance USDA Biopreferred program to ensure that agencies are fulfilling their obligation to shop Biopreferred. While the program has been successful in certifying products over the years, procurement agencies have not been held accountable to buy Biopreferred options where available.

Also critical to the development of the biobased economy is determining its value and identifying the segments which need investment and research and development. Key to this is updating the North American Industry Classification System (NAICS) codes to establish measurements for biobased products as required under the 2018 Farm Bill.

- ***Accelerate Public and Private Research and Development to Drive Investment in New Tools.*** Provide significant advances in foundational tool development and practical applications through supportive grants for research and development of new tool start-ups. Foster coordination across agencies to advance research and development in biomanufacturing, strengthening and broadening the U.S.' synthetic biology capabilities and developing the future bioeconomy workforce.
- ***Expand incentives for Carbon Capture Utilization, and Sequestration.*** This technology presents a significant opportunity to transform the manufacturing sector and reduce greenhouse gas emission by turning carbon into value added products. Extend and expand incentives to support carbon utilization and innovative technologies to bolster the potential of direct air capture technologies. USDA should develop a verification methodology suitable for products of biological carbon capture and utilization (CCU) to expand opportunities for U.S. biomanufacturing as directed by the 2018 Farm Bill.
- ***Incentivize green manufacturing infrastructure.*** Spur investment and development of biobased manufacturing through supportive grants and tax incentives.
- ***Develop a Federal Low Carbon Fuel Standard (LCFS).*** A LCFS that is technology and feedstock neutral and builds on the success of the Renewable Fuel Standard (RFS) to ensure agriculture and low carbon, sustainable fuels are part of the solution will significantly reduce emissions in transport.
- ***Incentivize Advanced and Cellulosic Fuel Development.*** Ensuring the growth of advanced and cellulosic biofuels industry will require long-term tax incentives to avoid creating uncertainty for investors and companies trying to raise capital. The development of a long-term sustainable aviation fuel specific blender's tax credit could attract significant investment and address existing structural and policy disincentives that have prevented the aviation biofuels industry from taking off.
- ***Bring New Sustainable Fuel Technologies to Market and Recognize Environmental Benefit.*** Direct the EPA to approve stalled pathways and facility registrations for advanced and cellulosic biofuel technologies to spur investment and development in sustainable fuels projects as proposed in S. 193. Because of biotech innovations, the production of biofuels is becoming more efficient and environmentally sustainable. To reflect these improvements, EPA should update its greenhouse gas modeling as proposed in S. 218.
- ***Investment in Research and Development and Grants to Develop and Deploy Advanced Biofuels.*** To spur investment and development of new biorefineries and deployment of advanced biofuels, USDA's Biorefinery Assistance program and the Department of Energy research and development programs should be feedstock neutral. Investments in USDA's Higher Blends Infrastructure Incentive Program (HBIIP) will help consumers access low carbon fuels.
- ***One Health Approach to Public Health Preparedness.*** One Health represents a much-needed collaboration that would align human health, animal health, and environmental health strategies to create smarter, multifaceted, and coordinated efforts, including to help enhance the ability of our planet to adapt to climate change. The thoughtful and bipartisan *Advancing Emergency Preparedness Through One Health Act* (S. 1903/H.R. 3771) from the 116th Congress directs the U.S. Health and Human Services and USDA to coordinate with other agencies and state and local leaders to advance a national One Health framework to better prevent, prepare for, and respond to zoonotic disease outbreaks like COVID–19. Doing so will help insulate human populations

from future infectious diseases, antimicrobial resistance (AMR), and other heath challenges arising from climate change.

- ***Advance Global Climate Solutions.*** Build broad global support for the U.S. government's recent regulatory modernization for agricultural biotechnology and proactively advance biotechnology as a valuable tool to combat climate change through broad trade strategy approaches and efforts to reengage in multilateral forums.

Conclusion

BIO is committed to working with the Committee, Congress, and the Administration to address the climate crisis. We urge you to support policy that advances pioneering technology breakthroughs. With science we can return our nation and the world to health and prosperity by taking bold and drastic action to address the climate crisis.

Appendix I

100 Days of Innovation

Our nation is at a critical juncture and how we approach the next 100 days will be essential in terms of ending the pandemic and rebuilding our economy in a way that is more resilient, more dynamic, and more inclusive. America remains the most vibrant and entrepreneurial nation in the world. We have been tested time and time again and have always emerged stronger and more united. As the new Administration and new Congress begin, there is a unique opportunity for the private and public sectors to come together to galvanize our nation's scientific and entrepreneurial capacity, to mobilize new waves of homegrown innovation and American ingenuity and to organize our country around the clear and bold mission of ending the pandemic and getting more American's back to work. To do that we must:

1. **Ensure a Speedy Transition and an Expedited Senate Confirmation Process for Agency Leadership Critical to Advancing Public Health, Nutrition, and Environmental Goals.**
2. **Reengage as a Leader on the World Stage, Including Rejoining the World Health Organization and the Paris Climate Accords.**
3. **Develop and Approve More Vaccines, Therapeutics, and Diagnostics To Prevent and Treat COVID–19[:]**

   Specific Recommendations

   - Provide increased R&D funding for a broad array of innovative technologies with the potential to fight COVID–19 and other emerging infectious diseases.
   - Ensure ample funding to complete research priorities and procurement of existing vaccines and therapeutics.
   - Expand government coordination mechanisms beyond the first wave of COVID–19 vaccines, treatments, and diagnostics.
   - Encourage more public-private partnerships and private investment through sound public policy.
   - Continue expedited EUA and full approval processes for existing and next wave of COVID vaccines and therapies.
   - Ensure that companies can continue to partner with HHS, BARDA and DOD without regard to their current global supply chain.
   - Increase funding for CDC surveillance activities to help evaluate the effectiveness of COVID vaccines and therapeutics and drive evidence-based decision making on development of updated or new medical countermeasures.
4. **Promote Robust and Equitable Patient Access to COVID–19 Vaccines, Therapeutics, and Diagnostics[:]**

   Specific Recommendations

   - Eliminate all patient cost-sharing across government and commercial insurance markets for COVID-related vaccines, treatments, and diagnostics, including for administration and ancillary services.
   - Ensure state Medicaid programs cover all FDA-approved COVID–19 treatments and diagnostics, including those approved under an EUA, without delay and without prior authorization requirements.
   - Cover COVID–19 treatment for the uninsured via Medicaid at 100% Federal match.

- Ensure that provider relief funds and other similar assistance is targeted to providers who serve Medicaid, the uninsured, and other vulnerable patients.
- Expand and adequately fund the range of sites administering COVID–19 vaccines and treatments beyond acute care settings, including home infusion of therapeutics.
- Mount a coordinated and well-funded national campaign to build vaccine confidence and facilitate vaccination, particularly in minority communities and among essential workers.
- Develop a national vaccination plan to accelerate distribution and administration of COVID–19 vaccines in an equitable manner.
- Leverage Federal research funding to diversify Federal clinical trial networks and promote minority inclusion in COVID–19 trials.
- Encourage governors to expand the vaccine eligible populations to the ACIP recommendations expediently.

5. Better Prepare for Future Infectious Disease Outbreaks[:]

Specific Recommendations

- Support a steady-state of public and private R&D on emerging infectious diseases by providing tax incentives for private investment in early-stage clinical R&D of medical countermeasures.
- Adequately fund and resource agencies engaged in biodefense and emergency preparedness such as ASPR, BARDA, USDA, and the CDC, so they have the infrastructure in place for immediate response and can improve long-term strategic preparedness planning.
- Enable the creation, maintenance, and utilization of advanced manufacturing capabilities domestically, particularly for biological products by incentivizing private investment in facilities and equipment, supporting initiatives for training a new and expanded workforce, and ensuring a clear regulatory pathway.
- Increase physical and virtual inventories of critical emergency supplies in the Strategic National Stockpile.
- Pursue a "One Health" coordination approach across the government that recognizes the interrelationship between human, animal, and environmental health.
- Rebuild and invest in the state and local public health infrastructure.

6. Drive Economic Revival and BIO's Pledge Resiliency Through Adoption of Advanced Biotechnology Solutions[:]

Specific Recommendations

- Develop streamlined and expedited regulatory pathways for breakthrough technology solutions to climate change and nutrition challenges.
- Expand support for scale-up of biorefineries and other biobased manufacturing.
- Incentivize the adoption of sustainable agricultural practices and low-carbon fuels.
- Enforce requirements that Federal agencies should be purchasing biobased products—"Buy Green America."
- Incentivize the use of existing or future COVID–19 relief and recovery funding to purchase biobased products to meet the demand for personal protection equipment (PPE), sterilizing and cleaning equipment and cleaning products, and with respect to broader efforts to "build back better."
- In addition to these immediate actions, BIO calls on the Federal Government, working with state, local, and private-sector partners, to conduct a comprehensive review of COVID outbreak and pandemic response to identify additional steps that could/should have been taken or that could improve the nation's response and recovery in the future.

BIO's Pledge

Working With Our Member Companies and Other Partners, BIO Will:

- Expand *covidvaccinefacts.org* to provide the public with easily understandable, transparent, and credible information about the safety and efficacy of COVID–19 vaccines and how they can obtain access to them.

- Facilitate cooperative agreements to expand manufacturing capabilities of vaccines to meet the demand.
- Promote continued diversity in COVID clinical trials.
- Always stand up for science.
- Highlight steps being taken by the Administration, Congress, and BIO's member companies to resolve the COVID–19 pandemic in BIO's public communication portals, meetings and events.

Appendix II

July 31, 2020

Hon. SONNY PERDUE,
Secretary,
U.S. Department of Agriculture,
Washington, D.C.

Re: U.S. Department of Agriculture *Solicitation of Input from Stakeholders on Agricultural Innovations* (Docket No. USDA–2020–0003)

Dear Secretary Purdue,

The Biotechnology Innovation Organization (BIO) is pleased to respond to the U.S. Department of Agriculture's (USDA) *Solicitation of Input from Stakeholders on Agricultural Innovations.*[1]

BIO represents 1,000 members from the biotech ecosystem around a central mission—to advance public policy that supports a wide range of companies and academic research centers that are applying biology and technology to improve the lives of people and the health of the planet. Our members operate at the nexus of environmental, human, and animal health. They are developing biology-based technologies to enhance cultivation and food production and produce sustainable fuels, renewable chemicals, and biobased products. With our growing understanding of the plant, animal, and microbial worlds and supportive policies and regulations we can modernize agriculture, energy, and manufacturing.

These innovative breakthroughs can reduce greenhouse gas emissions throughout agricultural supply chains and strengthen producers resiliency to climate change while increasing production and help tackling hunger by bringing more nutritious offerings to all tables; and protect against this pandemic and the next by enhancing the response to public health emergencies and speed the transition of the U.S. economy to one that is more biobased and resilient. Already, innovative technologies have been widely adopted to increase productivity while reducing the footprint of agricultural production. Increasing use and acceptance of these technologies will enable U.S. agriculture to meet the Department's goal set forth in the Agriculture Innovation Agenda (AIA) of increasing agricultural production by 40 percent to meet the needs of the global population in 2050 while cutting the environmental footprint in half.

The U.S. has led the way in developing these innovations due to thoughtful, bipartisan public policy. This has created a favorable climate in which to undertake the lengthy and risky job of investing and developing the next biotech breakthroughs; allowed producers to use new technologies; and ensured a pathway to market for new products. However, America's continued success and leadership are not guaranteed, and it should not take its global leadership for granted. Foreign countries are taking overt steps to streamline regulatory systems and speed pathways to market, often with direct government support as part of national bioeconomy strategies.

COVID–19 has also exposed the vulnerabilities and inequalities in how communities are disproportionately impacted, our capacity to respond to crisis, our ability to maintain our supply chains, and to withstand an economic downturn. These challenges will only grow more prevalent and damaging because of climate change. To ensure America is able to respond to future challenges in cleaner, more efficient ways, maintain its global leadership, and allow its farmers, ranchers, sustainable fuel producers, and manufacturers to have access to cutting edge technologies, the United State must invest in new technologies and have risk-proportionate regulations that spur biological innovations. The government should also focus on removing barriers and assisting beginning and socially disadvantaged farmers and ranchers in accessing and utilizing these technologies, so all producers can adapt to the challenges ahead. By accelerating and deploying innovation American agriculture can be resilient, self-sustaining, and drive our economic recovery.

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[1] *https://www.govinfo.gov/content/pkg/FR-2020-04-01/pdf/2020-06825.pdf.*

Below are five key drivers for successful growth of the bioeconomy and to enable U.S. agriculture to meet the Department's goals set forth in AIA:

1. **Advance Modern Regulatory Approaches to Keep Pace with Innovation**

   Innovative biotechnologies have allowed producers to increase crop yields, enhance food animal production, improve soil health, and provide biomass and waste feedstocks for sustainable fuels and biobased manufacturing. Expanding the adoption of innovative technologies and practices that reduce the environmental footprint of agriculture while combatting climate change will be necessary to provide the world with adequate food, feed, fuel, and fiber.

   As such, it is critical that the government establish risk-proportionate, transparent regulations that spur biological innovations while protecting health and the environment. Enabling regulatory systems to keep pace with advancements in biology is essential if society is expected to fully benefit from food, health, and industrial products developed using the very latest cutting-edge platform technologies; such as, gene editing, synthetic biology, cell culturing, and fermentation.

2. **Provide Robust Funding of Public and Private Sector Scientific Research**

   We must foster an innovation ecosystem that unleashes the transformative potential of science and take steps to ensure the gains from these innovations are broadly shared for the benefit of humanity. This research and development will require the strong support of land-grant universities and Historically Black Colleges and Universities (HBCUs), to produce and develop young scientists and engineers critical to moving the industry forward.

   Federal research programs under USDA's National Institute of Food and Agriculture (NIFA) Agriculture and Food Research Initiative (AFRI) have been fundamental to the applied research, extension, and education of food and agricultural sciences to improve rural economies and create new sources of energy. These programs have been essential for the foundational research and agricultural workforce development that complements and underpins large systems-level research, education, and extension activities needed to maintain America's global preeminence in food, agricultural, and bioenergy production.

   Other Federal Government research and development programs have been essential to the development of clean energy technologies that strengthen the economy, protect the environment, and reduce dependence on foreign oil. While there has been increasing research and development in biotechnology platform technologies—such as gene editing, synthetic biology, cell culturing, and fermentation—increased Federal funding and coordination between agencies will be critical to maintain America's leadership in an increasingly competitive race to generate breakthroughs. The new innovations unlocked from supportive scientific research and development will enable agriculture to increase production while reducing greenhouse gas emissions across agriculture, transportation, and industry.

3. **Modernize Infrastructure**

   Ensuring farmers and ranchers can deploy innovative technologies that increase production to create a resilient bioeconomy while reducing pollution will also require important investments in infrastructure. This includes, but is not limited to increased lab capacity, widespread access to broadband internet technology, pipelines and distribution capacity for carbon dioxide and sustainable fuels. It will also require the government working with financial institutions and investors to promote access to capital for startups and scaleup in the biobased manufacturing sectors across agricultural, energy, and material products.

4. **Incentivize Farmers**

   Supporting America's farmers, ranchers, and foresters who want to adopt new technologies and innovative practices will be critical to USDA achieving the goals set forth in the AIA. To foster sustainability and economic resiliency in agriculture and preserve America's rich environmental diversity all producers must have access to and benefit from new markets that reward practices for reducing the environmental impact of agriculture.

5. **Build Public Support and Increase Market Access for Innovative Technologies**

Innovation flourishes when science and consumer values are aligned and complement one another. BIO understands that consumers want more information about innovative biotechnologies; to know what is in their food and whether their food is safe. Moreover, it should be clear that biofuels and biobased products are sustainable. As such, the government must help build trust and foster an inclusive environment to address our most pressing societal, nutritional, and environmental concerns to achieve the goals put forward in the AIA.

The following comments expands on these principles, highlights existing and developing technologies describing how increasing the utilization of biological innovations will enable U.S. agriculture to meet the Department's goals set forth in AIA for the betterment of society.

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Advance Modern Regulatory Approaches to Keep Pace with Innovation

I. Food and Farm Applications

Plant Biotech—Plant Biotech Innovations Benefits

Biotech crops have already contributed to food security, sustainability, and climate change solutions. The acceptance of biotechnology has enabled large shifts in agronomic practices that have led to significant and widespread environmental benefits. No-till agriculture has been widely adopted due to the superior weed control from biotech crops that are able to tolerate the newer class of lower-impact herbicides. In addition, a reduction in plowing has also enabled farmers to significantly lower the consumption of fuel and decrease greenhouse gas emissions. No-till farming also leads to better conservation of soil and water and a decrease in soil erosion and soil compaction. Biotechnology has also made possible pest control measures that are more precisely targeted at specific problem pests while dramatically reducing impacts on non-target species. According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA)[2] biotech-enhanced farming systems saved 452 million acres of lands from plowing and cultivation, and decreased use of pesticides by 8.2 percent since 1996.

Biotech has also enabled plants maintain yields in the face of drought and less water. While high-yielding biotech crops have a direct bearing on improved food security and poverty alleviation with increased production. As highlighted by the United Nations biotechnology can contribute to combating global hunger and malnutrition. Approximately 140 million children in low-income groups are deficient in Vitamin A. This situation has compounded into a public health challenge. The

[2] *http://www.isaaa.org/resources/publications/briefs/54/executivesummary/default.asp.*†
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World Health Organization reports that an estimated 250,000 to 500,000 Vitamin A-deficient children become blind every year, half of them dying within 12 months of losing their sight. Golden Rice, a crop produced using the tools of biotechnology, contains three new genes that helps it to produce provitamin A.[3] Because of these benefits, 150 Nobel Laureates and 13,270 scientists and citizens wrote in support of crops and foods improved through biotechnology.[4]

As great as these developments have been towards enabling agriculture to increase production while reducing its environmental impact; developing and deploying new innovations in crop production will be critical in adapting to the challenges brought on by climate change[.]

Future Plant Biotech Opportunities

Gene editing is a process scientists use to make targeted modifications to a plant's DNA to strengthen the plant. Gene editing is the most recent breakthrough in a continuum of breeding methods that have been used to develop more beneficial food, fiber, and fuel for centuries. Our growing understanding of DNA allows this to happen in years, rather than decades. In many cases, the changes made through gene editing could happen naturally through an evolutionary process, making the gene-edited plant the same or very similar to products developed through other existing breeding methods.[5]

Gene editing can fast track genetic improvements in food, fiber, and fuel crops to keep pace with global warming and a growing human population[6] and enable growers to produce higher yields with lower fertilizer, water, and nitrogen inputs.[7] Environmental stressors cause $14 to $19 billion in plant losses every year. The single biggest cause of those losses is limited water, and that will likely get worse with climate change.[8] This technology can help us create more resilient crops able to withstand more variable weather events due to climate change by increasing plant tolerance to heat, floods, salinity, droughts and extreme cold.

Climate change will also exacerbate crop loss from insects by 10 to 25 percent because insect populations and their appetites surge in warm temperatures.[9] However, researchers are using gene editing to limit the threat to crops. Gene edited insects, like the genetically modified diamondback moths have the potential to reduce wild pest populations.[10] Gene editing hold great potential help plants become more resilient to a range of environmental stressors including pest and disease. As an example, the deadly fungus—*Fusarium oxysporum* Tropical Race 4 (TR4)—has decimated banana plantations in southeast Asia for 30 years and has made its way to Latin America.[11] However, gene editing is being used to create a banana resistant to TR4. Not only can this technology create disease-resistant varieties, it can also bring more genetic diversity to the fruit to mitigate future disease.[12]

Gene editing can also boost the nutrient levels of fruits and vegetables. Increasing the vitamin and mineral contents of plants, particularly staple crops, such as, potatoes, corn, soybeans, and wheat can address hunger issues globally and, in the U.S., where large portions of the population do not meet their nutrient requirements.[13]

Incentivizing the utilization of biotech in specialty crops can also help address the lack of fresh fruits and vegetables in food deserts in urban and rural communities. Consumers are already enjoying non-browning features in apples and potatoes. Extending the shelf life of produce can increase the availability of fruits and vegetables.

Not only will this innovation make nutritional food more available to consumers, it will cut down on food waste. According to USDA, in 2018 Americans threw away roughly 150,000 tons of food each day with fruits and vegetable accounting for 40 percent of that total.[14] Globally, the U.N. Food and Agriculture Organization (FAO)[15] estimates that worldwide, the amount of food wasted is enough to feed two

[3] *https://unchronicle.un.org/article/biotechnology-solution-hunger.*
[4] *https://www.supportprecisionagriculture.org/nobel-laureate-gmo-letter_rjr.html.*
[5] *https://innovature.com/basics.*
[6] *https://www.nytimes.com/2019/06/17/science/food-agriculture-genetics.html#click=https://t.co/yb95Eso0kY.*
[7] *https://innovature.com/article/dr-kasia-glowacka-plants-may-thrive-less-water.*
[8] *https://www.nsf.gov/awardsearch/showAward?AWD_ID=0820126.*
[9] *https://science.sciencemag.org/content/361/6405/916.*
[10] *https://www.cnn.com/2020/01/29/us/genetically-engineered-moths-crop-protection-study-scn/index.html.*
[11] *https://www.wired.co.uk/article/banana-disease-tr4-latin-america.*
[12] *https://www.bio.org/blogs/bananas-are-brink-extinction-gene-editing-can-reverse.*
[13] *https://innovature.com/article/dr-taylor-wallace-gene-editing-could-mean-healthier-foods-and-healthier-planet.*
[14] *https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0195405.*
[15] *https://www.wfpusa.org/articles/8-facts-to-know-about-food-waste-and-hunger/.*

billion people—more than double the number of people struggling with hunger. The global carbon footprint of all this wasted food was about 3.3 billion tons of carbon-dioxide equivalents, seven percent of all global emissions.[16] Using technology to cut down on food waste can help us address hunger and tackle climate change.

Synthetic biology also has major potential to improve agricultural production. Using tools in the synthetic biology toolbox, scientists typically stitch together long stretches of DNA and insert them into an organism's genome.[17]

Innovations like gene editing and synthetic biology hold tremendous potential to solve urgent challenges in agriculture which will only be compounded by climate change. Producers will need access to these innovative technologies to increase production while cutting down on their environmental footprint. Ensuring regulatory systems keep pace with these advancements will be essential for agricultural production to keep up with a growing population while reducing the environmental impacts.

Modernize Plant Biotech Regulations

A regulatory climate that fosters innovation is an important component to ensuring the development and deployment of tools producers will need for meeting the agricultural and environmental challenges in the future. A 2011 study found that between 2008–2012, bringing a new plant biotechnology trait to market cost $136 million and took approximately 13.1 years, with regulatory requirements accounting for more than ⅓ of the time required. The study also projected these costs and timeframes to increase in future years.[18] These costly barriers for market entry have historically prohibited the participation of many academics and small- and medium-sized businesses in this sector and has unfortunately limited the deployment of these innovations to crops where these significant costs can be recouped.[19]

Executive Order on Modernizing the Regulatory Framework for Agricultural Biotechnology Products (E.O. 13874)

BIO appreciates the Administration and USDA's efforts to create a predictable, streamlined, science-based regulatory system to spur investment in and deployment of innovative solutions. Last year's Executive Order on Modernizing the Regulatory Framework for Agricultural Biotechnology Products (E.O. 13874)[20] set forth agency reforms that could facilitate the growth of technological innovation in agriculture for the foreseeable future. E.O. 13874 builds on calls to improve the regulatory process that has spanned multiple administrations.[21]

SECURE Rule

USDA's Animal and Plant Health Inspection Service (APHIS) Final Rule for biotechnology regulations, 7 CFR part 340, issued on May 14, 2020 also helps ensure that regulations keep up with innovation. Referred to as the SECURE rule,[22] which stands for Sustainable, Ecological, Consistent, Uniform, Responsible, Efficient, is the first comprehensive revision of APHIS' biotechnology regulations since they were established in 1987.

BIO, overall, supports the USDA's final revisions to its plant biotechnology regulatory system. USDA has an excellent track record regulating plant biotechnology based on science and risk. The final rule acknowledges a history of safe use of plant biotechnology and the similarity of many gene edited plants to those derived from conventional breeding techniques.[23]

Regulatory Barriers to Address

The SECURE rule is a meaningful step forward in fostering innovation, enabled by its use of exemptions for certain, familiar, and low-risk plants and adoption of a new, more efficient risk assessment system. However, the lengthy timeframe over

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[16] *https://www.washingtonpost.com/news/energy-environment/wp/2016/03/28/the-enormous-carbon-footprint-of-the-food-we-never-eat/.*

[17] *https://www.genome.gov/about-genomics/policy-issues/Synthetic-Biology.*

[18] *https://croplife.org/wp-content/uploads/pdf_files/Getting-a-Biotech-Crop-to-Market-Phillips-McDougall-Study.pdf.*

[19] *https://www.cast-science.org/publication/regulatory-barriers-to-the-development-of-innovative-agriculturalbiotechnology-by-small-businesses-and-universities/.*

[20] *https://www.whitehouse.gov/presidential-actions/executive-order-modernizing-regulatory-frameworkagricultural-biotechnology-products/.*

[21] *https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/2017_coordinated_framework_update.pdf.*

[22] *https://www.usda.gov/media/press-releases/2020/05/14/usda-secure-rule-paves-way-agricultural-innovation.*

[23] *https://archive.bio.org/sites/default/files/docs/toolkit/USDA_Part_340_Issue_Brief_FINAL.pdf?_ga=2.217235934.974532664.1591207008-377855674.1537910566*

which the new rules will be implemented, and relatively narrow exemptions will delay development and commercialization for many innovative products. Those issues will need to be resolved going forward to ensure that innovative products face a clear, risk-based timely path to market. Visibly absent from this rule however were any revisions to the part 340 regulatory systems for future advances relevant to non-plant GE organisms. Also, because the SECURE rule allows developers to self-certify exemption from USDA regulations without notifying the agency, the rule raises issues related to transparency about products entering the marketplace. As discussed in more detail later in our comments, BIO will continue to drive a process to develop an inclusive and impactful approach to transparency for biotechnology in food and agriculture.

Microbial Biotech—Benefits of Microbial Technology in Farm, Food, and Feed Applications

Farm

Synthetic biology can be used in a variety of ways to reduce agriculture's environmental impact. One example is through the development of soil microbes.[24] Globally four percent of greenhouse gases are attributed to making ammonia, nitrogen fertilizer. When applied, half goes to crops and half ends up in water due to runoff. This excess nitrogen runoff can lead to "dead zones" in our large lakes and oceans.[25] Plants like soybeans and other legumes have microbes in their roots that take on this chemical engineering process naturally fertilizing themselves. Corn, wheat, and rice, which make up half the global fertilizer usage do not have these microbes. Using synthetic biology you can take the DNA code from the microbes in soybeans, redesign it to work with the microbes in corn.[26] Then you apply it as a seed treatment, and it will fertilize that crop so you can wean corn off fertilizer over time. By creating the right combination of microbes, scientists can make more resilient, efficient cropping systems.[27]

Plant biostimulants can improve a plant's natural nutritional processes, which results in enhanced tolerance to abiotic and other environmental stresses that improves overall plant health, growth, quality, and yield. In doing so, these products can increase the uptake and utilization of existing and applied nutrients. Plant biostimulants also can increase yield and quality without increasing applied fertilizer, water, or expanding planted acres, thus, sustainably enhancing the efficient use of these inputs and natural resources. Comprehensively, these technologies will not only result in a significant reduction in agriculture's climate and water-quality footprint, but it is a win-win for farmers, as the costs for their crop inputs and labor needs would decrease.

Food

Altering microbes with synthetic biology also gives us new ways to sustainably develop food ingredients. Vanillin—one of the most popular synthetic ingredients in the world—makes up 99 percent of vanilla flavoring consumed but relies on coal and oil mining to produce. Through synthetic biology we can make vanillin that is molecularly identical to the bean without burning fossil fuels.[28] Separately, using synthetic biology to edit brewer's yeast to produce hemoglobin is key to the development of new alternative proteins.[29] This is the base technology that makes product taste like meat, *i.e.,* the high concentration of heme, gives meat its signature texture and is key to several alternative meats such as the impossible burger.

Using microbials and synthetic biology, we can boost nature's ability to grow more food on less land and create food ingredients without harming the environment.

Feed

Applications of biology-based innovation to animal feed holds potential for providing additional agricultural solutions. Enteric fermentation from ruminant animals—such as cows, sheep, goats, and buffalo are a major contributor of greenhouse gas emissions from agriculture. These animals, which use microflora to assist in the

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[24] *https://www.bio.org/blogs/synthetic-biology-sustain-agriculture-and-transform-food-system.*

[25] *https://www.bloomberg.com/news/features/2019-11-06/ginkgo-bioworks-ceo-wants-biology-to-manufacture-physical-goods.*

[26] *https://onezero.medium.com/how-microbes-could-upend-americas-toxic-dependence-on-nitrogen-fertilizer-548451117a63.*

[27] *https://innovature.com/article/microbes-nourish-plants-naturally.*

[28] *https://wholefoodsmagazine.com/columns/debates/synthetic-biology-key-to-a-healthier-planet-or-threat-to-organic/.*

[29] *https://www.bio.org/blogs/synthetic-biology-sustain-agriculture-and-transform-food-system.*

digestion of otherwise indigestible starchy plants, such as grasses, produce significant volumes of methane as a byproduct of the digestive process.[30]

Despite trends in plant-based protein, animal protein production is not expected to decrease any time soon. Not only has U.S. consumption of meat and poultry continued to increase,[31] but global animal protein consumption is expected to jump 15 percent by 2027, especially in areas with growing global middle classes with increased access to disposable income.[32] Due to methane's high, short-term global warming potential compared to CO_2, solutions are immediately needed to facilitate this expansion sustainably.

Existing innovations, such as feed additives for ruminant livestock, have been demonstrated to reduce methane levels in ruminant animals by up to 30 percent.[33] The addition of enzymes[34] to chicken feed promotes better protein digestibility, which helps reduce residual nitrogen emissions from manure. While probiotics[35] in animal feed help improve gut health of the animal. Using methanotrophs and other microorganisms, such as *E. coli,* have also demonstrated the feasibility of converting natural gas and methane into proteins for animal feed. Where feasible, anaerobic digestion can be applied to convert manure and other carbonaceous wastes into renewable natural gas. However, many of these post-excrement solutions are not practical for free range ruminates. Innovation in ruminant feeds and animal genetics will be critical to expand upon these environmental benefits as growth in animal protein continues.

Regulatory Barriers to Address

Barriers to Microbial Technologies

While the SECURE Rule will help streamline the deployment of innovative plant technologies, it has created uncertainty for microbial technology. Under the previous regulations. developers of innovative microbial products could confirm whether a particular product was subject to regulation using USDA's "Am I Regulated Process." The SECURE rule provides less certainty and fewer mechanisms for evaluating whether a product is subject to regulation, resulting in an unclear and uncertain regulatory process for microbial products of biotechnology.

BIO requested in its comments[36] on the proposed rule, *Movement of Certain Genetically Engineered Organisms*[37] develop, propose, and implement a plan to facilitate research, develop, and commercialize non-plant GE organisms, including microbes and insects. The comment noted failure to do so will create a significant competitive disadvantage for these products and delay their introduction to the market.

The SECURE rule is lacking a clear and predictable regulatory framework for non-plant GE organisms potentially subject to part 340. This uncertainty has significant potential to slow research, development, and commercialization of entire categories of innovative agricultural products with the potential to present novel lasting solutions to some of agriculture's most pressing challenges.

Accordingly, BIO urges APHIS to promptly develop and issue guidance for non-plant GE organisms' potentially subject to regulation under Part 340. Without guidance, developers of non-plant GE organisms will lack any semblance of clear, predictable, risk-based regulatory options. In the absence of leadership from USDA companies may choose to commercialize their product in countries with a more predictable regulatory framework and path to commercialization. APHIS, should ensure any movement restrictions imposed on non-plant organisms, whether microorganisms or invertebrates, should be based on the fact that the organism itself poses plant pest risk and not on the fact that the non-plant is used to control plant pests.

Regulatory uncertainty with feed additives

As for feed additives, many of these new innovative products lack a suitable regulatory product category for timely approval of solutions that improve animal health without being veterinary drugs. For example, if a feed additive were to address

[30] *http://www.fao.org/in-action/enteric-methane/background/what-is-enteric-methane/en/.*

[31] *https://www.nationalchickencouncil.org/about-the-industry/statistics/per-capita-consumption-of-poultry-and-livestock-1965-to-estimated-2012-in-pounds/.*

[32] *https://www.agri-pulse.com/articles/11933-plant-based-animal-protein-demand-shows-no-sign-of-letting-up.*

[33] *https://newfoodeconomy.org/feed-additive-methane-cow-burps/.*

[34] *https://www.novozymes.com/en/news/news-archive/2017/03/more-from-one-acre-new-report.*

[35] *https://www.novozymes.com/en/advance-your-business/agriculture/animal-health-nutrition/product/alterion.*

[36] *https://www.bio.org/sites/default/files/2020-04/BIO%20Comments%20on%20340FNL%20080519.pdf*

[37] *https://www.federalregister.gov/documents/2019/06/06.*

methane emissions from cattle, that product would require one of three regulatory pathways. One is GRAS (Generally Recognized As Safe) notice to FDA, which will take an estimated 2 years for approval and limits the claims that can be made. Two is an Association of American Feed Control Officials (AAFCO) new ingredient definition submission, which may take between 3 and 5 years, and would limit the types of claims the feed producer could make. Three is a Food Additive Petition with FDA's Center for Veterinary Medicine (CVM), which may also take 3 to 5 years for approval and would also limit the claims the producer could make because it is not a full drug approval. None of these pathways offer the kind of quick assessment that is necessary to bring innovation to market to address climate change. Faster assessment route for these technologies will be critical in addressing emissions from livestock.

Animal Biotech

The outbreak of COVID–19 has brought to light the interconnectedness between human and animal health. Like the current coronavirus, scientists estimate that more than six out of every ten known infectious diseases in people can be spread from animals, and three out of every four new or emerging infectious diseases in people come from animals.[38] In addition to the dreadful health implications, the resulting economic costs of a pandemic are profound. The World Bank estimates that, between 1997 and 2009, the global costs from six zoonotic outbreaks exceeded $80 billion.[39] COVID–19 has already produced one of the sharpest economic downturns in U.S. history and is costing the U.S. treasury alone trillions of dollars.

The U.S. was woefully unprepared for this pandemic. We must employ modern approaches to be ready for future outbreaks. Improvement of animal genetics will also be a critical aspect to helping livestock producers around the world adapt to climate change, develop resiliency, and reduce emissions in milk and protein production.

Benefits of Animal Biotech

Human Health

Innovations in animal biotechnology can yield significant benefits to human and animal health, agriculture and food production, and the environment. Among these potential benefits is the ability to prevent, prepare for, and respond to outbreaks of infectious diseases such as coronavirus, Ebola, Zika, avian influenza (HPAI), and MERS, by creating more disease-resistant animals and providing disease treatments for humans.

Genetically designed cattle are being developed to produce fully human polyclonal antibodies to provide treatments for infectious diseases such as COVID–19. Scientists create a cow embryo with parts of human chromosomes, including human antibody genes, and turn off the animal antibody genes. Once grown, researchers inject a non-infectious part of the novel coronavirus into the cow, which produces human antibodies to the virus. Scientists draw blood from the cows, extract and purify the antibodies with the hope that these antibodies may treat the coronavirus in humans.[40]

Similarly, scientists have developed a chicken that is resistant to contracting and transmitting avian influenza.[41] Other innovations in animal biotechnology may be able prevent, prepare for, and respond to outbreaks of infectious diseases by providing prevention strategies and treatments for humans. These breakthroughs are even more important given reports such as the swine flu strain with human pandemic potential increasingly found in pigs in China.[42]

Biotechnology can also strategically reduce and even eliminate the populations of insects that cause the greatest harm. Mosquitoes are not just a pest, but responsible for outbreaks of diseases like West Nile, Zika, and dengue. Genetically modified mosquitoes can be designed to help decrease and eventually diminish the overall population of mosquitoes. The U.S. Environmental Protection Agency (EPA) has granted permission to release these mosquitoes in parts of Florida and Texas. If the solution goes worldwide, we may be able to eradicate the number one killer of children in Africa, malaria.[43]

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[38] *https://www.cdc.gov/onehealth/basics/zoonotic-diseases.html.*

[39] *http://documents.worldbank.org/curated/en/612341468147856529/pdf/691450ESW0whit0D0ESW120PPPvol120web.pdf.*

[40] *https://www.bio.org/blogs/can-cows-help-treat-covid-19.*

[41] *https://www.fooddive.com/news/gene-edited-chicken-cells-may-stop-the-spread-of-bird-flu/556976/.*

[42] *https://www.sciencemag.org/news/2020/06/swine-flu-strain-human-pandemic-potential-increasingly-found-pigs-china.*

[43] *https://www.bio.org/blogs/its-one-health-oclock.*

Animal Health

It is not just diseases transmitted between animals and humans that can have devastating consequences for the economy. In 2015, the outbreak of avian influenza devastated poultry producers in Minnesota. The outbreak infected more than 100 farms in the state, forced the destruction of millions of birds, and cost the state economy nearly $650 million.[44] Porcine Reproductive and Respiratory Syndrome (PRRS) is a disease that attacks the pigs' reproductive and respiratory systems, making it difficult for them to give birth and breathe. It can devastate an entire herd of 1,000 pigs in just 2 short months. African Swine Fever (ASF) has been devastating herds throughout Asia.[45] Researchers at Iowa State University (ISU) estimate an outbreak in the U.S. could cost up to $50 billion.[46] Gene editing can prevent these future outbreaks, as researchers are working to develop pigs with genetic resistance to PRRS,[47] ASF,[48] and Foot-and-Mouth Disease (FMD). These technologies can be used to make other animals resistant to disease, protecting farmers and the food supply.

Sustainable Animal Production

Precision breeding of animals to produce more meat or milk will allow for the reduction of the total number of animals in production, thus reducing the aggregate environmental impact. For example, even though there are fewer than half the dairy cows in the United States today as there were in 1950s, average milk production per cow has nearly doubled, largely because of genetic improvements through traditional breeding.[49] While these improvements took over 60 years to accomplish, the use of technologies, such as gene editing, could allow us to make similar improvements in a fraction of the time.

The first bioengineered food animal approved to date, the AquAdvantage salmon, is a fish that can grow large and healthy with fewer resources, helping to reduce the environmental impact of raising fish. Through biotechnology the salmon grows to market-size using 25 percent less feed than traditional Atlantic salmon on the market today. This makes an already efficient protein producer even better because it requires fewer wild fish to be converted into salmon feed. Further by being developed in domestic facilities close to major metropolitan areas, it significantly cuts transportation distance from farm to table. Unlike imported salmon, this salmon has a carbon footprint that is 23 to 25 times less than for traditional farmed salmon.[50]

Improvement of animal genetics will also be a critical aspect to helping livestock producers around the world adapt to climate change. Globally, but especially in tropical and subtropical environments, protecting herds from increasing temperatures expected with climate change will be very important.[51] Research is currently being done to improve animal genetics, such as in cattle, to adapt to expected increasing temperatures.[52] The UN FAO has also reported that improving fertility, use of genomics and genetic improvement can play a significant role in reducing emissions from the livestock sector.[53]

Regulatory Impediments

Unfortunately, the current regulatory approach to these technologies is an impediment to innovation and commercialization. The Food and Drug Administration (FDA) uses its "new animal drug" authority under the Food, Drug, and Cosmetics Act to assess animal biotechnologies. Evaluating food animals under this pharmaceutical-based framework is essentially forcing a square peg in a round hole. Under this system, genetically engineered animals and their progeny could be considered "drugs" and farms and ranches could be regulated as "drug manufacturing facilities." For developers, the FDA's current evaluation process is time-consuming, opaque, unpredictable, and disproportionate to the actual risk posed by the products being evaluated.

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[44] *https://www.mprnews.org/story/2017/03/08/bird-flu-outbreaks-elsewhere-worry-minnesota-farmers.*

[45] *http://www.fao.org/ag/againfo/programmes/en/empres/ASF/situation_update.html.*

[46] *https://www.card.iastate.edu/products/publications/synopsis/?p=1300.*

[47] *https://innovature.com/article/agricultural-innovations-protect-your-favorite-foods.*

[48] *https://innovature.com/article/gene-editing-could-protect-pigs-diseases.*

[49] *https://www.wpr.org/how-we-produce-more-milk-fewer-cows.*

[50] *https://aquabounty.com/sustainable/.*

[51] *https://www.bio.org/blogs/recombinetics-animal-gene-editing-could-transform-beef-industry.*

[52] *https://futurism.com/scientists-want-to-genetically-engineer-heat-resistant-cows-to-survive-climate-change.*

[53] *http://www.fao.org/3/a-i8098e.pdf.*

FDA has announced that it plans to also regulate gene-edited animals under this system—even those products with edits that could have occurred naturally or through conventional breeding. This puts at risk an entirely new generation of technologies and threatens to drive research, jobs, and innovation overseas. Similar concerns were raised by a bipartisan group of Members in the House of Representatives in a letter to FDA last year.[54]

In more than 2 decades, the United States has approved only one biotechnology food animal for production and sale. Fast action is needed, or the U.S. will be prevented from deploying this promising technology and risk losing our leadership position in livestock genetics and in global meat and dairy production and export. We are already out of sync with the rest of the world, including European authorities (and livestock breeders), who are increasingly characterizing such approaches simply as advanced breeding. Other countries, like China, Canada, Australia, and Brazil, will be deploying this technology with or without the guidance of the United States. They will also begin to become more formidable exporters of their beef, pork, poultry, and fish products.[55]

As USDA rightly note in its *Task Force on Agriculture and Rural Prosperity,* Federal regulations are limiting technological innovation in animal biotech.[56] To overcome these regulatory barriers, BIO supports USDA's[57] efforts to create joint agreement with FDA whereby the USDA leads regulatory oversight of biotechnology-derived food animals and the FDA leads oversight of non-food and biomedical animals. In addition, FDA should conduct a review of its process and implement specific process changes to improve its decisionmaking, transparency, and timelines for reviews. Developers and other stakeholders need confidence that FDA will be held accountable for approval timelines and ensure that the pathway to commercialization is predictable, clear, consistent, and based on risk.

Taking these steps will ensure America's farmers and ranchers have access to cutting-edge technologies to remain globally competitive and resilient to disease and climate change, the United States must have risk-proportionate regulations that spur biological innovations, while protecting health and environment.

One Health

In addition to technology, better coordination will ensure that our country is better prepared for the next pandemic. The One Health collaboration eliminates barriers that often exist between human health, animal health, and environmental health regulatory strategies to create smarter, multi-faceted and coordinated efforts. The bipartisan, *Advancing Emergency Preparedness Through One Health Act of 2019,*[58] (H.R. 3771/S. 1903) would direct the U.S. Department of Health and Human Services and USDA to coordinate with other agencies and state and local leaders to advance a national One Health[59] framework to better prevent, prepare for, and respond to zoonotic disease outbreaks like COVID–19.

II. Sustainable Fuels

Benefits of Sustainable Fuels to Agriculture

The development of sustainable fuels enables agriculture to be a key contributor in addressing emissions from the transportation sector, which is the leading source of greenhouse gas emissions according to the EPA.[60] Not only is this one of the largest sectors of emissions, it is growing.

Emissions Reductions

Biofuels and those produced using biological systems provide a strong and immediate solution to reducing emissions from all forms of transportation, including aviation, which has an immediate and long-term nee for liquid fuels. Development of sustainable fuels allow agriculture to play a crucial role in addressing climate change. It is critical that we recognize that these are solutions that are available today, and do not require a mass turnover in vehicles. It is commonly known that carbon emissions act much like compounding interest. Just in the way that a dollar

[54] *https://www.bio.org/sites/default/files/2020-05/190726%20-%20EC%20Letter%20to%20FDA%20re%20Gene%20Editing.pdf.*
[55] *https://thehill.com/opinion/energy-environment/373361-regulatory-restructure-of-biotech-is-critical-to-the-future-of-us.*
[56] *https://www.usda.gov/sites/default/files/documents/rural-prosperity-report.pdf.*
[57] *https://www.agri-pulse.com/articles/13210-perdue-says-mou-with-fda-could-be-solution-to-animal-biotech-regulation.*
[58] *https://www.congress.gov/bill/116th-congress/house-bill/3771.*
[59] *https://archive.bio.org/sites/default/files/OneHealth_Final.pdf.*
[60] *https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WUHR.pdf.*

saved today is better than a dollar saved tomorrow, limiting carbon emissions today is far more valuable than limiting the same or a greater volume of emissions at a later date.[61]

Because of biotech innovations, the production of biofuels is becoming more efficient and environmentally sustainable. Biocatalysts, such as enzymes, lower energy requirements, increase reaction rates, can reduce the number of process steps necessary to make chemical transformations. Enzymes are selective, specific, and have a high catalytic rate; they are more efficient, producing chemical products with higher purity and fewer byproducts or wastes. Enzymes are enabling biofuel producers to convert corn stover, wheat straw, wood chips, sawdust, waste, and sugarcane bagasse into fuel, and to collectively increase biofuel yield and energy efficiency throughout the sector. Biocatalysts (*e.g.,* bacteria) are enabling production of fuels and chemicals from new waste and residue streams. New bio-boosting chemicals are increasing biomass yields while eliminating the need for antibiotics in feed bioproducts for livestock. Companies have commercialized enzymes for producing cellulosic ethanol from agricultural waste and are currently operating cellulosic biorefineries.[62]

We are already reaping the benefits of the development of advanced and cellulosic biofuels. The use of low-carbon biofuels, primarily used in passenger cars, has resulted in significant greenhouse gas reductions, with cumulative CO_2 savings of nearly 600 million metric tons (mmt) since the RFS was enacted.[63]

The greenhouse gas emission reductions and benefits will only expand with the utilization of new conversion technologies and the development of advanced and cellulosic biofuels across all transportation sectors. As USDA highlighted last year, greenhouse gas emissions from corn-based ethanol are about 39 percent lower than gasoline. The study also states that when ethanol is refined at natural gas-powered refineries, the greenhouse gas emissions are even lower, around 43 percent below gasoline.[64] Current Federal policy supporting these fuels, the RFS, requires lifecycle greenhouse gas reductions of at least 50 percent *versus* the relevant petroleum-based alternative for a fuel to qualify as an advanced biofuel, and at least 60 percent for cellulosic biofuels.

Existing advanced and cellulosic biofuel technologies are far surpassing these requirements. As highlighted in an Environmental and Energy Study Institute (EESI) report, "according to Argonne's GREET model, an energy crop like miscanthus can have negative greenhouse gas emissions, meaning that over the crop's life cycle, carbon sequestration outweighs emissions. Argonne researchers show that, compared to gasoline, biofuel from energy crops can reduce emissions by 101 to 115 percent. Corn stover, a residue from corn, can reduce emissions by 90 to 103 percent."[65] As the industry improves its efficiencies and practices, the greenhouse gas reductions of approved advanced and cellulosic biofuels are likely to be substantially greater. Further, new technologies such as gas fermentation, provide alternative routes to advanced biofuels, including sustainable aviation fuel (SAF), from a variety of biomass residues.

The development and expansion of algae and aquatic plant cultivation has great potential for the development of advanced biofuels. Microalgae are aquatic plants that can be induced to rapidly accumulate lipids, often greater than 60 percent of their biomass, while consuming large amounts of carbon dioxide. They can be cultivated using closed loop systems, open ponds, and photo-bioreactors, using less land, energy, and water than land crops. The characteristics of algae biofuels include high flash point, biodegradability, and low or no aromatic or sulfur compound, so they are being used to produce a variety of biofuels such as bioethanol, bio-butanol, jet fuel, biodiesel, bio gasoline, green diesels, and methane.[66]

Air Quality Benefits

The environmental benefits of biofuels go beyond greenhouse gas reductions. The outbreak of COVID–19 has highlighted the importance of clean air to human health. Harvard University found that small increases in exposure to long-term levels of

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[61] Frank, Jenny. "Quantifying the Comparative Value of Carbon Abatement Scenarios Over Different Investment Timing Scenarios" National Biodiesel Board Conference and Expo, 28 January 2020, Tampa, Florida. Next Generation Scientists for Biodiesel.

[62] *https://www.bio.org/industrial-biotechnology-unique-potential-pollution-prevention*.

[63] *https://ethanolrfa.org/wp-content/uploads/2019/02/LCARFSGHGUpdatefinal.pdf*.

[64] *https://www.usda.gov/media/press-releases/2019/04/02/usda-study-shows-significant-greenhouse-gas-benefits-ethanol*.

[65] *https://www.eesi.org/articles/view/biofuels-versus-gasoline-the-emissions-gap-iswidening#:~:targetText=Argonne%20researchers%20show%20that%20compared, for%20the%20RFS%20from%202010*.

[66] *https://farm-energy.extension.org/algae-for-biofuel-production/*.

tiny particulate matter were linked to a big jump in the mortality rate for COVID–19. Each extra microgram of fine particulate matter per cubic meter that people were exposed to over the long-term was linked to an eight percent increase in the mortality rate.[67] Similar results were found by the University of Cambridge which overlaid nitrogen dioxide (NO_2) and nitrogen oxide (NO) levels from more than 120 monitoring stations across England with figures on coronavirus infections and deaths. They found a link between poor air quality and the lethality of COVID–19 in those areas.[68]

As BIO stated in its comments to the EPA Scientific Advisory Board (SAB) *Review of COVID–19 Pandemic Scientific and Technical Issues to Inform EPA's Research Actives,*[69] "our member companies offer several solutions that can not only help combat this pandemic, but also lessen the impact of a future pandemic by helping to establish a resilient, sustainable bioeconomy."

Harmful tailpipe emissions, including particulate matter (PM) from the transportation sector disproportionately affect areas comprised of minority populations. For example, according to a study by the Union of Concerned Scientists (UCS), African Americans and Latinos breathe in about 40 percent more particulate matter from cars, trucks, and buses than white Californians.[70] Another UCS study found Northeast communities of color breath 66 percent more air pollution from vehicles.[71]

According to the National Bureau of Economic Research, the United States saw fine particulate pollution increase 5.5 percent between 2016 and 2018. According to the American Lung Association, State of the Air report for 2019, more than four in ten Americans live in counties that have unhealthy levels of ozone pollution or particular matter.[72] Prior to COVID–19, the World Health Organization[73] found that 4.2 million deaths[74] every year occur as a result of exposure to ambient air pollution. Since then, numerous studies have found that long-term exposure to levels of tiny particulate matter were linked to a significant increase in the mortality rate for COVID–19.[75]

Sustainable fuels represent a readily available solution to addressing air quality by reducing tailpipe emissions including particulate emissions, hydrocarbons, and carbon monoxide, which helps prevent the formation of ground-level ozone. Data from 222 EPA sensing sites show that ozone levels have fallen during the period in which ethanol blending increased.[76] Additional data from the University of Illinois-Chicago (UIC) show substantial reductions in particulate matter and benzene with the addition of biofuels.[77] The American Lung Association, Upper Midwest Region found higher volumes of biofuels can reduce ozone-forming pollutants and evaporative emissions.[78]

Such benefits are not unique to ground transportation; research has demonstrated that SAF reduce contrails, particulate matter and mass emissions compared to conventional fossil jet fuels, with the potential to improve air quality near airports and reduce the climate impacts of aviation at high altitude.[79] Additionally, sustainable fuels produced via microbial fermentation of industrial waste gases can limit the impacts of carbon pollution on human and environmental health locally. Sustainable fuels can be produced from the organic fraction of municipal solid waste (MSW), a much healthier option than MSW incineration which can contribute to air pollution.

As we begin to bring the economy back online, it is critical we do so with a cleaner, more resilient energy sector. Biofuels are an immediately available path toward decarbonizing the transportation sector and improving air quality while lowering fuel prices, driving economic growth, and creating jobs. However, this will require stable policies and regulations.

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[67] *https://www.researchgate.net/publication/340492612_Exposure_to_air_pollution_and_COVID-19_mortality_in_the_United_States_A_nationwide_cross-sectional_study.*

[68] *https://www.medrxiv.org/content/10.1101/2020.04.16.20067405v5.*

[69] *https://yosemite.epa.gov/sab/sabproduct.nsf//0/2996BA363B41C2598525854C0048EA69?OpenDocument.*

[70] *https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles-california-2019.*

[71] *https://www.ucsusa.org/about/news/communities-color-breathe-66-more-air-pollution-vehicles.*

[72] *http://www.stateoftheair.org/key-findings/.*

[73] *https://www.who.int/health-topics/air-pollution#tab=tab_1.*

[74] *https://www.who.int/gho/phe/outdoor_air_pollution/burden/en/.*

[75] *https://www.newscientist.com/article/2241778-are-you-more-likely-to-die-of-covid-19-if-you-live-in-a-polluted-area/.*

[76] *http://www.ethanolrfa.org/2014/12/real-world-ozone-and-particulate-data-expose-fallacy-of-minnesota-study/.*

[77] *http://www.erc.uic.edu/assets/pdf/UIC_Cook_County_Slides.pdf.*

[78] *https://www.cleanairchoice.org/fuels/e85.cfm.*

[79] *https://www.nature.com/articles/nature21420.*

Stable Policies for Sustainable Fuels

Renewable Fuel Standard

When allowed to work, the RFS has enabled billions of dollars of investment in new technologies that have led to the rapid growth of the renewable fuels industry, the development of new fuel technologies, and the biobased economy. The growth of the biofuels industry has bolstered our rural communities and provided agriculture producers stable commodity markets, benefitting our nation's economic and energy security.

Unfortunately, the demand destruction caused by the EPA's drastic expansion of small refinery exemption waivers or SREs has had a major impact on the industry, costing jobs, stifling investment in innovation, and undermining efforts to reduce greenhouse gas emissions in the transportation sector.

In January 2020, the U.S. Court of Appeals for the Tenth Circuit ruled in *Renewable Fuels Association* v. *EPA* that EPA had exceeded its authority in granting SREs under the Renewable Fuel Standard to three refineries in 2016 and 2017, and that moving forward, EPA may only issue SREs to refineries that have continuously received exemptions for every compliance year since 2011.

Despite this ruling, refiners have now filed at least 58 retroactive SRE requests.[80] This comes on top of another 27 SRE applications pending for 2019 and 2020. Unfortunately, rather than comply with the ruling in the 10th Circuit and immediately reject the retroactive requests it is perpetuating the uncertainty about the RFS by letting these pending applications linger.

Beyond SREs, innovative biofuel producers are also stymied by EPA's delays in the approval of new advanced and cellulosic biofuel pathways and petitions for production facilities. These delays are arbitrarily keeping advanced and cellulosic biofuels from reaching the marketplace, hindering the growth of the industry. EPA's failure to approve the registration for corn ethanol facilities that have registered for producing cellulosic biofuel from corn kernel fiber (CKF).

As a result of the uncertainty of the RFS and the delays in new technologies coming to market, companies who have researched and developed technologies in the United States are looking to commercialize advanced and cellulosic biofuel technologies in countries like India and China which are investing heavily in biofuels to improve their air quality.

BIO appreciates USDA's continued support of the biofuels industry. To ensure success of the sustainable fuels industry, enable agriculture to reduce emissions and bring even greater job growth to rural America, we urge the Department to push EPA to end its unwarranted expansion of SREs and move forward on stalled pathways and facility registrations.

Further, we request the Department to encourage and support EPA to interpret the RFS broadly and accommodate all pathways and approve facility registrations that could fall within the existing statute. Specific areas that would have an impact immediately to accelerate the production of low carbon sustainable fuels are related to biological carbon capture and utilization (CCU), the interpretation and eligibility of "renewable biomass", the use of biointermediates, and life-cycle and tracking methodologies for sustainable fuels from waste agricultural residues such as CKF. This would have immediate benefits for the agricultural sector by create more demand for waste feedstocks and renewable biomass.

Transition from a RFS to a Clean Fuel Standard

As the Department explores options to harness the power of agriculture to decarbonize our transportation sector, we urge it to support new policies and programs that are technology and feedstock neutral and are based off of performance and their ability to deliver carbon reductions. Toward that end it will be critical for the Department to work with Congress in developing a Clean Fuel Standard (CFS) that builds on the success of the RFS and ensures agriculture and biofuels are part of the solution in reducing emissions.

Given the success of the California model, other states[81] and regions[82] are beginning to consider establishing their own CFS programs to address emissions and air pollution. Not only does the establishment of these programs provide an additional value to biofuels, helping spur investment, production, and consumption of advanced biofuels, a national CFS would spur immediate, and additional carbon savings by allowing America's farmers to contribute by adopting practices that enhance soils

[80] *https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rfs-small-refinery-exemptions.*

[81] *https://www.act-news.com/news/california-leads-with-low-carbon-fuel-standard-programs/.*

[82] *http://blog.opisnet.com/rfs-lcfs.*

natural ability to sequester carbon. When a CFS is coupled with a voluntary carbon crediting and verification program it would allow farmers to contribute quickly and effectively to fighting climate change.

Adoption of a CFS would not only incentive advanced biofuels like sustainable aviation fuel, but it would also incentivize fuels which have traditionally been left out of the RFS. Advanced technologies for the conversion of waste carbon oxides to sustainable aviation fuels and cellulosic diesels from woody residues that are poised for success today but have traditionally been left out of the RFS due to regulatory interpretations. A CFS that builds off the volumes and infrastructure put in place by the RFS is a simple, yet elegant way to steadily reduce emissions in transportation, allowing all forms of cleaner mobility to contribute, and bridge the divide between rural America and urban America.

III. Biobased Manufacturing

Support Farmers and Revitalize Manufacturing

The expansion of biobased manufacturing can revolutionize industry by creating a sustainable value chain that use biological processes to convert renewable, low cost, or waste feedstocks into everyday products. It creates new markets for agricultural crops, crop residues and waste streams, as well as opportunities for innovation in producing consumer goods.

These technologies represent novel, innovative ways to address plastic pollution and climate change. Already some 8 mmt of plastics enter our ocean on top of the estimated 150 mmt that currently circulate our marine environments.[83] Through the application of biotechnology, we can create renewable chemicals, which can be used to produce sustainable plastics that are recyclable or biodegradable. While these materials are molecularly like their petrochemical equivalent, they reduce greenhouse gas emissions since they are produced from renewable or waste resources instead of oil and gas.

According to the U.S. Energy Information Administration, U.S. chemical production uses 28 percent of the total energy used by all industrial sectors.[84] Without action, these emissions are expected to grow. In January, Louisiana regulators approved an air quality permit that will allow Sunshine Project, to pump 13.6 million tons of carbon dioxide into the atmosphere every year. That is equivalent to adding 2.6 million cars to the road annually. In 2018, only 13 coal plants emitted more.[85] A report in Environmental Research Letters identified 88 petrochemical projects along the Gulf Coast that are either in the planning stage or under construction. If all are completed, their combined emissions output could reach 150.8 mmt, the equivalent of 38 coal plants.[86–87]

However, biobased products can provide a solution to the increasing rise in emissions in petrochemical plastic production. The USDA found that the development of renewable chemicals and biobased products removed 12.7 mmt of CO_2 from the manufacturing sector in 2016 alone in its report, *An Economic Impact Analysis of the U.S. Biobased Products Industry.*[88] This is due to the displacement of petroleum and reduction of fossil fuels in the manufacturing and use of biobased products. The report goes on to note:

> The use of biobased products reduces the consumption of petroleum equivalents by two primary mechanisms. First, chemical feedstocks from biorefineries have replaced a significant portion of the chemical feedstocks that traditionally originate from crude oil refineries. Biorefineries currently produce an estimated 150 million gallons of raw materials per year that are used to manufacture biobased products. Second, biobased materials are increasingly being used as substitutes for petroleum-based materials, which have been used extensively for many years. An example of this petroleum displacement by a biobased material is the use of natural fibers in packing and insulating materials as an alternative to synthetic foams, such as Styrofoam. In this report we updated the oil displacement values from the 2016 report to reflect economic growth. In 2016 the estimated oil displacement is estimated to be as much as 9.4 million barrels of oil equivalents.

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[83] *https://oceanconservancy.org/trash-free-seas/plastics-in-theocean/#:~:text=Every%20year%2C%208%20million%20metric,currently%20circulate%20our%20marine%20environments.*

[84] *https://www.eia.gov/energyexplained/use-of-energy/industry.php.*

[85] *https://www.eenews.net/climatewire/stories/1062133995.*

[86] *Ibid.*

[87] *https://iopscience.iop.org/article/10.1088/1748-9326/ab5e6f/pdf.*

[88] *https://www.biopreferred.gov/BPResources/files/BiobasedProductsEconomicAnalysis2018.pdf.*

In addition to the environmental benefits, USDA found that the value added to the U.S. economy by biobased products was $459 billion in 2016. While employment in the industry increasing from 4.22 million jobs in 2014 to 4.65 million jobs in 2016.

Even greater reductions of greenhouse gas emissions are possible through the expansion of biotechnology in manufacturing. World Wildlife Fund found "if existing biotech solutions were used extensively in other traditional industries, such as detergent, textile, and pulp and paper manufacturing, another 52 mmt of greenhouse gas emissions reductions would be achieved annually."[89]

Biotechnology is enabling the production of biobased plastics providing a sustainable alternative to petroleum-based plastics. More than half of all plastic ever created was produced in the last 15 years, and right now, about 335 mmt of new, virgin plastic is created each year. Virtually all that new plastic will be made from oil and gas. Plastics now account for 3.8 percent of global greenhouse gas emissions and at the current rate willaccount for 15 percent of global emissions by 2050.[90]

Because some bioplastics are derived at least in part from corn, sugarcane, or other plants, they have a smaller carbon footprint, with lower cradle-to-plant-gate greenhouse gas emissions than their fossil fuel-based counterparts.[91] Substituting the annual global demand for fossil-based polyethylene (PE) with biobased PE would save more than 42 mmt of CO_2. This equals the CO_2 emissions of ten million flights aground the world per year.[92] Replacing conventional 1,4-Butanediol (BDO) with biobased BDO would save over 7 million tons of greenhouse gas emission per year, or the equivalent of taking 1.5 million cars off the road.[93] In addition to reducing greenhouse gas emissions, biobased BDO can produce compostable plastic packaging, reducing plastic waste.

All biomanufacturing processes—whether enzymatic or microbial—share the unique characteristic of avoiding use of toxic feedstocks and process reagents, which in turn minimizes toxic waste and byproducts. Manufacturers must manage byproducts of bioprocesses to prevent pollution.[94] Just as enzymes improve biofuel production, manufacturers are using enzymes commercially to produce pharmaceuticals and other chemical compounds, food ingredients, detergents, personal care products, textiles, and paper products, avoiding use of toxic feedstocks and process reagents, which in turn minimize toxic waste and byproducts.[95] By utilizing enzymes, textile mills used less energy and reduced their CO_2 emissions by 12 mmt. This technology also has the added benefit of reducing the use of water in textile production by 8.1 billion cubic meters, equal to the annual consumption of 140 million households.[96]

Sugar from crops like corn and wheat can be fermented using yeast to create renewable bio-succinic acid, which is commonly used as an emollient or fragrance carrier in various skin creams and lotions. Succinic acid is effective in combating acne and reducing skin flakiness and wrinkles. By using biotechnology, many personal care products can be made using a range of renewable, sustainable resources, including agricultural feedstocks. Carbon captured from industrial processes can be recycled and fermented using microbes to create renewable non-toxic isopropanol, a common alcohol used to extract and purify oils found in skin care products, such as acne treatments. Using synthetic biology, carbon-rich gases can be used to develop esters, a class of chemical compounds used to create certain aromas and fragrances in perfumes and cosmetics. By capturing and recycling these gases to be converted to esters instead of going into the atmosphere, environmental impact is reduced. Replacing petroleum-based butylene glycol with butylene glycol produced from a sustainable and renewable sugar fermentation process reduces greenhouse gas emissions by 51 percent and allows consumers to avoid petroleum-based ingredients in their personal care products.[97]

Biotechnology can also improve the environmental footprint of textiles. Replacing petroleum based paraxylene with a bio-paraxylene produced from a mix of sugar cane and corn-based ethanol results in a 70 percent reduction in carbon emissions.

[89] *http://assets.panda.org/downloads/wwf_biotech.pdf.*

[90] *https://www.nature.com/articles/s41558-019-0459-z?utm_source=commission_junction&utm_medium=affiliate.*

[91] *https://ihsmarkit.com/research-analysis/bioplastics-offer-a-smaller-carbon-footprint.html.*

[92] *https://www.european-bioplastics.org/bioplastics/environment/.*

[93] *https://www.genomatica.com/wp-content/uploads/Genomatica-Sustainability-and-Social-Responsibility-2019.pdf.*

[94] *http://www.bioprocessintl.com/manufacturing/facility-design-engineering/minimizing-the-environmental-footprint-of-bioprocesses-303905/.*

[95] *https://www.thebalance.com/enzyme-biotechnology-in-everyday-life-375750.*

[96] *https://www.novozymes.com/en/news/news-archive/2019/05/biological-solutions-on-the-catwalk-to-find-answers-for-sustainable-fashion.*

[97] *https://www.genomatica.com/wp-content/uploads/SOFW-LCA-Article.pdf.*

Bio-paraxylene can be used to produce a 100 percent bio-polyester. This can lead to a 25 percent to 50 percent reduction in carbon emissions when compared to petroleum based polyester products. Further bio-polyester produced using bio-paraxylene can be recycled in the same recycling infrastructure as petroleum-based polyester.[98] Gas fermentation, which uses biology to convert waste industrial emissions to ethanol production, can produce textiles through conversion of this sustainable ethanol into fibers.[99]

Traditional carpets take up the second-largest amount of U.S. landfill space. Approximately 3.5 billion pounds of carpet are put in U.S. landfills every year. Carpets are made up of a complex array of chemicals, either made of nylon, polyester, or polypropylene. Biotechnology can manipulate the polyester to form every element of the carpet, from base to tufts. The flooring, when discarded, can be returned to the manufacturer, ground up, and repurposed as another carpet, reducing the need for petroleum to manufacture new carpet.[100] Biological gas fermentation combined with gasification, can convert mixed flooring wastes into the same chemicals used in carpet production.

Overcoming Regulatory Barriers

These novel, innovative approaches to address domestic and global climate challenges are desperately needed. Just as it did with air pollution from transportation, COVID–19 has brough to light the impact petrochemical production has on human health, particularly on communities of color. This is exemplified in what has been called "Cancer Alley" in Louisiana.[101] As Beverly Wright, the founder and executive director of the Deep South Center for Environmental Justice in New Orleans stated in the *New York Times* April 29, 2020 article, *'A Terrible Price': The Deadly Racial Disparities of [COVID]–19 in America,* "As soon as I heard about [COVID], I started getting nervous about the relationship between $PM_{2.5}$ and this virus."

Regulatory proposals to address plastic waste and pollution should set a performance standard that recognizes reductions in emissions in the production of chemicals and plastics. Further government efforts to promote and incentivize recyclability and reduce plastic waste should also seek to promote the use of bioplastics. Finally, the government should give broad regulatory acceptance of, and where applicable, regulatory preference for, innovative and sustainable biobased products.

With these policies and principals we can achieve our goal of creating value added markets for commodities, rebuilding our national economy and workforce in a forward-looking, self-sufficient manner with the added benefit of addressing climate change and enhancing human health through improved air quality.

Provide Robust Funding of Public- and Private-Sector Scientific Research

The Federal Government's long history of generously funding research is an important foundation for the nation's bioeconomy and the development of the revolutionary technologies highlighted throughout BIO's comments. The successful adoption and deployment of biotechnologies in agriculture, renewable energy, and the bioeconomy have been enabled by USDA, the U.S. Department of Energy (DOE), and the Department of Defense (DOD), among other Federal agencies.

As America's foreign competitors are investing greater amounts in research to lure the development of new technology offshore, these programs to support and incentivize foundational research and development activities are ever more critical to maintaining America's global preeminence in food, agriculture, bioenergy, and biobased manufacturing production. This investment also translates into opportunities for large private-sector investment in applied research and development.

I. Invest in Agricultural Research

Benefits of Research and Development

Research has been central to the improvements in agricultural productivity. As the National Coalition for Food and Agricultural Research (NC–FAR) highlights, recent analysis by the International Food Policy Research Institute of 292 studies of the impacts of agricultural research and extension published since 1953 found an average annual rate of return on public investments in agricultural research and extension of 48 percent—an extremely high rate of return by any benchmark.[102]

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[98] *https://www.virent.com/technology/sustainability/.*

[99] *https://www.lanzatech.com/2019/10/07/world-first-products-made-from-recycled-pollution-reduce-emissions-and-keep-carbon-in-the-ground/*

[100] *https://www.fastcompany.com/3067849/the-first-100-recyclable-carpets-are-here.*

[101] *https://www.businessinsider.com/louisiana-cancer-alley-photos-oil-refineries-chemicals-pollution-2019-11.*

[102] *https://www.ncfar.org/need.asp.*

USDA Research, Education, and Economics (REE) programs have been critical to this success. USDA National Institute of Food and Agriculture (NIFA) and the Agriculture and Food Research Initiative (AFRI) have been essential for the foundational research and agricultural workforce development that complements and underpins large systems-level research, education, and extension activities. This core competitive grant program has been essential in establishing America the preeminent global leader in food, agricultural, and bioenergy production.

USDA's Agricultural Research Service (ARS) plays a critical role in partnering with the university community and industry to advance science-based solutions. Research and Extension Programs such as McIntire-Stennis, 1890 Extension, Evans Allen, Hatch Act, and Smith-Lever have been assisting farmers and ranchers in adopting best practices that increase productivity while improving soil, water, and air quality.

Provide Greater Investment in Research and Development

Public and private investments in U.S. agricultural research and practical application have paid huge dividends to the United States. However, this unparalleled success story in the nation's food and agricultural system is in large part the product of past investments. Federal funding for food and agricultural science has been essentially flat for over 20 years despite much greater demonstrated needs and has reportedly declined by about 25 percent in real terms since 2003.[103]

As researchers with ISU CARD pointed out in its report *Measuring Public Agricultural Research and Extension and Estimating their Impacts on Agricultural Productivity: New Insights from U.S. Evidence*[104] with the world expected to reach 9.6 billion people—a 29 percent increase over 2013—by 2050, society must increase agricultural productivity without causing immense environmental damage and hunger. To achieve this will require greater investment in agricultural research and extension.

The need to modernize our nation's aging food and agricultural science infrastructure, both at USDA labs and universities, is critical. Greater funding should be made to strengthen land-grant universities and HBCUs. Not only to bolster research for scientific agricultural advances, but to train the next generation of ag scientists and researchers and farmers and ranchers. Additional investments in research and education is also critical in assisting producers in increasing their use of precision agriculture, deployment of new crops, and sequestering more carbon in their soil.

Programs such as USDA's Biotechnology Risk Assessment Research Grants Program (BRAG) supporting the generation of new information that will assist Federal regulatory agencies in making science-based decisions about the potential effects of introducing into the environment genetically engineered organisms, including plants, microorganisms—such as fungi, bacteria, and viruses—arthropods, fish, birds, mammals and other animals excluding humans. Continuation of programs like BRAG will be critical in supporting these technologies with advancing modern regulatory approaches need to advance innovation.

II. Sustainable Fuels

Benefits of Research and Development

Bolstering funding of DOE, USDA, and other government research programs is necessary for the growth of the advanced biofuels industry. DOE's Office of Energy Efficiency and Renewable Energy (EERE) invests in clean energy technologies that strengthen the economy, protect the environment, and reduce dependence on foreign oil.

According to DOE's *Aggregate Economic Return on Investment in the U.S. DOE Office of Energy Efficiency and Renewable Energy,*[105] research and development (R&D) investments provide significant economic benefits. A total taxpayer investment of $12 billion (inflation-adjusted 2015 dollars) in EERE's R&D portfolio has yielded more than $388 billion in net economic benefits to the United States.

The Bioenergy Technologies Office (BETO) within EERE funds vital research and development of technologies to convert our nation's biomass resources into clean, renewable fuels. BETO recognizes that biofuels are especially needed in the aviation industry, where liquid fuels are still the only viable fuel source for commercial airlines.

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[103] *https://www.ncfar.org/NCFAR_Testimony_FY_20_House_040519.pdf.*
[104] *https://lib.dr.iastate.edu/agpolicyreview/vol2016/iss1/3/.*
[105] Dowd, J. "Aggregate Economic Return on Investment in the U.S. DOE Office of Energy Efficiency and Renewable Energy." (Oct. 2017) Available at: *https://www.energy.gov/sites/prod/files/2017/11/f39/Aggregate%20ROI%20impact%20for%20EERE%20RD%20-%2010-31-17.pdf.*

USDA regional perspective has also been critical. Research through NIFA has helped support the development and production of advanced biofuels compatible with agricultural systems. It has brought together researchers, landowners, communities, and private industry to grow bioenergy and develop new biomass crops and supply chains.

Federal Aviation Administration (FAA) programs are also critical to support the research and development, commercialization, and deployment of Sustainable Aviation Fuel. FAA's Office of Environment and Energy's R&D Program provides scientific understanding, development of new technologies, fuels and operations, and analyses to support achieving the Next Generation Air Transportation System (NextGen), and its goals of environmental protection that allow for sustained growth. The NextGen program is working with partners to develop solutions to reduce the impacts associated with aviation noise and exhaust emissions and increasing energy efficiency and availability. In alliance with research institutions and industry stakeholders, the program will accelerate the maturation of engine and airframe technologies to reduce aviation noise, fuel use, and emissions. FAA's Center of Excellence (COE) is charged with discovering, analyzing, and developing science-based solutions to the energy and environmental challenges facing the aviation industry. Through COE, FAA has been supportive of alternative jet fuel testing and analysis efforts through the ASCENT. This program is working collaboratively with its 16 main universities and five affiliate universities.

These programs have been vital to research and development and growth of the advanced and cellulosic biofuels sector.

Greater Investments in Research and Development

As the government seeks to reduce emissions throughout the economy its critical for the Federal Government to recognize that liquid fuels will remain the main source of energy for transportation and to continue to invest in research and development of technologies to convert biomass and waste feedstocks into clean renewable fuels.

Research and development in sustainable fuels should also remain feedstock neutral. To advance the next generation of biofuels, DOE should also support policy, research, and infrastructure directed to the use of using corn cobs, stover, and corn kernel fiber as a fuel to generate steam and electricity and as a source of cellulosic feedstock for ethanol.

III. Biobased Manufacturing

Benefits of Research and Development

Research supported by USDA ARS has been critical in finding new uses of agricultural commodities and by products. Research related to biobased products focuses on developing technologies leading to new and improved non-food products that expand markets for farm products, replace imports and petroleum-based products, and offer opportunity to meet environmental needs. Research also addresses the development of appropriate feedstocks for biobased products.

DOE EERE programs including BETO and the Advanced Manufacturing Office (AMO) have been essential in supporting, developing, and deploying new, novel technologies that help domestic manufacturing become more sustainable resilient, adaptable, and globally competitive.

Globally, there is a strong push to decarbonize fuels and materials from wastes and residues. Conversion technologies are being developed in Europe and Asia, where there is both supportive policies and significant investment in research, development, and demonstration projects. Technologies that have been developed in the U.S. are often initially commercialized elsewhere. We urge the Department to consider support for pilot and demonstration scale projects in the U.S., and, where appropriate, provide funding to support U.S. industry partnerships with international collaborators to speed the rate of deploying U.S. based technologies at home and abroad.

Greater Investments in Research and Development

As USDA highlighted in its 2018 report *An Economic Impact Analysis of the U.S. Biobased Products Industry* many countries world-wide are investing in these technologies, and the U.S. should do so as well. Research is critical to spurring innovation and increasing the variety and efficacy of biobased products and fully utilizing biobased feedstocks. Many of the biobased innovation available today began in university laboratories. Supporting the source of these important developments will be vital to enhancing the growth of the industry. The government should increase opportunities for private sector and university collaboration through ongoing National Science Foundation (NSF), USDA, and DOE funding grants.[106]

Also critical to the development of the biobased economy is determining its value and identifying the segments which need investment and research and development. Key to this is updating the North American Industry Classification System (NAICS) codes. BIO supported language in the 2018 Farm Bill.[107] BIO applauds USDA's comments to the 2017 NAICS Updates for 2022 to establish a measurement for biobased products.[108]

Funding of base biological and environmental research also has broad implication in environmental remediation, and reengineering of microorganisms and plants with direct relevance to energy, climate, and the environment and enhancing the sustainability of biobased products and renewable fuels.

Support of land-grants and HBCUs will also be critical for STEM education so that as the bioeconomy grows, we have a domestic workforce that can take advantage of the increasing number of high-paying scientific jobs.

IV. Investing in Platform Technologies

To achieve the goals set out in the AIA and meet the challenge of feeding a growing world and tackling climate change will require significant investments in platform technologies such as gene editing and synthetic biology.

Investments in next generation biotechnologies and genomics also have great potential to meet this challenge and achieve the Departments goals set forth in the AIA. Gene editing for multi-trait seed improvements can enable agriculture to increase production by up to 400 mmt, reduce emissions by up to 30 megatonnes of CO_2, reduce freshwater withdrawals by up to 180 billion cubic meters, reduce the number of micronutrient deficient by up to $100 million, while generating up to $100 billion in additional farmer income.[109]

As highlighted earlier, advancements in animal biotechnology can further our nation's efforts to safeguard animal health, food safety, and the environment. Increasing genomic research in animal agriculture will also unleash enormous progress in terms of food production and security.

Just like animal biotech, research and development of plant protein and cellular agriculture can provide solutions for improving the productivity and environmental sustainability of food, feed, and animal production and addressing the increasing demand for protein in a growing world. These technologies have tremendous potential for expanding our nation's bioeconomy and diversifying our food supply to adapt and mitigate disease and environment. Supportive research by USDA AFRI can help advance the development and optimization of cell lines, cell culture media, scaffolding, and cultivators (bioreactors) for producing meat through cellular agriculture.

Increasing research in synthetic biology will unlock innovations in agriculture and food productions, energy, and manufacturing. Biotechnology companies have identified opportunities to incorporate synthetic biology [110] in groundbreaking advances in industrial biotechnology manufacturing processes. Companies have begun using science to optimize the processes for producing renewable chemicals, biobased products, and biofuels. With synthetic biology techniques, industrial biotechnology companies can save time by shortening the number of steps used in traditional processes, reducing costs while developing new products. They can also reduce the products' impact on the environment. With proper support synthetic biology can transform our economy.

Because of strong Federal support, the United States is a leading nation in the development of synthetic biology. This success and high research productivity are not lost on foreign governments, including China, who are trying to kick-start their biomanufacturing sectors to catch up to, or even leapfrog, the U.S. Our continued growth will be fueled by robust scientific research, strong intellectual property rights, well-functioning technology transfer, dynamic capital investment, science- and risk-based regulation that minimizes obstacles, and public support that embraces the positive influence of biotechnology.

Supportive grants for research and development and startup will provide significant advances in foundational tool development and practical applications ranging from bioenergy, biomanufacturing, to biomedicine. The recommendations put forward by the National Academies of Sciences Engineering Medicine report, *Safe-*

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[106] *https://www.biopreferred.gov/BPResources/files/BiobasedProductsEconomicAnalysis2018.pdf.*
[107] *https://republicans-agriculture.house.gov/uploadedfiles/greenwood_testimony.pdf*
[108] *https://www.regulations.gov/document?D=USBC-2020-0004-0046.*
[109] *https://www.ncfar.org/HSS_20200713_Presentation.pdf.*
[110] *https://www.bio.org/blogs/synthetic-biology-innovation-industrial-biotechnology.*

guarding the Bioeconomy[111] can give further guidance in advancing the bioeconomy for the betterment of the U.S. and society.

BIO has also supported S. 3734, the Bioeconomy Research and Development Act[112] to strengthen and broaden engineering biology by establishing an initiative to advance research and development, advance biomanufacturing, and develop the future bioeconomy workforce. The legislation would also establish a committee to coordinate research in engineering biology across the Federal agencies.

DOD's Synbio Manufacturing MII initiative also has great potential for collaborative, pro-innovation opportunities to expand American leadership in biotechnology.

Modernize Infrastructure

Growing a resilient bioeconomy of the future will also require important investments in infrastructure, such as increased, widespread access to broadband internet technology, pipelines, construction of bioreactors and biobased manufacturing facilities, and distribution capacity for carbon dioxide and sustainable fuels. It will also require the government working with financial institutions and investors to promote access to capital for startups in the biobased manufacturing sectors across food, material products, and energy.

COVID–19 showed the vulnerabilities in our supply chain. To mitigate the effect climate change will have on it in the future, it is critical we develop a cleaner, more resilient agricultural, energy, and manufacturing infrastructure.

I. Access to Broadband

COVID–19 has highlighted the importance of broadband to the modern economy and the digital divide rural communities are facing. The Federal Communications Commission[113] estimated in 2017 that it would cost $80 billion to bring high-speed internet to remaining parts of the country that do not have access, while a more recent U.S. Department of Agriculture[114] report estimated it would require between $130 and $150 billion over the next 5 to 7 years, to adequately support rural coverage and 5G wireless densification.

Despite this cost, bringing high-speed internet infrastructure to rural areas is essential to building a bioeconomy. Farmers and ranchers who participate in carbon markets will need reliable internet access to transmit the data that emissions reductions from soil carbon sequestration are real and verifiable. Reliable access to the internet is also critical to the deployment of next generation precision agriculture technologies which will be essential to sustainably increasing production.

The internet is also critical to ensuring biobased manufacturers and biofuel producers can remain economically competitive

II. Grants and Loan Guarantees for biorefineries.

USDA has been a critical partner in supporting and providing financial support to the development of advanced biofuels and renewable chemicals.

The Biorefinery Assistance Program loan guarantee program provides manufacturers access to capital for large-scale projects in rural communities. Without the loan guarantee program, new innovative companies might never be able to pool sufficient capital to commence development of a project in rural communities with a small population. These biorefineries are proven drivers of job and economic growth for rural communities.

The 2018 Farm Bill expanded access to this program to renewable chemical and biobased product manufacturers; however, it only provided mandatory funding to the program through Fiscal Year 2020. To spur growth of additional biorefineries in rural communities, USDA should provide loan guarantees to new projects from the funding already allocated to this program. Additional funding should be provided in future years to support the construction of additional biorefineries.

III. Investments in Biofuels Infrastructure

Pumps and Pipelines

USDA has been a great champion in promoting the development of infrastructure needed to expand the marketplace to supply more renewable fuel to America's drivers through the Biofuel Infrastructure Partnership (BIP) and the proposed Higher Blends Infrastructure Program (HBIIP).

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[111] *https://www.nap.edu/resource/25525/interactive/.*
[112] *https://www.congress.gov/bill/116th-congress/senate-bill/3734.*
[113] *https://transition.fcc.gov/Daily_Releases/Daily_Business/2017/db0119/DOC-343135A1.pdf.*
[114] *https://www.usda.gov/sites/default/files/documents/case-for-rural-broadband.pdf.*

In addition to funding the installation and conversion of pump infrastructure, the government should also make investments in pipelines and terminals to deliver greater volumes of sustainable fuels as well as distribute CO_2 developed from biofuels. Having greater distribution capacity can help avoid the supply disruption the food industry faced due to COVID–19 when the closure of ethanol facilities led to a CO_2 crunch.

Sustainable Aviation Fuels

The development of sustainable aviation fuels also represents a growing opportunity for the development of biofuels producers and biomass producers. To support that effort investments should be made in infrastructure to incentivize the creation and use of sustainable aviation fuels in commercial aviation to reduce fuel costs, pollution, and the overall environmental footprint of U.S. aviation.

USDA Collaboration

In 2016, the U.S. Navy Great Green Fleet demonstrated the potential of advanced biofuels in reducing emissions in maritime engines. Named to honor President Theodore Roosevelt's Great White Fleet, the year-long initiative in the John C. Stennis Strike Group (JCSSG) used alternative fuel sources, energy conservation measures, and operational procedures to reduce its fuel consumption. The fleet used biofuels made from ten percent beef tallow provided from farmers in the Midwest and 90 percent marine diesel, and it was cost competitive with traditional fuels. It is used as a drop-in alternative, meaning no modifications to engines or operational procedures are required.[115]

The Great Green Fleet was the result of the DOD, USDA, and DOE, providing funding under the Defense Production Act toward the construction of biorefineries that produce cost-competitive, drop-in military biofuels.[116] As a result, these refineries are now coming online, capable of producing fuels for the military and aviation sector.

The military is the nation's largest single consumer of fuel, so the Navy's purchase of 450,000 gallons of biofuel for the exercise signaled a potentially huge defense market for liquid renewables. However, when the program essentially ended in 2017, along with the Navy's issuance of short-term contracts, it left investors wary of financing biofuel refineries.

Given the size of the military's fuel demand issuing a requirement for Federal agencies to use a certain volume of biofuels could spur long-term investment[117] in the development of sustainable fuel facilities.

IV. Tax Incentives

The biobased economy and industrial biotechnology contribute greatly to the U.S. economy. Enacting sustained, supportive tax policy will lead to even greater growth domestically in this industry. Targeted tax policies will enable emerging technologies in advanced biofuels, renewable chemicals, and biobased products to overcome the challenging capital environment for first-of-a-kind biorefinery construction and allow them to bring their technologies to commercial deployment. This will unleash our members' scientific innovation potential and grow the bioeconomy.

Biofuels

Biofuel tax provisions supporting the development of advanced and cellulosic biofuels—particularly the Second Generation Biofuel Producer Tax Credit (PTC), the Special Depreciation Allowance for Second Generation Biofuel Plant Property, the Biodiesel and Renewable Diesel Fuels Credit, and the Alternative Fuel Vehicle Refueling Property Credit—are incredibly important to our companies that are making significant investments to create new agricultural supply chains, build infrastructure for liquid biofuels, and develop innovative new technologies. These credits have enabled our industry to create new jobs, contribute to rural prosperity, and diversify our nation's energy supply. For example, the biodiesel tax credit has supported the production of biofuels used in aviation.[118]

The expiration and continued on-again off-again nature of these incentives has created uncertainty for investors and the industry about the availability of these credits, jeopardizing the long-term investments necessary for the development of

[115] *https://www.navy.mil/submit/display.asp?story_id=95398.*

[116] *http://www.biofuelsdigest.com/bdigest/2014/09/19/breaking-news-us-navy-doe-usda-award-210m-for-3-biorefineries-and-mil-spec-fuels/.*

[117] *https://www.bloomberg.com/news/articles/2020-07-09/biofuel-revolution-was-doomed-by-policy-and-investment-failures.*

[118] *https://www.nata.aero/assets/Site_18/files/GIA/121SMS/Aviation%20Industry%20Coalition%20Support%20for%20Biodiesel%20credit%20extension%20Neal%20Brady.pdf.*

biofuels. While these tax incentives enjoy broad [119] bipartisan [120–121] support [122] for these tax incentives their short-term availability makes it difficult for companies to make long-term planning decisions. Ensuring the growth of advanced and cellulosic biofuels industry will require long-term tax incentives to avoid creating uncertainty for investors and companies trying to raise capital.

The development of a long-term SAF specific blender's tax credit [123] could attract significant investment to the sector and address existing structural and policy disincentives that have prevented the aviation biofuels industry from taking off.

Renewable Chemicals

To realize the full potential of the domestic renewable chemicals industry, existing renewable energy, manufacturing, or environmental tax incentive regimes should be opened to renewable chemicals. Providing a Federal income tax credit for domestically produced renewable chemicals, could create domestic jobs and other economic activity that can help secure America's leadership in the important arena of green chemistry. Like current law for renewable electricity production credits, the credits would be general business credits available for a limited period per facility.

Carbon Capture and Utilization

Maintaining and extending the 45Q tax credits for CCUS will help drive investment and development of innovative new technologies which can capture carbon. The credit monetizes carbon to produce valuable products. Capturing waste carbon from power plants and manufacturing facilities can be converted into valuable products such as advanced biofuels, animal feed, and chemicals. As a result, CCUS helps displace petroleum and other carbon feedstocks. Already, integrating CCUS with biofuels projects is producing negative emissions fuels.[124]

Opportunity Zones

The Opportunity Zone (OZ) tax incentive has spurred investment in under-capitalized communities. Any corporation or individual with capital gains can qualify. However, the OZ guidance is unclear to investors and developers if biobased technologies can qualify for OZ tax incentivizes. A relatively minor clarification to OZ Guidance could potentially unlock billions of development dollars for bioeconomy manufacturing facilities.

V. Bolstering the Supply Chain

Biobased manufacturing can be a solution to making sure those on the ground fighting the pandemic have the protection they need. Demand for personal protective equipment (PPE) is currently outpacing supply. To ensure that we can adequately fight the virus, it is critical that doctors, nurses, first responders, and scientists developing potential cures have access to PPE.

Increasing production of renewable chemicals made from innovative biotechnologies and synthetic biology will help us meet the growing demand of PPE. Development of PPE and other products from biobased materials can also help address the increase in waste from disposable masks and other PPE which is posing new problems for the Earth's oceans.[125] One study estimated if every person in the United Kingdom used a single-use face mask a day for a year it would create an additional 66,000 metric tons of contaminated waste and 57,000 metric tons of plastic packaging.[126] Since these products can be biodegradable or recyclable, they can significantly reduce the amount of waste. It will also increase the demand for biomass feedstocks as producers are faced with a downturn in commodity prices.

In addition to PPE, biobased products can help meet the growing need for testing products to track the virus and research cures. It can also help us meet the demand for sterilizing and cleaning products. In addition to ethanol producers, biotech companies are developing key ingredients that can help in the production of hand sani-

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[119] *https://finkenauer.house.gov/sites/finkenauer.house.gov/files/documents/Second%20Gen%20Biofuels%20Extender%20Support.pdf.*

[120] *https://www.biotech-now.org/wp-content/uploads/2019/11/Second-Gen-Biofuels-Letter-11-26-18.pdf?_ga=2.27182452.850446835.1573066958-1287514846.1535039721.*

[121] *http://kce.informz.net/KCE/data/images/Final%20Signed%20Feb%202019%20Loebsack%20LaHood%20Biodiesel%20Letter.pdf.*

[122] *https://finkenauer.house.gov/sites/finkenauer.house.gov/files/3435_001.pdf.*

[123] *https://www.bio.org/letters-testimony-comments/sustainable-aviation-fuels-saf-tax-incentive-letter-congress.*

[124] *https://www.gasworld.com/velocys-signs-ccus-agreement-with-oxy/2017915.article.*

[125] *https://www.fastcompany.com/90520661/masks-gloves-and-other-coronavirus-waste-are-starting-to-fill-up-our-oceans?.*

[126] *https://www.greenbiz.com/article/how-face-masks-gloves-and-other-coronavirus-waste-are-polluting-ocean.*

tizers. Green surface cleaners can meet the growing demand to sterilize surfaces in hospitals, public places, and homes. While enzyme developers are enhancing detergents that can increase cleaning efficacy even in low temperature washing, circumventing the need for hot water and reducing the environmental footprint of the sterilization process.

To meet this demand, the Department and the Administration need to make greater investments in research, development, and deployment of biobased products to tackle COVID–19. We would encourage USDA to use whatever authorities it has to bolster the biobased sector, including expedited distribution of loans under the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program to build expedited capacity for biorefineries producing renewable chemicals, increasing promotion of the benefits biobased products can provide in addressing the COVID–19 under the BioPreferred Program and ensuring Federal agencies are adhering to the program's procurement requirements.

Incentivize Farmers

I. Carbon Sequestration

To increase agricultural production while reducing the environmental impacts and emissions from production will require incentivizes throughout the entire value chain, especially at the farm level.

Promoting greater utilization of crops and practices that impart more carbon into the soil and out of the atmosphere through their roots will be critical to keeping warming below 2 °C. This can be accomplished through simple, low-cost incentives to farmers for capturing carbon. The FAO noted that soils can sequester approximately 20 petagrams of carbon in 25 years, that's more than ten percent of anthropogenic emissions.[127] The *United States Mid-Century Strategy for Deep Decarbonization* estimated that U.S. lands have been a net "carbon sink" for the last 3 decades and through enhancement they could offset up to 45 percent of economy wide emissions by 2050.

What is needed from government is the establishment of infrastructure to measure and verify those carbon sequestrations at the local farm level. Furthermore, farmers need assistance in understanding and accessing the current voluntary and compliance markets for these credits. Common sense policy will make sure that America agriculture continues to lead on this new frontier of climate change mitigation and restoration.

Toward this end, BIO is supportive[128] of the Growing Climate Solutions Act[129] (GCSA) (S. 3894/H.R. 7393) introduced by Senators Mike Braun (R–IN) and Debbie Stabenow (D–MI) and Representatives Abigail Spanberger (D–VA) and Don Bacon (R–NE) This bill will support America's farmers, ranchers, and foresters who want to adopt innovative practices that combat climate change, while continuing to provide the world with food, feed, and fiber.

II. Incentivizing New Technologies

GCSA or other carbon markets can foster acceptance for new technologies that can further reduce the environmental impact of agriculture, including tools like precision plant breeding, biostimulants, and microbial inoculants and enhancing animal feed with enzymes and other additives to reduce emissions in livestock. These improved agricultural practices increase crop yields and provide several environmental benefits including capturing nitrogen directly from the atmosphere and increasing root growth that binds carbon to the soil.

Combined with modern agricultural techniques and sustainable farming practices such as planting cover crops and no-till, these innovative technologies that enhance productivity can play a key role in sequestering carbon dioxide in the soil, improving soil health, and protecting America's waterways.

To further encourage the use of these technologies additional incentivizes could be created. The Section 45Q provides a performance-based tax credit to power plants and industrial facilities that capture, store, and/or utilize carbon oxides that would otherwise be emitted into the atmosphere as CO_2. Expanding the credit to new technologies that are being developed to amplify soil carbon sequestration through forestry and crops would incentivize producers to utilize this technology reducing atmospheric carbon.

[127] *http://www.fao.org/fileadmin/user_upload/soils-2015/docs/Fact_sheets/En_IYS_ClCng_Print.pdf.*

[128] *https://www.bio.org/press-release/bio-supports-growing-climate-solutions-act.*

[129] *https://www.congress.gov/bill/116th-congress/senate-bill/3894.*

Build Public Support and Increase Market Access for Innovative Technologies

I. Build Public Support and Market Access

Growing Trust in Innovation

Innovation flourishes when science and consumer values are aligned and complement one another. The U.S. government's regulatory approach toward innovative products should be supported by credible transparency measures. A proactive approach to transparency stands to build trust with the broader agri-food ecosystem.

During the public comment period on the SECURE Rule,[130] BIO advocated[131] for a process to improve public access to information about new agricultural biotechnology products. While the final rule does not contain a mechanism for mandatory notification, BIO encourages increased openness about products entering the marketplace and best practices developers use in advancing beneficial products to the commercial marketplace.

BIO is advocating that the U.S. government play a role in driving an inclusive and impactful approach to transparency. We encourage agencies to ensure that regulatory policies are durable and legally defensible. Further, we encourage agencies to articulate to the public the rationale for their approach, including safety assessments.

The U.S. Government should establish a biotechnology clearinghouse that is geared toward consumers and builds off the Food and Drug Administration's Agricultural Biotechnology Education and Outreach Initiative.[132] This clearinghouse should provide information about common uses of biotechnology, like gene editing, and the safety of innovations commonly used in the food and agricultural system.

We look forward to working with agency experts to evaluate mechanisms to affirm and communicate the safety and benefits of biotechnology.

To learn more please visit BIO's Growing Trust in Innovation webpage: *https://www.bio.org/growing-trust-innovation*.

BioPreferred

Managed by USDA, the goal of the BioPreferred program is to increase the purchase and use of biobased products from agricultural feedstocks. The BioPreferred Program was created by the 2002 Farm Bill and reauthorized and expanded in the 2018 Farm Bill. The program's purpose is to spur economic development, create new jobs and provide new markets for farm commodities. The increased development, purchase, and use of biobased products reduces our nation's reliance on petroleum, increases the use of renewable agricultural resources, and mitigates adverse environmental and health impacts.[133] Prior to the 2018 Farm Bill, due to limitations in verification methodology, the BioPreferred program only incentivized procurement of plant-based products. The 2018 Farm Bill requests USDA to develop verification methods for products made from biological CCU. This will expand opportunities for biobased products made from waste resources.

The BioPreferred Program is transforming the marketplace for biobased products through two initiatives: purchasing requirements for Federal agencies and their contractors; and voluntary product certification and labeling. As highlighted above, the label is helping drive consumer recognition of biobased products that are displacing about 300 million gallons of petroleum per year—the equivalent to taking 200,000 cars off the road.[134] However, while Federal law, the Federal Acquisition Regulation, and Presidential Executive Orders direct all Federal agencies and their contractors to purchase biobased products in categories identified by USDA through the BioPreferred Program,[135] oftentimes Federal agencies fail to give preference to biobased products. To ensure the BioPreferred Program drives growth of the bioeconomy, the Administration should ensure Federal agencies follow through with the requirements to give preference to biobased products and identify noncompliance.

[130] *https://www.bio.org/letters-testimony-comments/bio-comments-usdas-proposed-part-340-revisions*.

[131] *https://www.bio.org/letters-testimony-comments/bio-submits-letter-office-management-and-budget-part-340*.

[132] *https://www.fda.gov/food/agricultural-biotechnology/agricultural-biotechnology-education-and-outreach-initiative*.

[133] *https://www.biopreferred.gov/BioPreferred/faces/pages/AboutBioPreferred.xhtml*.

[134] *https://www.usda.gov/media/press-releases/2016/10/03/usda-report-shows-growing-biobased-products-industry-contributes*.

[135] *https://www.gsa.gov/governmentwide-initiatives/sustainability/buy-green-products-services-and-vehicles/buy-green-products/biobased-and-biopreferred-products*.

The following recommendations put forward in *An Economic Impact Analysis of the U.S. Biobased Products Industry*[136] can make this achievable:

- Improve the ability of the Federal Government, including the General Services Administration and other acquisition departments of Federal agencies, to track the purchase of biobased products in acquisition systems. Currently, there is not a singular way of doing so, and it is difficult to accurately determine the increases in the use of biobased products by the Federal Government.
- Expand marketing and consumer education of the BioPreferred Program's USDA Certified Biobased Product label. Currently, many consumers are confused or are unaware of what a biobased product is, and they do not recognize or understand the label. While there are certainly benefits to having products labelled as USDA Certified Biobased, increased market recognition would help the biobased products industry grow and encourage more companies to pursue certification.
- Leverage the similar goals between the USDA and the DOE to cooperate on increasing the purchase of biobased products. Both agencies have similar objectives in terms of growth and less reliance on nonrenewable resources, and research supported by both agencies can provide greater power and increased success.

Demonstrate Sustainability

Developing carbon markets are not only beneficial to incentivizing producers to sequester carbon in the soil, but can bring greater value to sustainable fuels, biobased products, and food and feed applications. These markets allow the manufacturers of biobased chemicals, plastics, food, animal feed, and everyday materials to reliably demonstrate their true environmental benefit, from farm to consumer.

Additional mechanisms should be developed to better enable producers to showcase the benefits of these technologies.

Trade

An effective U.S. Government trade policy is critically necessary to address tariff and nontariff barriers that affect the trade of, and innovation in, biotech products globally. In particular, the U.S. bioeconomy needs a proactive trade agenda focused on enhancing IP protection abroad, a harmonized and science-based regulatory environment, fair and equitable technology transfer policies, and access and enforcement policies that appropriately value American innovation and are governed by the rule of law. We applaud that the United States is actively negotiating agreements with key trading partners such as China to address systemic trade practices such as forced technology transfer and IP theft that threatens biotechnology ecosystem across sectors.

With respect to agricultural biotechnology, U.S. leadership is essential to ensure that U.S. agriculture can benefit from advances in science that reduce its environmental footprint while improving crop production. Many U.S. trading partners, including China and Europe, maintain unjustified, non-science barriers that delay the approval of new plant biotech products. To reduce the potential for trade disruption, biotech companies will often delay commercialization of new products in the United States until China and Europe haveapproved the same products. Such delays impact U.S. competitiveness and cost oureconomy dearly. A recent study estimates Chinese delays between 2011 and 2016 reducedfarm income by $5 billion and U.S. GDP by $7 billion.[137]

For new innovations like gene editing, the global regulatory landscape is unclear, and there is a risk that genome-edited products will be brought under outdated, discriminatory, and highly burdensome regulatory frameworks previously adopted for transgenic ag-biotech products, even though many of the newer products being developed using gene editing do not contain DNA from outside the plants gene pool. This creates the potential for enormous barriers to entry for this emerging industry, potentially limiting the use of this game-changing technology to only a handful of companies and in only large-scale crops. The United States currently is working with like-minded governments to chart a more reasonable path forward for new innovations in biotechnology like gene editing. The U.S. government also has joined many governments from across the Americas, Africa, and Asia to support agricul-

[136] *https://www.biopreferred.gov/BPResources/files/BiobasedProductsEconomicAnalysis2018.pdf.*

[137] *https://www.bio.org/press-release/new-report-shows-substantial-economic-costs-chinese-delays-ag-biotech-approvals.*

tural applications of precision biotechnology.[138] This international effort is a clear signal to the world that innovations in precision biotechnology, like genome editing, should not face arbitrary and unjustified treatment by regulatory authorities. We applaud these efforts and encourage renewed urgency in their implementation.

Conclusion

BIO applauds USDA for taking a proactive approach and seeking information about facilitating the transformative breakthroughs for agriculture to meet the challenges of the 21st Century and increase agricultural production by 40 percent while cutting the environmental footprint by 50 percent.

Achieving this goal and addressing the challenges of climate change and inequality in society, will require the rapid development and deployment of biology-based technologies throughout the agricultural supply chain. It will require USDA and the Federal Government to establish supportive policies and regulations, provide robust funding for research and development, modernize infrastructure, support all farmers and ranchers, and build public support of new technologies.

We urge the Administration to seize the opportunity to expand on this American leadership, by acting and supporting the pro-innovation technologies and policies we outlined in our comments. We look forward to our continued partnership in this critical endeavor.

SUBMITTED STATEMENTS BY HON. DAVID SCOTT, A REPRESENTATIVE IN CONGRESS FROM GEORGIA

STATEMENT 1

ON BEHALF OF BARBARA P. GLENN, PH.D., CHIEF EXECUTIVE OFFICER, NATIONAL ASSOCIATION OF STATE DEPARTMENTS OF AGRICULTURE

On behalf of the National Association of State Departments of Agriculture (NASDA), we appreciate the opportunity to submit this statement outlining the priorities of state departments of agriculture on policies related to climate resilience. We request that this statement be included in the record of the upcoming, February 25th hearing of the Committee on Agriculture focusing on "Climate Change and the U.S. Agriculture and Forestry Sectors".

NASDA represents the commissioners, secretaries, and directors of the state departments of agriculture in all 50 states and four U.S. territories. State departments of agriculture are responsible for a wide range of programs including food safety, combating the spread of disease, and fostering the economic vitality of our rural communities. Conservation and environmental protection are also among our chief responsibilities.

In November 2020, NASDA along with several other national organizations representing farmers, ranchers, forest owners, the food sector, and environmental advocates formed the Food and Agriculture Climate Alliance (FACA). This alliance is dedicated to working together to define and promote shared climate policy priorities. On November 17, 2020, FACA released more than 40 policy recommendations to guide the development of Federal climate legislation.

Many of the FACA recommendations are reflective of NASDA priorities and we would ask that the Committee on Agriculture consider the following as part of any future legislative or oversight activities of the Committee:

- *NASDA asks that any legislative or oversight activities undertaken by the Congress related to climate focus on advancing science-based outcomes.*
- *NASDA asks that any legislative or oversight activities undertaken by the Congress promote fairness and equity within the agriculture community through climate solutions.*
- *NASDA encourages Congress to enact and fund voluntary, incentive-based climate smart agricultural programs as part of the farm bill and other legislative vehicles that consider agriculture's unique role in building resiliency and climate adaptation.*
- *NASDA asks that the Congress fund research programs and forecasting tools that will help agriculture adapt to the effects of a changing climate, including increased pests and disease, changes in suitable cropping and livestock production systems and increases in extreme weather events.*

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[138] *https://www.usda.gov/media/press-releases/2018/11/02/wto-members-support-policy-approaches-enable-innovation-agriculture.*

- *NASDA supports expanding Federal tools, including the soil health provisions of the 2018 Farm Bill, to incentivize and measure soil health improvements. Soil health incentives can encourage farmers to adopt practices that improve soil heath and increase carbon sequestration. Improved protocols for measuring the gains in soil carbon from soil health improvements can support development of markets for soil carbon capture and storage.*
- *NASDA asks that the Congress enact policies that credit ongoing efforts of many farmers and ranchers that have previously adapted climate smart strategies to reduce emissions, sequester carbon, and improve resiliency.*
- *NASDA supports the creation of voluntary, incentive-based climate smart agricultural programs that are practical, and provide benefits for farmers and ranchers.*

NASDA stands ready to assist this Committee in any way possible as it carves a path forward on this important policy issue.

Please contact Zachary Gihorski (**Redacted**) if you have any questions or would like any additional information.

STATEMENT 2

ON BEHALF OF BASF CORPORATION

Background

BASF Corporation is the largest affiliate of BASF SE. Headquartered in Florham Park, New Jersey, it is a leading producer and marketer of chemicals and related products in the United States. BASF has the broadest portfolio in the chemical industry. Through science and innovation, we serve customers in nearly every industry.

BASF has more than 150 production and R&D sites throughout North America, and roughly 14,616 employees in the U.S. and Puerto Rico.

Research Triangle Park (RTP), North Carolina is the North American headquarters for the Agricultural Solutions division including regulatory affairs. RTP is also the global headquarters and a major R&D site for the Seeds & Traits business and Bioscience Research, as well as strategic marketing for herbicides and insecticides, and insecticide R&D and formulation development.

Introduction

Farming today is more complex than ever before; the unpredictability of the weather, control of pest and weeds, market price volatility, scarcity of natural resources, and all this in a world heading toward nine billion people. Farmers are playing an increasingly important role today, advancing sustainable agriculture practices as the world faces the challenge of feeding a growing population with healthy crops, while respecting and preserving limited resources.

The good news is that scientific knowledge is advancing at an ever-increasing speed. Knowledge of plant genomics, advancements in crop breeding techniques, crop protection improvements, and data acquisition and interpretation are all opportunities to build a more sustainable and resilient food and agricultural system for the future.

BASF provides farmers with crop protection products, seeds and digital solutions designed to sustainably meet their crop production needs. We believe that adoption of technology and innovation is one of the key elements to reducing agriculture's environmental footprint while also making farmers and ranchers more resilient to climate change.

BASF Sustainabilty Commitments

We are continuously introducing sustainable solutions into the market to improve quality of life and conserve resources. With that in mind, BASF committed to clear and measurable targets to boost sustainable agriculture by 2030.

Climate Smart Farming

> Target: 30% reduction in CO_2 emissions per ton of crop produced by 2030 in wheat, soy, rice, canola and corn

BASF will support farmers to become more carbon efficient and resilient to volatile weather conditions with technologies that increase yield, make farm management more effective, and decrease environmental impact.

Sustainable Solutions

> Target: 7% annual increase in our share of solutions with substantial sustainability contribution

BASF will increase the number of sustainable solutions it brings to farmers year by year. Therefore, the company is continuously investing in its strong R&D pipeline, steered systematically by sustainability criteria. BASF's R&D pipeline contains solutions that support the efficient use of resources and reduce the environmental footprint.

Digital Farming

> Target: bring digital technologies to over 980 million cumulative acres of farmland globally by 2030

Digitalization can make agriculture more resource-efficient and sustainable. Therefore, BASF will help farmers with digital tools to grow their businesses profitably, while reducing their environmental footprint. Using digital technologies allows farmers to produce more with less, to make farming processes more efficient from field monitoring to the food supply chain. BASF's xarvioT digital products enable more precise application of crop protection products, nutrient management, automated buffer zones and monitoring of biodiversity.

Smart Stewardship

> Target: To ensure safe use of our products with the right stewardship

BASF takes its commitment to safety for human health and the environment very seriously, offering the right stewardship with every product not only to satisfy applicable legal requirements but also to ensure the safe use of its products around the farm and in the field. The company provides access to stewardship tools and services that are tailored to every farmer's daily work. These include protective equipment, customized training, digital solutions, and new and future-oriented application technologies such as drones that reduce working time and minimize potential exposure to agrochemicals.

Innovation and Technology As Part of the Climate Solution

Over the last decades, agriculture technologies and innovation have been deployed at a significant scale around the globe, but more can still be done. As we work to increase production with limited resources and unreliable weather patterns, the continued deployment of new and existing technologies will be critical to address climate change.

Innovations in plant breeding are enabling BASF to enhance yields and climate resiliency. The utilization of crop protection innovations will also allow farmers to produce more on the same amount of land.

Additionally, optical sensors have allowed improvements in identification of target pests (weeds, insects, and plant pathogens) allowing for more targeted applications of crop protection tools and fertilizers. Sensors are also used to identify plant stresses like water and nutrient deficiencies, or abiotic plant stresses that can reduce yield. These sensors will allow for growers to quickly adapt to changing environmental conditions during the growing season and will be key to manage limited environmental resources.

The benefit of these technologies can be broad in scope, but below are some of the potential outcomes of these innovation solutions:

- Lowering fuel and energy consumption thus reducing carbon dioxide emissions
- Reducing the use of agricultural inputs by pinpointing fertilizer and pest control needs
- Eliminating nutrient depletion through monitoring and managing soil health
- Reducing ecological impact through high-yielding and stress-resistant varieties
- Maximizing water use efficiency

As new technologies are developed, policies based on sound-science are necessary to ensure that new products and innovations are reaching the marketplace in a transparent and predictable manner so farmers and ranchers can take advantage of these tools as they face the increasing challenges of climate change.

Conclusion

BASF appreciates the opportunity to submit these comments and stands ready to work collaboratively to assist the U.S. House Committee on Agriculture as climate change policy is developed. BASF is well positioned to provide input around some of the technologies and innovations that will assist farmers and ranchers to become more resilient to climate change, while also reducing their overall environmental footprint. Thank you again for the opportunity, and we look forward to working with you.

SUBMITTED LETTERS BY HON. JIM COSTA, A REPRESENTATIVE IN CONGRESS FROM CALIFORNIA

LETTER 1

ON BEHALF OF JIM MULHERN, PRESIDENT AND CHIEF EXECUTIVE OFFICER, NATIONAL MILK PRODUCERS FEDERATION

March 3, 2021

Hon. DAVID SCOTT,
Chairman,
House Agriculture Committee,
Washington, D.C.;

Hon. GLENN THOMPSON,
Ranking Minority Member,
House Agriculture Committee,
Washington, D.C.

Dear Chairman Scott and Ranking Member Thompson:

The National Milk Producers Federation appreciates the opportunity to submit testimony for your hearing entitled "Climate Change and the U.S. Agriculture and Forestry Sectors" held on Thursday, February 25, 2021 at 12:30 p.m. We look forward to working with you and your Committee Members on this critical priority in the coming months.

The National Milk Producers Federation develops and carries out policies that advance the well-being of dairy producers and the cooperatives they own. The members of NMPF's cooperatives produce the majority of the U.S. milk supply, making NMPF the voice of more than 32,000 dairy producers on Capitol Hill and with government agencies.

U.S. dairy farmers have been environmental stewards for decades, tending with great care to their land and water, and they value a proactive approach to sustainability. As agricultural practices and technologies have evolved and improved over time, so too have dairy producers adapted. As a testament to dairy's endeavors, greenhouse gas (GHG) emissions to produce a gallon of milk dropped nearly 20% over the 10 years from 2007 to 2017 and the environmental footprint of a gallon of milk has significantly decreased since 1944 (*e.g.,* 90% less land, 65% less water, 63% smaller carbon footprint *per unit of milk*). We believe, however, that more can always be done and therefore support efforts to facilitate continuous improvement in this area.

Unfortunately, sustained low milk prices have made it increasingly difficult for dairy farmers to succeed and we are grateful for the significant improvements included in the 2018 Farm Bill enacted into law. In light of the COVID–19 pandemic which has only served to exacerbate these challenges, it is these improvements and more which are needed to make both milk production and advanced environmental protection a source of economic strength for all dairy farms.

To continue and enhance our efforts to combat climate change, the dairy industry has launched the Net Zero Initiative to reduce the industry's climate impact to become carbon-neutral by as early as 2050 and minimize the water quality impacts of dairy farming. As part of the groundwork needed to launch this initiative, the dairy industry has worked to develop scientific and economic models to quantify the economic and environmental benefits associated with certain dairy farm technologies and practices, and various technologies have been catalogued and evaluated based on their effectiveness, resilience, and business prospects.

Within the initiative, the industry hopes to deploy several demonstration farms around the country to explore the impact of multiple technologies and management practices that have an ability to aid in reducing dairy's carbon footprint and water quality impact. This effort will identify which technologies and practices work well for different types of operations, which will help inform policy discussions regarding the best ways to expand their adoption in pursuit of reducing dairy's environmental impact. In this context, carbon and other environmental markets will play an important role in helping us to achieve our goal.

We are eager to advance multiple proactive policy solutions to help bring our efforts to fruition. Under this Committee's jurisdiction, USDA conservation programs will be instrumental for attaining the dairy industry's sustainability improvements over the next 30 years, but modifications to these programs will help producers better keep pace with scientific and technological advancements. Enteric methane emissions account for approximately ⅓ of a dairy farm's GHG footprint. Enhancements could be made to conservation programs to help dairy farmers to adopt new approaches to feed management to reduce enteric methane emissions and subsequently reduce GHG emissions. USDA's NRCS is slated to review its Feed Management Practice Standard in 2021. Similarly, the Conservation Stewardship Program could be used more substantially to offer manure management practices for soil health benefits and cover crop adoption.

We are also excited to support multiple bipartisan proposals previously introduced by Members of this Committee. The Growing Climate Solutions Act, authored by Representatives Abigail Spanberger (D–VA) and Don Bacon (R–NE), creates a certification program at USDA to help solve technical entry barriers that make it difficult for dairy farmers and other producers to participate in carbon credit markets. The Farmer-Driven Conservation Outcomes Act, authored by Ranking Member Thompson and Representative Marcia Fudge (D–OH), directs USDA to establish a process for measuring, evaluating, and reporting on conservation program outcomes, giving USDA the tools to quantify the environmental benefits of related activities.

Outside of the immediate jurisdiction of this Committee, we support a 30 percent investment tax credit, introduced previously as the bipartisan Agriculture Environmental Stewardship Act, to cover the upfront capital costs of methane digesters and nutrient recovery technologies, which can help to reduce methane emissions and enable dairy farmers to use nutrients on and off the farm in a more sustainable manner. We also support activation of the Electric Pathway under the Renewable Fuel Standard (RFS) to provide meaningful new environmental opportunities to U.S. dairy farmers. The Electric Pathway allows electricity produced on-farm and sold to a commercial electrical grid to qualify as a renewable fuel under the RFS, which could yield significant dividends as many dairy farmers operate methane digesters to produce baseload electricity. Finally, we are urging the Food and Drug Administration to expedite its approval process for feed additives that can reduce enteric emissions.

While we have focused these comments on climate-related issues, we understand that a brief conversation occurred at the hearing on farm milk prices. We are currently working with our membership and across the entire dairy community on recommended improvements to policies that affect milk pricing, including Federal Milk Marketing Order issues like the Class I mover and cheese pricing, to ensure that dairy farmers of all sizes and in all regions are treated fairly and equitably. Our dairy farmer members from coast to coast are engaged in these discussions. It is critically important that these complex issues be thoroughly understood in order to help develop the consensus necessary to make progress on behalf of all dairy farmers, and are efforts are focused on ensuring an informed producer community.

In closing, we have appreciated the opportunity to work closely with you to develop a better safety net and array of risk management tools to help dairy producers better weather economic storms like the current one, and we are eager to work with you to advance important legislation to help the dairy sector build on its already significant sustainability efforts. Thank you again for the opportunity to comment.

Sincerely,

JIM MULHERN,
President & CEO,
National Milk Producers Federation.

LETTER 2

ON BEHALF OF CENTER FOR FOOD SAFETY, *ET AL.*

May 15, 2020

Hon. NANCY PELOSI,
Speaker,
U.S. House of Representatives,
Washington, D.C.;

Hon. MITCH MCCONNELL,
Majority Leader,
U.S. Senate,
Washington, D.C.;

Hon. KEVIN MCCARTHY,
Minority Leader,
U.S. House of Representatives,
Washington, D.C.;

Hon. CHARLES SCHUMER,
Minority Leader,
U.S. Senate,
Washington, D.C.

Re: Foodborne Illness Risk from Meat and Poultry Inspection Deregulation

Dear Speaker Pelosi, Majority Leader McConnell, Minority Leader McCarthy and Minority Leader Schumer:

The undersigned members of the Safe Food Coalition (SFC) write to urge you to vote against legislation that would lift prohibitions on the interstate sale of meat and poultry from state inspected facilities, and allow commercial sales from uninspected "custom" slaughter facilities, as an amendment to a fourth coronavirus relief package. Two proposals in particular—the New Markets for State-Inspected Meat and Poultry Act of 2019, S. 1720, and the Processing Revival and Intrastate Meat Exemption "PRIME" Act—would critically undermine food safety. At the same time, these laws would do little to address the anticompetitive market conditions that are at the heart of recent supply chain disruptions in the meat industry.

In 2018, members of the SFC wrote to the leaders of the Senate Agriculture Committee to oppose the New Markets for State-Inspected Meat and Poultry Act of 2018, S. 2814, as an amendment to the farm bill.[1] Portrayed as an effort to stimulate new small businesses, that legislation would have operated to harm many such enterprises by undercutting investments in food safety and increasing the burden of foodborne illness on American consumers. Most significantly, S. 2814 would have substituted uneven state inspection standards and enforcement for USDA's meat and poultry inspection program. Fortunately, Congressional leaders kept it out of the farm bill. However, this misguided legislation has recently commanded new attention.[2]

The proponents of S. 1720 now suggest that passing the law will help to alleviate the shortage in beef and pork processing capacity that has resulted from the closure of dozens of large meatpacking establishments with COVID–19 infection clusters among their workers. In a recent letter, the bill's proponents cite statistics indicating that beef, pork and poultry production is down by double-digit percentages.[3] Notably, meat and poultry exports, particularly to China, have soared during this same time period.[4] Regardless, what S. 1720's proponents fail to mention is that the capacity of state-inspected slaughter facilities is negligible compared to the massive federally inspected facilities that have closed. Overall, federally inspected facilities produce 98.9% of red meat sold in the United States.[5] Allowing interstate sales from state-inspected slaughterhouses therefore will have no significant impact on the "backlogs" of animals planned for slaughter.

More importantly, as SFC members explained in the 2018 letter, allowing interstate sales of meat and poultry from state inspected plants would expose consumers to increased foodborne illness risk. State meat and poultry inspection programs are not actually "equal" to Federal inspection, with arguably the exception of six states from which USDA already allows state inspected processors to ship across state lines through the Cooperative Interstate Shipment (CIS) program. Moreover, no state has authority to require a recall of adulterated food that has been inspected in a different jurisdiction, or to bar the sale of meat and poultry inspected by state programs with questionable safety records. S. 1720 would therefore increase the risk that adulterated meat and poultry will be sold and consumed. It would also create unfair competition for processors, including very small ones, who have invested in meeting Federal inspection requirements, it would undermine public confidence in the safety of the food supply because consumers would not be assured of Federal inspection, and it would undermine confidence in the government because none of these issues has been the subject of hearings in either house of Congress.

The PRIME Act has similarly evaded serious scrutiny up to now. The bill would allow meat and poultry from an *uninspected* "custom slaughter facility" to be sold to consumers at "restaurants, hotels, boarding houses, grocery stores, or other establishments located" within the state's borders. There is no size limitation on the facilities that might avail themselves of this exemption, nor any prescriptions for states regarding how, or whether, they regulate these "custom" establishments before their products are unleashed on unwitting consumers. Under current law, the custom slaughter exemption, which the PRIME Act would "amend," does not allow product from these facilities to enter into commerce. They are "exclusively for use by [the animal owner] and members of his household and his nonpaying guests and employees." 21 U.S.C. 623(a). The PRIME Act would be a dramatic departure from long-established food safety protections.

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[1] *See* Safe Food Coalition Letter to Sen.'s Stabenow and Roberts re S. 2814 (June 13, 2018) available at: *https://consumerfed.org/testimonial/safe-food-coalition-opposes-new-markets-for-state-inspected-meat-and-poultry-act-of-2018/*.

[2] *See, e.g., https://www.rounds.senate.gov/newsroom/press-releases/rounds-king-lead-colleagues-in-letter-to-senate-leaders-urging-inclusion-of-new-markets-for-state-inspected-meat-and-poultry-act-in-next-covid-19-relief-bill*.

[3] *Id.*

[4] *https://www.reuters.com/article/us-usa-pork-braun/us-faces-meat-shortage-while-its-pork-exports-to-china-soar-braun-idUSKBN22H2Q6*.

[5] *See* USDA National Agricultural Statistics Service "Livestock Slaughter, 2018 Summary," p. 7 (April 2019), available at: *https://downloads.usda.library.cornell.edu/usda-esmis/files/r207tp32d/8336h934w/hq37vx004/lsslan19.pdf*.

The COVID–19 pandemic has exposed vulnerabilities in our food system, and nowhere is this more apparent than in our meat and poultry slaughterhouses, where decades of industry consolidation has concentrated workers into large, crowded establishments where disease can spread swiftly, shutting down large segments of the food supply overnight. Yet Congress must not address these shortcomings by undoing the vital inspection safeguards that ensure the safety of our food. Rather than undermine Federal inspection requirements, we urge Congress to work with USDA and state authorities to extend and strengthen the existing Cooperative Interstate Shipment (CIS) program, laying the groundwork to support and enhance local and regional supply chains while also ensuring food safety standards are met.

We respectfully urge you to consider these issues, and to maintain food safety protections for meat and poultry shipped in interstate commerce and otherwise sold to consumers.

Sincerely,

Center for Food Safety
Center for Science in the Public Interest
Consumer Federation of America
Consumer Reports
Food & Water Watch
National Consumers League

Letter 3

On behalf of National Cattlemen's Beef Association, *et al.*

May 15, 2020

Dear Members of Congress:

The undersigned organizations submit this letter opposing inclusion of the New Markets for State-Inspected Meat and Poultry Act (S. 1720 or the bill) in the next COVID–19 supplemental response bill. If enacted, S. 1720 would amend the Federal Meat Inspection Act and Poultry Products Inspection Act and allow state-inspected meat and poultry products to be sold in interstate commerce.

The United States' Federal inspection system for meat and poultry products is the gold standard for the world. Not only would allowing interstate shipment of state-inspected meat and poultry as contemplated by the bill raise questions internationally, but the ability of state inspected plants to ship interstate was addressed 12 years ago.

The long running debate regarding allowing interstate shipment of state-inspected meat was resolved in the 2008 Farm Bill with the establishment of the Cooperative Interstate Shipment (CIS) program. That program allows small- and medium-sized state-inspected plants to ship product in interstate commerce if they satisfy the same rules their federally inspected counterparts meet. Every state with an inspection system can participate in the CIS program but only *six states*[1] have given their state-inspected plants this opportunity. In other words, state inspected plants that cannot ship in interstate commerce are being denied the opportunity by their state governments, not USDA.

Despite what some bill proponents assert, this issue is not about "big packers" *versus* "small packers." Thousands of small and very small packers and processors are subject to daily Federal inspection and enjoy the benefits it provides, including access to national and international markets. That there are thousands of small and very small federally inspected plants disproves the myth perpetuated by S. 1720 proponents who assert it is too difficult to meet Federal requirements. Those thousands of small and very small Federal processors deserve a level playing field where every company selling in interstate commerce is playing by the same set of rules.

Operating under state inspection is a business decision, it is not compulsory. Companies select the inspection regime that best fits their business needs. Changing the rules to allow state-inspected meat into interstate commerce would disadvantage the small and very small federally inspected plants that have invested time and money to develop food safety systems that comply with Federal requirements.

The U.S. Department of Agriculture's Food Safety Inspection Service has a small and very small plant outreach program specifically designed to assist such plants with a variety of food safety and other issues. If a state-inspected plant makes the business decision it wants to ship interstate, there are numerous resources, including the small and very small plant outreach program, to help it transition to Federal inspection.

In addition, the bill would create a food safety regulatory nightmare. State inspection authorities have no legal authority to control the disposition of product shipped

[1] *https://www.fsis.usda.gov/wps/portal/fsis/topics/inspection/state-inspection-programs/cis/states-participating*.

outside their state. If, for instance, a State X inspection authority discovered adulterated product had been shipped out of state, that State X would have no legal authority to take regulatory action outside its state boundaries. Conversely, if a product causes illnesses in State Y, not the state of origin, there would be no way for State Y to take regulatory action in the state of origin, assuming the product is traceable.

Allowing interstate shipment of state-inspected meat could also hurt international trade. State inspected product could find its way to processors as an ingredient in processed product that is exported, despite strict prohibitions. Or, more likely, another country would use the fear of state-inspected product being exported as an excuse for establishing non-tariff trade barriers against U.S. meat or poultry. The risk of damaging U.S. meat and poultry exports is real and too great to allow interstate shipment of state-inspected product.

Meat and poultry imports systems also would be thrown into chaos. If state-inspected products may be sold in interstate commerce, to meet its international obligations, the U.S. would have to accept imported meat and poultry from local and provincial inspection systems in foreign countries. Such an outcome would present an unacceptable food safety risk to U.S. consumers.

The discussion above demonstrates the reasons to oppose S. 1720 are many and for all of them the undersigned organizations oppose efforts to amend the Federal Meat Inspection Act and the Poultry Products Inspection Act to allow interstate shipment of state-inspected meat and poultry products.

Sincerely,

National Cattlemen's Beef Association
National Chicken Council
National Pork Producers Council
National Turkey Federation
North American Meat Institute

SUBMITTED REPORT BY HON. CHELLIE PINGREE, A REPRESENTATIVE IN CONGRESS FROM MAINE

Maine Forestry and Agriculture Natural Climate Solutions Mitigation Potential—Interim Report

Cover photos credits: Garlic in mulch courtesy Johnny Sanchez; Howland Research Forest from carbon flux tower courtesy Meg Fergusson.

ADAM DAIGNEAULT, ERIN SIMONS-LEGAARD, SONJA BIRTHISEL, JEN CARROLL, IVAN FERNANDEZ, AARON WEISKITTEL, University of Maine

August 2020

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Executive Summary

The State of Maine has recently set a goal to reduce gross greenhouse gas (GHG) emissions by 80% by 2050 and to have their net GHGs (gross emissions less carbon sequestration from forestry, agriculture, and marine sources) be equal to zero or 'net zero' by 2045. To achieve climate goals, we must also look for ways to remove carbon from the atmosphere (*i.e.,* negative emissions) and sequester it in soils. Natural climate solutions (NCS), such as cropland nutrient management, planting trees, and conservation, that sequester carbon or limit GHG emissions can affect near-term GHG mitigation goals in cost-effective ways and enhance long-term ecosystem services. However, a comprehensive assessment of potential NCS practices and their cost/benefits across Maine's primary sectors has yet to be attempted.

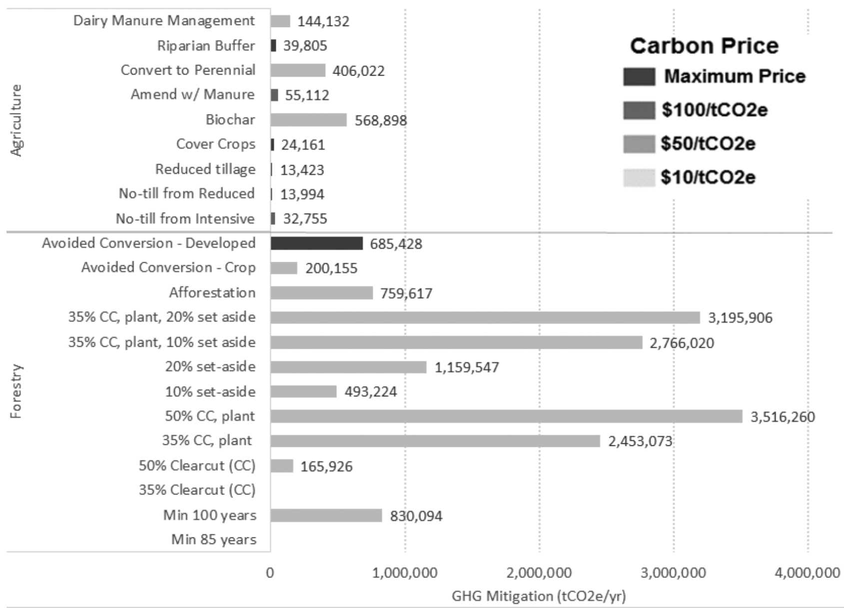
This report is part of the larger 'Maine Natural Climate Solutions Initiative' project that seeks to: (1) assess current practices to determine the degree to which foresters and farmers are using NCS; (2) determine the most cost-effective NCS for Maine; (3) understand key barriers to adopting NCS; and (4) generate information about which practices can be implemented on a broader scale. This was done by modeling a 'baseline' or 'business as usual' (BAU) pathway, to which all other scenarios or pathways were compared or measured against. Next, a list of potential NCS practices that could feasibly be implemented in Maine was established by a mix of expert input and data availability. Finally, an estimate of the 'cost' and 'effectiveness' of implementing the NCS practices under consideration was determined.

Maine's forests currently sequester nearly 70% of the state's annual gross greenhouse gas emissions and continued to do so under a range of alternative management scenarios and potential futures. Using a forest landscape model and data available for 9.1 million acres of forest in northern Maine, it was determined that most forest management NCS practices can be implemented at a cost of $10–$20 per ton carbon dioxide equivalent (tCO_2e), which is relatively inexpensive compared to most non-NCS opportunities (*Table ES1*). Increasing the intensity of active forest management could yield about 4.5 million tCO_2e/yr for this study area in additional carbon sequestration at a cost of $64 million/yr or $14/$tCO_2e$, which was significantly more effective than increasing rotation lengths. All scenarios tested have minimal potential leakage, while additional ecosystem services benefits were realized with some of the scenarios.

For Maine agriculture, farmers could collectively amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and construct and utilize anaerobic digesters to manage dairy manure waste, thereby mitigating up to 786,000 tCO_2e/yr in GHG emissions or about double the sector's current annual emissions (*Figure ES1*). This combined approach for the agricultural sector is estimated to cost $26.3 million/yr or $34/$tCO_2e$. Consequently, setting aside the issue of uncertainties, this analysis showed that Maine's agricultural sector has the potential to reduce its within-sector emissions or even be net-negative as a sector.

Although the analysis has some important limitations that will be refined in future efforts, this work represents a critical first step for exploring the potential benefits of incorporating NCS in Maine's climate action implementation. Currently, interviews and focus groups are being used to explore the potential technical, financial, social, and/or policy barriers and opportunities that stakeholders face in implementing the NCS practices. These findings will be incorporated into future modeling efforts and annual progress reports.

Figure ES1.
($/tCO₂e)



Summary of Maine NCS mitigation potential (tCO_2e/yr) and break-even carbon price.

1. Introduction

The State of Maine has recently set a goal to reduce gross greenhouse gas (GHG) emissions by 80% by 2050 and to have their net GHGs (gross emissions less carbon sequestration from forestry, agriculture, and marine sources) be equal to zero or 'net zero' by 2045 (An Act To Establish the Maine Climate Change Council To Assist Maine To Mitigate, Prepare for and Adapt to Climate Change, 2019). The Maine Department of Environmental Protection (DEP) tracks gross GHG emissions from numerous sources including the energy and agricultural sectors; however, they do not account for carbon (C) sequestration from the state's land use sectors (*Eighth Biennial Report on Progress Toward Greenhouse Gas Reduction Goals,* 2020). Furthermore, it is uncertain how many additional mitigation measures could be taken to help reduce Maine's GHG emissions, nor what it might cost to implement these practices.

Maine's GHG reduction goals reflect the evidence of current and potential future harmful impacts climate change could have on the state's people and ecosystems. Milder winters and earlier springs will adversely impact forestry and farming in Maine (Dupigny-Giroux, *et al.,* 2018). The Northeast is warming faster than the rest of the U.S. (Karmalkar & Bradley, 2017), and Maine's temperature has increased by 3.2° Fahrenheit since 1895, with greater increases along the coast. In Maine, we are acutely aware of the changing conditions in the Gulf of Maine, particularly in marine fisheries, and coastal communities. However, Maine's terrestrial environment is also being strongly influenced by changing climatic conditions that are likely to place increasing stress on Maine's forests, particularly those species that are either at their northern or southern limit, or vulnerable to emergent pests and pathogens. The growing season in Maine is two weeks longer than it was in 1950, and the state is experiencing an increase in precipitation intensity, with more likely to come (Fernandez, *et al.,* 2020). This increased precipitation can cause delays in planting, soil compaction, soil erosion, and agricultural runoff. The frequency of heavy rainfall events before the final frost has been increasing and could prevent farmers from taking advantage of earlier springs and reduce the number of days that fields can be worked because they are overly wet (Wolfe, *et al.,* 2018). Scientists also expect warmer winters to increase the pressure from pests and weeds. Of importance for Maine, rural communities have limited economic resilience because of a lack of redundancy in infrastructure and therefore have a limited ability to manage climate change impacts (Dupigny-Giroux, *et al.,* 2018). Adopting new technologies, modifying management practices, and changing which commodities are produced can help forestry and agricultural systems adapt; however, there are limits to adaptive capacity and more strategies need to be developed (Gowda, *et al.,* 2018).

Recent studies have emphasized the need to do more than reduce GHG emissions from fossil fuels if increasingly costly impacts are to be avoided. To achieve climate goals, we must also look for ways to remove carbon from the atmosphere (*i.e.,* negative emissions) and sequester it in soils. Natural climate solutions (NCS), such as reducing tillage intensity, planting perennial grasses and trees, and setting aside land that sequesters carbon or limits GHG emissions can affect near-term GHG mitigation goals in cost-effective ways and enhance long-term ecosystem services. Within the United States, NCS have the potential to mitigate 21% of net annual GHG emissions (Fargione, *et al.,* 2018). However, stakeholders from throughout Maine and the U.S. have determined that foresters and farmers need additional policies, tools, and incentives to adopt practices that promote better soil health at a scale that significantly contributes to climate change mitigation and adaptation.

There is a need for an accessible way for stakeholders to evaluate and prioritize the various practices that could be used to achieve GHG mitigation goals, and Maine-specific analyses will inform the state climate action plan and enhance effective implementation of NCS practices. To date, most NCS studies are global and national-scale, and state-level estimates are often reliant on assumptions more applicable elsewhere. The practices covered are also often typical of more conventional forestry or agricultural systems. Moreover, Maine foresters and farmers may face unique implementation barriers important in the state, but are not evident elsewhere. The analysis presented in this report attempts to address these considerations by helping to identify efficient, cost-effective solutions to improve forest and agronomic land management, reduce carbon-negative land use change, and promote soil health in Maine.

This report is part of the larger 'Maine Natural Climate Solutions Initiative' project which seeks to (1) assess current practices to determine the degree to which foresters and farmers are using NCS; (2) determine the most cost-effective NCS for Maine; (3) understand key barriers of adopting NCS; and (4) generate information about which practices can be implemented on a broader scale.

The report is organized as follows. First, we present the general methodology for estimating potential impacts from implementing NCS across Maine. Next, we present the model baseline and results from a wide range of scenarios and practices applied to the state's forest and agricultural sectors. We then conclude the main report with a summary of the key findings. Two appendices provide additional detail on the study results and model input data.

2. Methodology

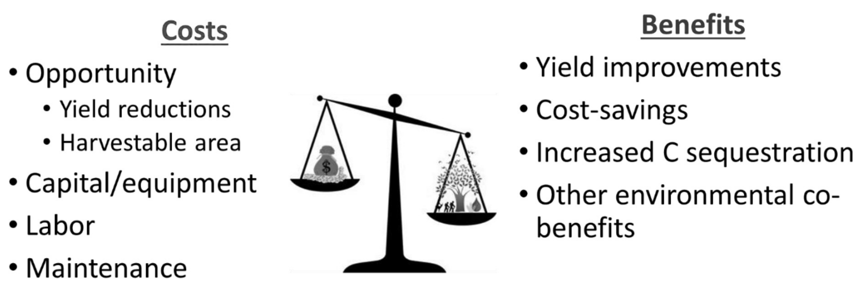
2.1 Estimating Costs and Benefits of GHG Mitigation

The main objective of this study was to estimate the GHG mitigation benefit and costs of implementing NCS practices in Maine's forest and agricultural sectors. ***First,*** to achieve this a model 'baseline' or 'business as usual' (BAU) pathway was established that all other scenarios or pathways will be compared to or measured against. In this case, we assumed a continuance of current policy and practices that essentially maintain the harvest, cultivation, and planting rates that have been apparent over the past decade. ***Second,*** we needed to define the geographical and temporal scale of the baseline. The framework for this study focused on impacts to two sectors (agriculture and forests) across the entire state, with a key exception of some of the forest modeling, which utilized a case study approach for a block of nine million acres of managed forestland in the northern part of the state. In terms of temporal scale, forest impacts were measured through 2100 (80 years), while the agriculture sector impacts were measured over the next 20 years. ***Third,*** we specified the environmental conditions that the model baseline should follow, namely the effect of climate change on biophysical growth and yield. In this analysis, the forestry modeling baseline assumed that Maine's climate would follow a low emissions and impacts trajectory, specifically the Representative Concentration Pathway (RCP) 2.6. We did not assume any climate change impacts for the agricultural sector due to lack of data.

The next key aspect of designing a mitigation modeling study was to establish a list of potential NCS practices that could feasibly be implemented in Maine. During such a process, there is often a debate about what mitigation should be included, both from a biophysical and socioeconomic perspective. Policy constraints and concerns about land-based mitigation practices include ways to properly 'measure, monitor, and verify' that practices are being implemented correctly and whether issues with permanence, additionality, and leakage make the project a risky investment. The set of NCS practices that we opted to analyze in this report was decided through a mix of expert input and data availability.

The last key aspect of the analysis was to estimate the 'cost' and 'effectiveness' of implementing the NCS practices under consideration. This is typically done using a suite of applications and methods that integrate both economic and biophysical modeling. Most of these models attempt to be empirically based but can be complicated by the complex nature of the land use sector. Implementing NCS practices across Maine's landscape is likely to accrue a number of costs and benefits relative to the baseline or BAU. Key benefits could include reduced GHGs or increased carbon sequestration, yield improvements, cost-savings from reduced expenditures, and other environmental benefits such as improved soil health and water quality (*Figure 1*). Key costs that may accrue include added capital, labor, and maintenance costs, land acquisition costs, yield (and revenue reductions), and loss in harvestable area. The latter two can be considered opportunity costs because it is essentially the income that one is willing to forego to achieve the benefits associated with implementing the practice. All monetary values in this study are inflation adjusted and reported in 2017 real dollars.

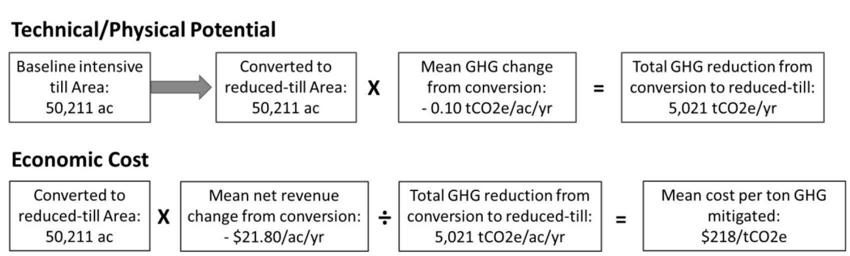
Figure 1.



Key costs and benefits of implementing natural climate solutions relative to business as usual.

Figure 2 provides an illustrative example of how the average benefits and costs of a given NCS practice are calculated, specifically the impact of shifting from intensive to reduced-till farming across 50,211 acres of potatoes planted in Maine. In this case, each acre of land converted to reduced-till is estimated to provide 0.10 metric tons of carbon dioxide equivalent (tCO_2e) per year of additional carbon sequestration, equating to just over 5,000 tCO_2/yr in total mitigation across the state. That amount of mitigation can then be used to estimate the total cost and/or the cost relative to their baseline practice by multiplying the total area converted by the mean net revenue (commodity output revenue less input costs) change, which equates to about $1.1 million per annum, or $21.80/ac. This figure can then be converted into the amount that an average potato farmer may be willing to accept to 'break even' by implementing this practice, which is quantified using the common mitigation cost metric of $/$tCO_2e$. In this example, that break-even carbon price for converting all eligible intensively tilled potato area in Maine to reduced till is estimated to be $218/$tCO_2e$. We replicated this methodology for the dozens of crop and forest management scenarios that we describe in detail below.

Figure 2.



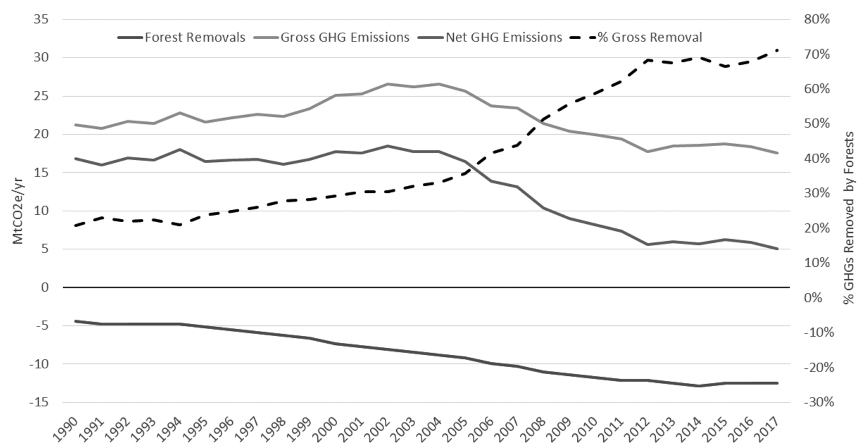
Example of how to calculate biophysical potential and economic cost of converting all eligible Maine potato farms from intensive to reduced crop tillage.

2.2 *Forestry*

2.2.1 Overview

Forests currently cover about 17.5 million acres or nearly 89% of Maine's area. The forest industry sector is statewide, multi-faceted, and provides about $8 billion/yr in direct economic impact. Furthermore, Maine's forests currently sequester nearly 70% of the state's annual gross greenhouse gas emissions (Domke, *et al.,* 2020; *Eighth Biennial Report on Progress Toward Greenhouse Gas Reduction Goals,* 2020), as carbon stored in new forest growth and harvested products is greater than the amount removed (*Figure 3*). However, significant changes to both natural forest and industry are expected in the decades to come via shifts in market demand, policy adjustments, and climate change. Furthermore, Maine's forest is a transitional ecotone with a broad mixture of species, which means that changing climatic conditions create significant stress as most species are either at their northern or southern limit. As a result, we seek to analyze the potential impacts on Maine's forest carbon sequestration through 2100 under a range of different management regimes. Furthermore, we evaluate the impact of our assumptions via sensitivity analysis. This section provides an overview of how the modeling of forest natural climate solutions was conducted.

Figure 3. Maine GHG Emissions and Forest Carbon Removals, 1990–2017



Source: Domke, *et al.,* 2020; Maine DEP, 2020.

2.2.2 Forest NCS Practices/Scenarios

We modeled a number of different forest practices with NCS potential that varied the approach to forest management and use on the nine million acre case study block of land in Maine. We established seven scenario foci with many including more than one set of scenarios within each focus (*Table 1*).

These were:

1. Extended Rotation: increased minimum stand age eligible for harvest from BAU 50 year to 85 or 100 years.
2. Clearcut/Partial harvest distribution: increased % of the area harvested by clearcut (from 10% to 35% or 50%). Wood supply was held constant by proportionally reducing overall harvest footprint, assuming on average 1 acre of clearcut would result in the same volume harvested as 2 acres of partial harvest.
3. Planting: added planting (or artificial regeneration) after clearcut with a 700 tree per acre mix of red and white spruce.
4. Set-aside: Reserved 10% or 20% of forestland, which was permanently removed from harvest.
5. Triad approach: Mix of BAU rotations, clearcuts with planting, and permanent set-asides.

6. Avoided Forest Conversion: Held 2010 forest area constant via renting land at cost of highest and best use if converted.
7. Afforestation: Plant trees in eligible areas not forested since at least 1990.

Impacts to aboveground carbon, harvested wood carbon, revenues, and costs were estimated using a mixed modeling approach, with most of the scenarios conducted with Landis, a landscape-level dynamic forest ecosystem model.

Table 1. Forest NCS Practices modeled with and without Landis-II.

Scenario Focus	Scenario Name	% Clearcut	Min. Stand Age	Plant after Clearcut	% Land Set aside
Landis-based Scenarios					
Baseline/BAU	BAU age (min 50)	10	50	No	0
Extended	Min 85 years	10	85	No	0
Rotation	Min 100 years	10	100	No	0
Clearcut/Partial	35% Clearcut (CC)	35	50	No	0
Harvest Dist.	50% CC	50	50	No	0
Clearcut & Plant	35% CC, plant	50	50	Yes	0
	50% CC, plant	50	50	Yes	0
Set-aside forest	10% set-aside	10	50	No	10
land	20% set-aside	10	50	No	20
Triad Approach	35% CC, plant, 10% set aside	35	50	Yes	10
	35% CC, plant, 20% set aside	35	50	Yes	20
Non-Landis Scenarios					
Afforestation	Afforestation	10	50	No	0
Avoided conversion	Avoided conversion	10	50	No	0

2.2.3 Landis-based modeling

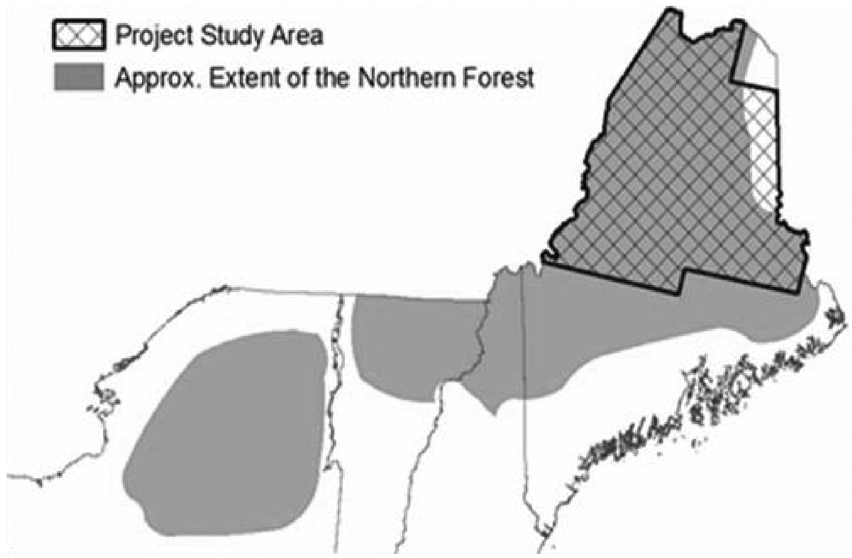
Forest landscape models (FLMs) have become an essential tool for predicting the broad-scale effects of anthropogenic and natural disturbances on forested landscapes. One open-source FLM that has become widely used to compare alternative future scenarios across large areas is the LANDscape DIsturbance and Succession (LANDIS) model (Gustafson, *et al.,* 2000; David J. Mladenoff, 2004; Scheller, *et al.,* 2007). First released in the mid-1990s, LANDIS was designed to stochastically simulate the spatio-temporal effects of repeated interactions between forest disturbance and succession based on a moderate number of user-specified parameters (D.J. Mladenoff, *et al.,* 1996; D.J. Mladenoff & He, 1999). Since its release, LANDIS or the updated version LANDIS–II have been used in more than 100 peer-reviewed publications to simulate the impacts of a wide variety of disturbances for which model extensions have been developed.

Within LANDIS–II, the forest is represented by a raster grid of interacting cells, aggregated by user-defined ecoregions (homogenous soils and climate). Successional processes including tree establishment, growth, competition, and mortality are modeled for each cohort (*i.e.,* group of trees defined by species and age) in each cell, and emergent conditions (*e.g.,* aboveground biomass) are tracked for each cohort. Each cell can contain multiple cohorts, and initial forest conditions are generally provided by, for example, land cover or forest type maps. Cells are modeled as spatial objects linked by the processes of seed dispersal, natural disturbance, and land use. Execution of LANDIS–II requires the parameterization of tree species life history attributes, specification and parameterization of key ecological processes, and spatial representations of initial forest and landscape conditions.

We used LANDIS–II to model the effects of alternative management strategies on the carbon dynamics of Maine's 13 most abundant tree species (*Appendix B*) between 2010 and 2070. Circa 2010, these 13 species comprised 86% of Maine's aboveground forest biomass. Initial forest conditions were provided by maps of tree species relative abundance developed for our study area using USFS Forest Inventory and Analysis plot data and Landsat satellite imagery.[1] Our study area (*Figure 4*) encompassed approximately 9 million acres of primarily commercial forestland. Owners within this area are predominantly considered large (>10,000 acres) land owners and represent a diverse range of ownership types (*e.g.,* Family, Timber Investment Management Organizations, Real Estate Investment Trusts, and Nonprofit Organizations).

[1] Following the methods of Legaard, *et al.,* 2020.

Figure 4.



Project study area for forest landscape projections using LANDIS–II encompassed approx. 9.1 million acres of predominantly commercial forestland in northern Maine.

The LANDIS–II model comprises a core program and user-selected modules that have been developed to simulate succession and a variety of disturbance agents. We used the Biomass Succession module (Scheller & Mladenoff, 2004) to model forest growth and succession, the Base Wind module (Scheller, *et al.,* 2007) to model blowdown, and the HARVEST module (Fargione, *et al.,* 2018) to model timber harvesting. We modeled two harvest prescriptions: clearcut and partial harvest. Partial harvests were designed to remove an average of 50% of the live biomass from a stand. Biomass removal was variable, representing a combination of complete overstory removal within harvester trails and uniform selection in the remainder of the selected stand. Our baseline or Business-as-Usual (BAU) scenario emulated the average cumulative harvest rate within the study area, as estimated from a Landsat-derived time series of forest disturbance (2000–2010) (K.R. Legaard, 2018). The BAU scenario (hereafter referred to as BAU min50) set the minimum stand age eligible for harvest as 50 years old, which follows historical trends for Maine timber harvests.

Annual net primary productivity (ANPP) is a key parameter in the modeling of forest growth and succession within LANDIS–II. We used the process-based PnET–II model (Aber, *et al.,* 1995) to estimate ANPP for each species in a manner similar to previous LANDIS–II studies (Ravenscroft, *et al.,* 2010). PnETII predicts monthly changes in photosynthesis and the production of biomass (foliar, wood, root) using species-specific traits (*e.g.,* foliar nitrogen) and climate inputs, including average minimum/maximum surface temperature and total monthly precipitation. To estimate future (2020–2070) ANPP for each species we incorporated monthly, downscaled climate projections for our study area. Gridded projections were based on the AO (Atmospheric-Oceanic) variant of the Hadley global environment model v2 (HADGE–AO) under a low-emission scenario (RCP 2.6) and obtained from the USGS Geo Data Portal (*USGS Geo Data Portal,* 2020).

Over the course of a simulation, LANDIS–II tracks aboveground biomass for each cohort in each cell, along with species and age information, and reports the results at a user-specified interval. We ran LANDIS–II at a 10 year time step and based on the results calculated total aboveground carbon at each interval 2010–2070 for each forest management scenario. In addition, for demonstration purposes we compared the status of a variety of ecosystem services ca. 2060 under a subset of the management scenarios relative to our baseline. We included spruce-fir carbon, late successional forest (>100 years old) for both spruce-fir forest (>75% balsam fir, spruce sp. relative abundance) and northern hardwood (>75% sugar maple, yellow birch, American beech relative abundance), as well as lynx foraging habitat (regenerating forest <40 years old with >50% spruce-fir relative abundance).

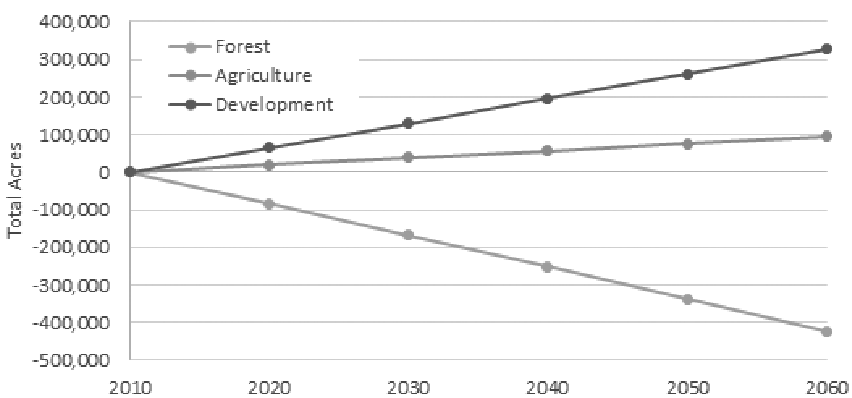
2.2.4 Non-Landis modeling

Two of the forest NCS assessments were estimated for the entire State of Maine based on a methodology that did not utilize the LANDIS model: (a) afforestation of marginal non-forest land with trees, and (b) avoided conversion of current forestland that is considered under threat of being changed into developed or agricultural use.

The afforestation (or forest restoration) estimates were derived based on methods from Cook-Patton, *et al.* (2020), which evaluated the potential for the contiguous U.S. at a high spatial resolution. Locations were initially constrained to areas where forests with ≥25% tree cover historically occurred. Additional assumptions excluded all cropland not located in areas with challenging soil conditions,[2] all developed land not designated in the National Land Cover Database as 'open space', and land designated as protected or wilderness areas. In total, we estimated that about 360,000 acres of land in Maine met the criteria for afforestation, with 65% of the area coming from pasture/grassland, 25% from open space, 10% from cropland, and the remainder from 'other' land covers. Afforested land was assumed to primarily be via natural regeneration and include a mix of tree species already growing in Maine. Annual tree biomass and carbon sequestration estimates from afforestation were derived from FIA. Mitigation costs included opportunity cost of the alternative land use (due to lost future revenue) as well as stand establishment and maintenance costs. Pasture and cropland values were based on USDA Cropland Reserve Program (2020) rental rates (where land has typically 'marginal' productivity), while developed land values were obtained from Davis, *et al.* (2020).

Avoided forest conversion (*i.e.,* deforestation) estimates were derived from methods similar to Fargione, *et al.* (2018). Future conversion was based on extrapolating historical trends forward, following the New England Landscape Futures (NELF) (*New England Landscape Futures Explorer,* n.d.) baseline projections. According to NELF, approximately 8,500 acres of land are estimated to be converted to development or agricultural land in Maine each year, with 76% of the conversion going to development (*Figure 5. Projected Cumulative Maine land cover change, 2010 to 2060.* (Source: NELF, 2020)). Costs of mitigation included opportunity costs of land sale, using the same sources as the afforestation estimates. Carbon sequestration estimates were based on an 'average' Maine stand in FIA, and assumed to accumulate at a mean rate of 3.1 tCO_2e/ac/yr. That is, landowners who are compensated for not converting their forest to other uses would be paid initially for maintaining their existing carbon stock as well as the additional carbon that could be accrued on their stand in the years after the initial payment.

Figure 5. Projected Cumulative Maine Land Cover Change, 2010 to 2060



Source: NELF, 2020.

2.2.5 Forest Carbon and Cost Estimation

As discussed above, forest carbon sequestration was primarily estimated using FIA data. In addition to evaluating impacts of different practices on aboveground

[2] Areas with challenging soil conditions were identified using land capability classes 4e, 5w, 6, 7, or 8 in the Gridded Soil Survey Geographic Database (*https://gdg.sc.egov.usda.gov/*).

growing stock of biomass and carbon, we also estimated the potential change in carbon in harvested wood products and landfills over time. The harvested wood product and landfill estimates were derived using the methods from Smith, *et al.* (2006), and were roughly equivalent to 20% of the total biomass/carbon removed/harvested from the stand (Bai, *et al.,* 2020). The remaining harvested carbon was assumed to be emitted immediately, either through combustion for energy or otherwise (Smith, *et al.,* 2006). Total carbon sequestration in any given year was the sum of aboveground forest carbon and harvested wood and landfill carbon.

Economic benefits and costs from implementing different types of forest practices were based on four primary components: (a) harvest revenue, (b) land acquisition costs, (c) planting costs, and (d) opportunity costs. Harvest revenues were estimated by multiplying the biomass harvested by mean state stumpage price for each product harvested (*Annual Stumpage Price Reports,* 2020). Planting costs were assumed to be a mix of seedlings ($0.37/plant) planted at a density of 800 trees per acre ($296/ac) and site prep which included two spray applications ($250/ac), for a total of $546/ac. Land acquisition costs and annual rents varied by current or highest and best use and were acquired from USDA (*Cropland Reserve Program Statistics,* 2020) and Davis, *et al.* (2020) Finally, opportunity costs were estimated as the change in harvest and other land use revenue relative to the baseline or business as usual case. We note that there are cases where revenues can potentially be higher than the BAU estimate, such as plantations on stands that were initially naturally regenerated.

2.2.6 Sensitivity Analysis

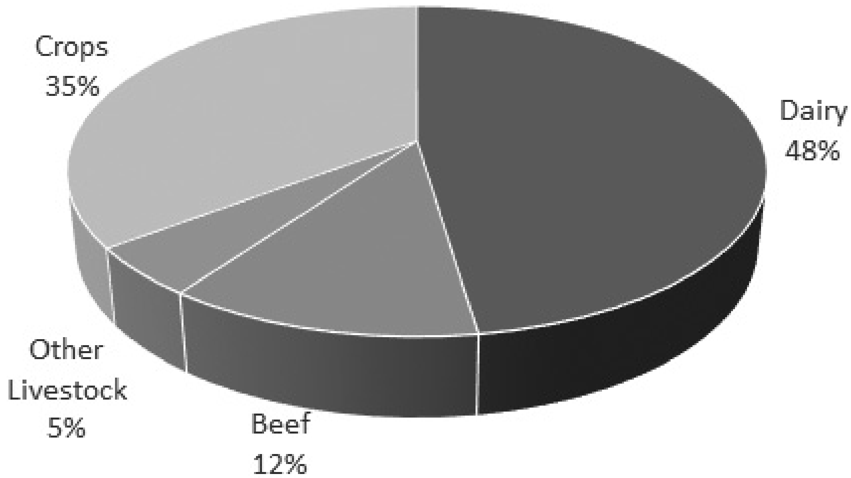
The Landis-based scenarios already evaluated the effect of varying minimum stand harvest age, percentage of land designated as no-harvest set asides, the distribution of partial and clearcut harvesting, and whether clearcut stands are artificially regenerated (*i.e.,* planted). In addition, we conducted additional sensitivity analysis to assess the impact of some of the core assumptions on our model estimates. The first sensitivity analysis evaluated the effect of climate change on forest growth and sequestration in the Landis model. In this case, we adjusted the climate change input files from RCP 2.6 to 8.5, which has a higher climate variability compared to historical trends. The set of sensitivity analyses that we conducted varied the harvest revenue, planting, and land acquisition costs to be +/−25% of the original assumption. Taking this approach allowed us to assess the relative importance of various input assumptions on the total and break-even costs of the different scenarios. Second, we conducted a sensitivity analysis that adjusted the stumpage price and planting costs that landowners may face under different stand and market conditions by a factor of ±25% compared to our core assumptions.

2.3 Agriculture

2.3.1 Overview

The agricultural sector in Maine emitted 0.38 million tons of CO_2e ($MtCO_2e$) in 2018, approximately 2% of total state emissions (17.51 $MTCO_2e$) across all reported sectors (Maine DEP, 2020). A bulk of the emissions are from livestock (via enteric fermentation and manure management), with dairy contributing 48% of the total agricultural sector emissions (*Figure 6*). Agriculture, excluding forestry, fishing, and aquaculture, encompasses 1.3 million acres (*2017 Census of Agriculture,* 2019), has an annual economic impact of $3.8 billion, supports 25,000 jobs, includes 8,000 farms, and represents about 5% of the state's GDP (Lopez, *et al.,* 2014). The primary crops grown in Maine include potatoes, blueberries, hay, and grains including corn, barley, and oats. These crops represent 76% of the total harvested acreage in 2017. Dairy and other livestock commodities represent over 20% of farm sales (*2017 Census of Agriculture,* 2019). Although 90% of Maine is covered by forest, agriculture remains an important part of Maine's cultural identity, local economies, and current and future food security.

Figure 6. Maine Ag GHG Emissions (2017)



Maine Agricultural GHG Emissions by major enterprise. Source: DEP, 2020.

2.3.2 NCS Practices/Scenarios

Despite representing a smaller sector of the Maine economy than forestry, changes to agricultural management practices can also contribute to state-wide climate change mitigation while enhancing adaptation and resilience in the agricultural sector. Agricultural natural climate solutions have been identified as an important strategy for improving farm viability by increasing carbon storage, limiting greenhouse gas emissions, improving soil health and water quality, and increasing farmer yields and profits per acre. NCS practices can be adopted by farmers with operations of all sizes and production methods. We analyzed a range of agricultural NCS that were already being implemented on some of Maine's farms or were determined to be feasible given Maine's climate and farming conditions. These practices are summarized in *Table 2.* Additional details are provided below and in *Appendix B*.

Table 2. Overview of agricultural NCS practices considered for this analysis

Practice	Overview	Application
Cropland and Grassland NCS		
Cover cropping	Permanently implement cover cropping as part of farm system for enhanced soil organic carbon accumulation; reduce erosional soil losses, enhance water infiltration, reduce N losses (N_2O, NO_3)	potatoes, corn, other grains, vegetables
Intensive to reduced till	Permanently switch to reduced till farming that is targeted on shallow soil disturbance to reduce C loss	potatoes, corn, other grains, vegetables
Reduced to no-till	Permanently switch to no-till farming for enhanced soil organic carbon accumulation through less disturbance of the soil	corn, other grains, vegetables
Intensive to no-till	Permanently switch to no-till farming for enhanced soil organic carbon accumulation through less disturbance of the soil	corn, other grains, vegetables
Biochar amendment	5.9 t/ac biochar broadcast applied to soil in year 1 of a 20 year cycle for enhanced soil C sink, improved soil health, reduced GHG losses and nutrient runoff	potatoes, corn, other grains, vegetables, hay, blueberries, apples
Manure amendment	Substitute fertilizer with manure and compost for reduced CO_2, CH_4, and N_2O losses	potatoes, corn, other grains, vegetables, hay, blueberries, apples
Perennial set asides	Permanently convert crop and pasture to no-harvest set aside grassland. Soil C enhanced through reduced disturbance	potatoes, corn, other grains, vegetables, hay, fruit
Riparian planting	Plant 35′ buffer of trees, shrubs, and grass along streams running along marginal cropland and pasture	potatoes, corn, other grains, vegetables, hay, fruit
Dairy Manure Management		
Large Complete Mix Anaerobic Digester with electricity generation	CH_4 emissions are reduced using a large model low-rate digester in which digestate is actively mixed in a heated tank with airtight cover. Digestate is gradually displaced by incoming manure substrate	1 digester per 2,500 cows

Table 2. Overview of agricultural NCS practices considered for this analysis—Continued

Practice	Overview	Application
Covered Lagoon/ Holding Pond Anaerobic Digester	Passive digester in which an impermeable cover and pipe system traps and collects CH_4 for reduced emissions. Technology is simple and well-established, but supplemental heat may be needed in northern climates	1 digester per 300 cows
Soild-liquid separation (SLS)	Process for separating dairy solids from liquids, either to reduce manure transit costs and associated emissions or as a pre-treatment for anaerobic digestion	Active SLS with a screen separator, 1 SLS per 1,000 cows
Small Complete Mix Anaerobic digester (AD) with electricity generation	CH_4 emissions are reduced using a small model low-rate digester in which digestate is actively mixed in a heated tank with airtight cover. Digestate is gradually displaced by incoming manure substrate	1 digester per 300 cows
Plug Flow Anaerobic digester (AD) with electricity generation	CH_4 emissions are reduced using a low-rate digester in which incoming high-fiber substrate displaces and moves digestate through the system, usually without active mixing. Consists of a long heated tank with airtight cover	1 digester per 300 cows

2.3.3 Analytical Approach

The agricultural NCS modeling was centered on a financial and agronomic response analysis that quantified the economic impacts (revenue, cost, *etc.*) of implementing NCS relative to the change in yields, GHG emissions, and carbon sequestration relative to the business as usual (BAU) or baseline case over the next 20 years. In this analysis, the baseline assumed that current yields and areas were held constant over time.[3] The NCS practices included cover crops, reduced-till, no-till, biochar amendments, amending soils with manure, manure management, and perennial set-asides (*Table 3*). GHG emissions factors and sequestration for the model baseline and NCS practices were based on an extensive literature review. Most baseline emissions factors were based on estimates from Poore and Nemecek (2018). Crop NCS mitigation factors were primarily estimated using the COMET Planner tool (Swan, *et al.,* 2020), while dairy manure management factors were primarily derived from the EPA Ag Star Livestock Anaerobic Digester Database (EPA, 2020). All impacts were estimated at the major crop, NCS practice, and county-level. Most of the results in the main report are presented at the aggregate state level, while more detailed results are presented in *Appendix B*.

Baseline and current NCS practice area by major crop category in Maine (*Table 3*) were drawn or extrapolated from data provided in the 2017 USDA NASS Census of Agriculture (*2017 Census of Agriculture,* 2019). Baseline crop production area values were: 50,211 acres of harvested potato, 38,660 acres of lowbush blueberry, 175,231 acres of hay and haylage, 32,571 acres of corn grown for grain and silage, 39,419 acres of other grains, 7,441 acres of apples and other perennial crops, and 12,028 acres of vegetables other than potato. In developing *Table 3,* several assumptions were made. All area currently in no-till production (21,676 acres) was assumed to be in silage or grain corn systems.[4] Area in reduced tillage (31,953 acres) was split between potato, other vegetables, and other grains.[5] Given uncertainty around the proportion of potato rotation crops reported as cover crops vs. small grains, we used the sum of harvested potatoes in the top three potato-producing counties (49,772 acres) as an estimate for cover crop adoption, assuming a 1:1 rotation.[6] The area of other vegetable land in cover crops was assumed to be the total (55,462 acres) minus the amount in potato systems. The total value of other grains was assumed to be equivalent to additional cover crop land, since small grains often function as cover crops. We assumed that all annual systems could be transitioned to rotations that are more diverse than what is currently implemented and therefore we assigned starting values of zero.[7] Current adoption of biochar amendments was assumed to be zero based on our understanding that this practice is uncommon at

[3] Due to lack of data, we were unable to model the impact of climate change on crop yields.

[4] Informed by personal communication with E. Mallory and J. Jemison, Spring 2020.

[5] Definitions of reduced tillage vary by system and may not align perfectly with the NRCS definition. Based on data from an organic vegetable farmer focus group (N. Lounsbury, unpublished data, February 26, 2020) we assumed a large fraction of vegetable land (50%; 6,104 acres) is employing some form of reduced tillage. The potato acreage employing a reduced tillage practice such as one-pass hilling was estimated by adding the area of potatoes harvested in the top three potato-producing counties assuming a 1:1 rotation (99,544 acres) and subtracting the total land in intensive production in these counties (81,030 acres) to arrive at 18,514 acres. The 13,439 reduced tillage acres remaining from the statewide total was assigned to other grains.

[6] Informed by data from potato farmer focus group (N. Lounsbury, unpublished data, January 23, 2020) indicating this rotation is common.

[7] The meaning of 'diverse rotations' varies by system and can overlap with cover crop adoption.

present.[8] The acreage on which nitrogen fertility is offset with dairy manure amendment (74,943 acres) was split between corn and hayfields such that a large fraction of silage and grain corn (90%; 29,314 acres) were assumed to have implemented this practice, with the remainder (45,629 acres) allocated to hay and haylage.[9]

Table 3. Estimated Baseline Area in NCS Practices for Maine (acres)

Major Crop	Total Crop Area*	No-till	Reduced tillage	Cover crop	Diverse rotations	Biochar Amend	Amend w/ manure	Convert to perennial set-aside	Riparian Buffer
Potato	50,211	X	18,514	49,772	0	0	0	0	0
Lowbush blueberry	38,660	X	X	0	X	0	X	X	0
Hay & haylage	175,231	X	X	X	X	0	45,629	X	0
Silage & grain corn	32,571	21,676	0	0	0	0	29,314	0	0
Other grains	39,419	0	13,439	39,419	0	0	0	0	0
Apples & other perennials	7,441	X	X	X	X	0	X	X	0
Other vegetables	12,028	0	6,014	5,690	0	0	X	0	0
Total Study Area	355,561	21,676	37,967	94,881	0	0	74,943	0	0

* = not all crop area is currently in a NCS practice; More than 1 practice can be implemented on a given acre (*e.g.,* no-till and cover crop); X = not eligible for NCS practice.

2.3.4 Agricultural enterprises

The following section briefly describes the farm systems that we included in our analysis. We constructed representative cost budgets for the primary crops grown in Maine based on enterprise farm budgets for Maine or New England and expert consultation. *Table 4* summarizes the per acre yield, price, revenue, and cost for each agricultural enterprise as well as net revenue and net GHG emissions. Price per unit was estimated from a five year average of the commodity's price in Maine from 2012–2017 (*Crop Values Annual Summary,* 2020). Detailed budgets and accompanying assumptions are included in *Appendix B.* The methodology and estimates for calculating net GHG emissions are also explained in *Appendix B.*

Table 4. Key Maine agricultural enterprises baseline farm financial and GHG input data.

Enterprise	Yield (unit/ac/yr)	Price ($/unit)	Revenue ($/ac/yr)	Cost ($/ac/yr)	Net Revenue ($/ac/yr)	Net GHG (tCO_2e/ac/yr)
Hay	6 tons	$165	$992	$323	$670	0
Potato	240 cwt	$10	$2,510	$1,382	$1,129	2.11
Blueberries	4,445 pounds	$0.47	$2,102	$1,504	$598	0.32
Wheat	45 bushels	$19	$844	$312	$532	1.03
Corn	100 bushels	$4	$369	$574	−$205	1.21
Barley	48 bushels	$5	$233	$373	−$139	0.18
Vegetables	varies	varies	$22,117	$17,276	$4,841	1.58
Apples	30,244 pounds	$0.31	$8,196	$5,966	$2,230	2.24
Dairy	158 cwt	$23	$3,567	$4,442	−$875	6.19

Apples

There are 449 farms with apple orchards in Maine covering 2,668 acres. 38% of these orchards are smaller than one acre, and another 39% are between one and five acres in size (*2017 Census of Agriculture,* 2019). Soil amendments with biochar and manure are NCS practices that can be implemented in orchards. We estimated that, on average, a typical apple system made $8,196/bearing-fruit-acre (bfa) in revenue and had $5,966/bfa in total costs. As a result, the system produced $2230/bfa in net revenue per year. Additional information about the apple system is available in *Appendix B.*

Blueberries

Approximately 60,000–65,000 acres of farmland in Maine are in wild or lowbush blueberry production, of which 850 acres are certified organic. Blueberries have a 2 year production cycle such that approximately half of this total acreage is harvested per annum. Between 66 and 70 million pounds of blueberries are produced annually in Maine (Drummond, *et al.,* 2009; Rose, *et al.,* 2013). Blueberry pricing has been a challenge for the industry in some recent years, with wholesale prices for conventional blueberries falling between $0.27–$0.75/lb between 2012 and 2018 (Calderwood & Yarborough, 2019). We estimated that an average blueberry system

[8] N. Lounsbury, unpublished data, January 23, 2020; S. O'Brien, unpublished data, Fall 2019.

[9] Though many diversified vegetable farms also utilize manure as a soil amendment, this use was excluded from the present analysis, which assumed on-farm use of manure for forage and feed production by commercial dairies.

made $2,102/ac in revenue and had $1,504/ac in total costs. As a result, the system produced an average of $598/ac in net revenue per year. Additional information about the blueberry system is available in *Appendix B.*

Dairy

There are approximately 450 farms with dairy cows in Maine, a majority of which have herd sizes <50 cows. The current 218 commercial-scale dairy farms house an estimated 28,000 cows.[10] Economic risks from market price fluctuations are offset for conventional dairies through the "tier program["] (Drake, 2011), while pricing for organic milk is usually set in advance by 2–3 year contracts. About 30% of Maine dairy farmers are certified organic, with organic milk making up 7% of milk volume produced. Dairy cows are fed a roughage-based diet of forage, hay, and corn silage which is generally locally produced. In addition, grazing is common during the summer, and diets may be supplemented with concentrate. While manure represents a resource that can be used as part of integrated farm systems, storage during winter and mud season is a necessity. Land access is a major limiting factor to dairy production in Maine, in part because lack of contiguous fields raises costs of manure transport.[11] We estimated that, on average, a typical dairy farm made $3,567/cow in revenue and had $4,442/cow in total costs. As a result, the system produced −$875/ac in net revenue per year for the 2012–2017 timeframe.[12] Additional information about the dairy system is available in *Appendix B.*

Grains (barley, corn, and wheat)

Several types of grains, including grain and silage corn, barley, and wheat, are grown in Maine. These crops are primarily grown as feed for livestock and/or as part of rotational cropping systems. Several NCS practices can be implemented for grains, including no-till, reduced tillage, cover crops, and soil amendments. We estimated that, on average, the net revenue for barley, corn silage, and wheat were −$139/ac, −$205/ac, and $532/ac, respectively. When coupled with a dairy farm, the negative net revenue per acre for barley and corn silage can be offset as feed for livestock. Acting as rotation crops in a potato system, barley and wheat function similarly to cover crops, requiring less intensive management and allowing soils to 'rest.' Additional information about each of these grain systems is available in *Appendix B.*

Hay

According to USDA NASS, 174,000 acres of farmland in Maine are used for forage, including hay (*2017 Census of Agriculture,* 2019). Most hayfields are perennial sods consisting of clovers and grasses including bluegrass, orchard grass, quackgrass, and timothy. Periodic additions of lime are needed to reduce acidity, helping to manage weeds and maintain hayfield productivity (Kersbergen, 2004). More intensive management of hayfields including occasional tillage and re-seeding of desired species, as well as fertility applications, is also common for some applications (Hall, 2003). Hayfields are inherently no- or low-tillage production systems. Additional NCS practices that might be applicable in managed hayfields include strategic integration of organic amendments including manure or biochar into production. We estimated that, on average, a typical hayfield system made $992/ac in revenue and had $191/ac in variable costs and $132/ac in annualized fixed costs. As a result, the system produced $670/ac in net revenue per year. Additional information about the hay system is available in *Appendix B.*

Potato

Potatoes are a high-value crop, but also expensive to grow.[13] Approximately 50,000 acres of potatoes in Maine were grown in 2017 (*2017 Census of Agriculture,* 2019) for three key markets: processing (~30,000 acres), seed (~11,000 acres), and tablestock (~9,000 acres).[14] Most growers are using a 1:1 rotation with one year of potatoes and one year of a much less valuable cash crop like a grain, or an unharvested cover crop. Some growers are using a 2:1 rotation with a longer "off"

[10] R. Kersbergen, personal communication, Spring 2020.
[11] R. Kersbergen, personal communication, Spring 2018.
[12] N.B., the negative net revenue for dairy over the 5 year period of our data maybe due to milk prices being lower than average over a longer historical period and/or the set of fixed costs that we accounted for, which may not be relevant for all Maine dairy farms.
[13] J. Jemison, personal communication, February 2018.
[14] J. Jemison, personal communication, February 2018.

period from potatoes.[15] Potato cropping involves key vulnerable periods with respect to potential soil erosion and loss of organic matter. The multiple tillage/cultivation passes inherent to potato planting and hilling are harmful for soil organic matter retention and soil structure. Despite the adoption of one-pass hilling by some growers, potato cropping systems remain by necessity tillage-intensive. We estimated that, on average, a typical potato system made $2,510/ac in revenue and had $1,035/ac in variable costs and $347/ac in annualized fixed costs. As a result, the system produced $1,129/ac in net revenue per year. Additional information about the potato system is available in *Appendix B.*

Diversified vegetable farm

This farm type is by nature diverse, often growing a wide variety of crops in complex multi-year rotations. According to USDA NASS data there were 881 Maine farms growing fresh market vegetables (not including potato farms) harvested for sale in 2017. Some of the prevalent crops are snap beans, potatoes, peppers, squash, sweet corn, and tomatoes (*2017 Census of Agriculture,* 2019). Diversified vegetable systems usually rely on regular tillage, both for weed control and preparation of a seedbed for planting (Myers, 2008). However, reduced-till practices are possible and of interest to growers, so reduced-till and perhaps adoption of no-till in some cropping sequences represent possible NCS. Cover cropping is utilized by many diversified vegetable farmers at present, but their use of the practice is sometimes constrained by limited acreage and the opportunity cost of taking land out of production.[16] Further adoption or increased intensity of cover cropping is likely feasible in these systems with altered incentive programs. We estimated that, on average, a typical diversified vegetable system made $22,117/ac in revenue and had $11,724/ac in variable costs and $5,552/ac in annualized fixed costs. As a result, the system produced $10,394/ac in net revenue per year. Additional information about the diversified vegetable system is available in *Appendix B.*

2.3.5 NCS Mitigation costs and effectiveness by practice

Each NCS practice was assessed for its ability to reduce GHG emissions from Maine agriculture, as well as the cost that it might take to do so. The costs of each NCS practice were based on a mix of yield and revenue changes, capital expenditures, operating costs, and land rental rates. Periodic costs such as capital equipment or land acquisition were annualized over the study period (20 years) using a discount rate of 5% so that they could be directly compared with annual costs. More details on the sources of these costs are provided in *Appendix B.*

2.3.6 Sensitivity Analysis

The Maine agriculture NCS practice model is dependent on a range of assumptions that varied in our literature review. These include the impact of practices on crop yields, farm revenue, and implementation costs. As a result, we conducted a sensitivity analysis where we use low, medium (core), and high parameter values for each of these key input assumptions. This approach allowed us to assess the relative influence of each parameter on the key model estimates, namely total mitigation cost and break-even carbon price for each practice. Note that we opted to exclude sensitivity of GHG mitigation factors from this analysis due to the wide variation in max and min estimates. Furthermore, we did not analyze the effect of climate change on crop yields and mitigation potential due to lack of data.

3. Results

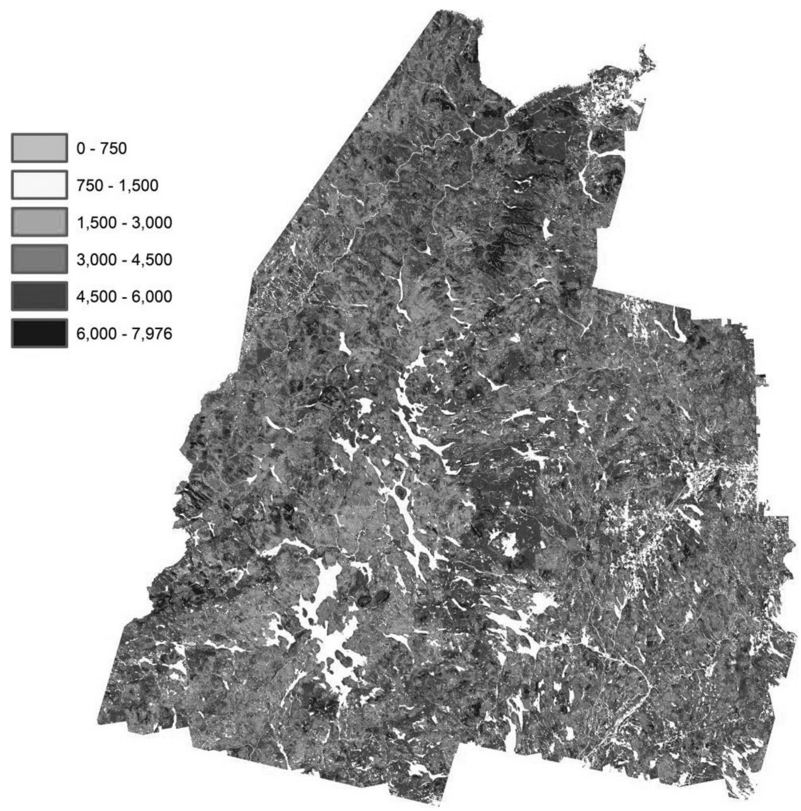
3.1 Forestry

3.1.1 Model Baseline

Circa 2010, LANDIS–II estimates based on initial forest conditions indicated there was approximately 1.33 Tg of aboveground carbon distributed broadly across our study area (*Figure* 7). At the cell-level, aboveground carbon ranged from 116–7,976 g m^{-2}, with an average of 4,250 gm^{-2}, reflecting complex variation in tree species relative abundance and forest age across northern Maine.

[15] N. Lounsbury, unpublished data, January 23, 2020.
[16] R. Clements, unpublished data, 2019.

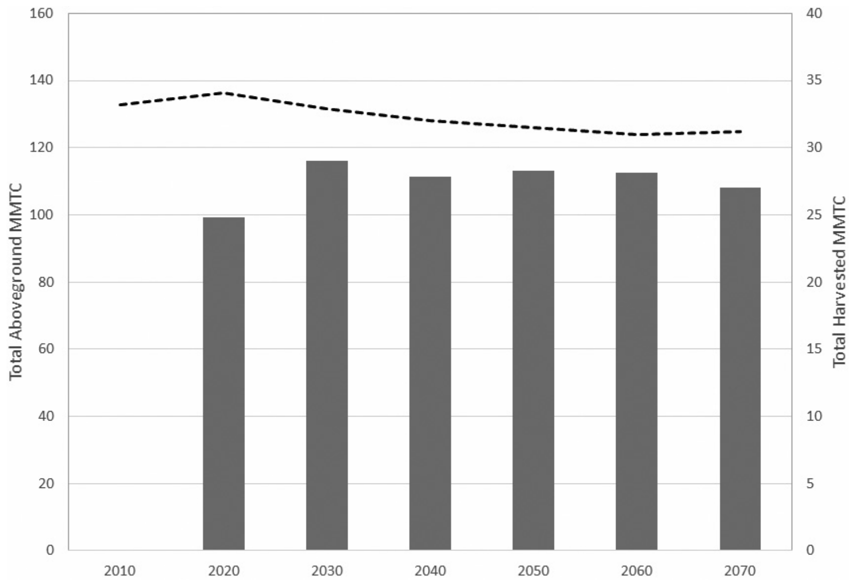
Figure 7. Total Aboveground Carbon ca. 2010 gm^{-2}



Spatial distribution of total aboveground carbon ca. 2010, also representing the starting conditions for forest landscape simulations 2010–2070.

Under the baseline (*i.e.,* BAU min50 under RCP 2.6) scenario total aboveground carbon declined 7%, from approximately 1.33 Tg to 1.24 Tg, between 2010 and 2070 (*Figure 8*). On average 0.27 Tg of aboveground carbon was projected to be harvested every 10 years. The average total harvest footprint every 10 years was projected to be 1,486,963 acres, which translated into an annual harvest rate of approximately 1.7% for the study area.

Figure 8.



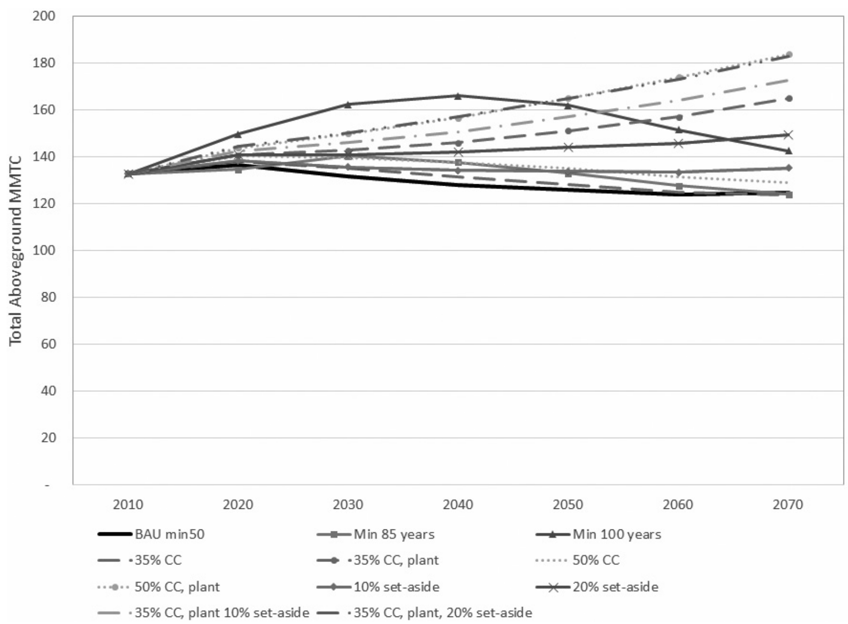
Total, live aboveground million metric tons of carbon (MMTC) (standing; dashed line) and total harvested MMTC (gray bars) every 10 years (*e.g.,* 2010–2020, 2020–2030, *etc.*) under the baseline or Business-as-usual (BAU) scenario, 2010–2070.

Harvest levels in the 9.1 m acres of northern Maine tracked in the Landis model were estimated to be maintained around 9.3 million green tons per year, which is consistent with trends over the past 10 years. These harvests were expected to be a similar mix of sawlogs, pulpwood and low-diameter biomass that were converted into the relevant forest products, again matching historical trends. As a result, the BAU harvest of about 145,000 acres each year—of which 90% was partial harvest—was estimated to accrue $120 million/yr in stumpage revenue. These estimates were the values for which all the other Landis-based scenarios were compared against in this study.

3.1.2 Forest NCS practice results

3.1.2.1 Forest management in Landis

Total aboveground carbon followed a wide variety of trends, including increasing and declining, under RCP 2.6 and the different management scenarios (*Figure 9*). In general, total aboveground carbon was lower than the initial amount under the extended rotation scenarios, with the exception of the Min 100 years, which was the only scenario that projected a reversal in direction (rapidly increasing until 2040 and then rapidly declining). Increased clearcutting also resulted in a declining trend unless paired with planting. A set-aside resulted in a relatively stable aboveground carbon pool at 10%, or slightly increasing at 20%. Circa 2070, all scenarios were higher than BAU min50, ranging from +1% (35% clearcut) to +40% (50% clearcut, plant or 35% clearcut, plant, 20% set-aside).



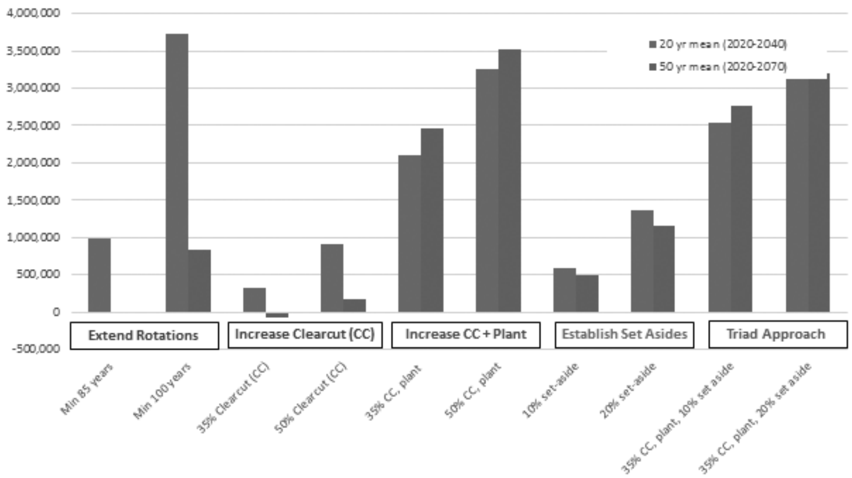
Comparison of total aboveground carbon stock (MMTC) under RCP 2.6 and the different forest management scenarios 2010–2070. See *Table 1* for scenario descriptions.

Converting the aboveground and harvested carbon into annual figures allows us to estimate the annual change in carbon sequestration over different time periods, as well as the cost of doing so relative to the BAU (typically in the form of lost revenues or increased planting and management costs). *Figure 10* indicates that extending the minimum stand age before harvest out to 100 years increased forest carbon over the first 20 years as many stands that were harvested under BAU were left to mature. However, those increases in carbon diminish over time as the same stands were then harvested between 2040 and 2070. In contrast, stands that involved active planting and/or set-asides continued to sequester carbon on a steady basis over the next 50 years. We estimated that simply clearcutting stands but not artificially regenerating them produced minimal carbon gains above the BAU case.

Adjusting management to have longer rotations or 20% of total forest area established as no-harvest set asides resulted in a noticeable reduction in timber harvests (13–17% below BAU) over the next 50 years (*Figure 11*). All other scenarios projected changes of 8% or less. This finding suggests that for many of the proposed forest management options, it is possible to increase forest (and harvested wood product) carbon while simultaneously maintaining a consistent timber supply that is close to historical levels. Furthermore, the ability to maintain timber supply across the landscape suggests that there could be minimal 'leakage' of forest carbon loss to other parts of the globe as a result of implementing forest NCS in Maine.

Figure 10. Mean Annual Forest + Product Carbon Baseline

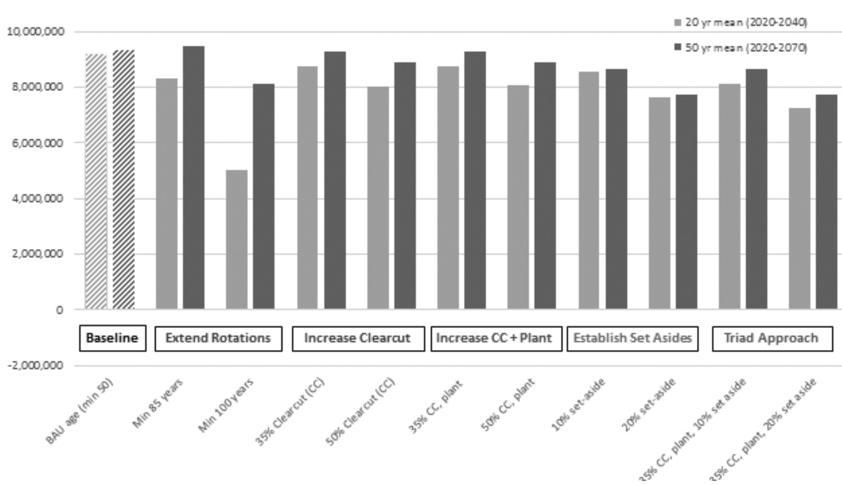
(tCO_2e/yr)



Mean annual forest and harvested wood product carbon change from BAU.

Figure 11. Mean Harvest Volume

(gt/yr)

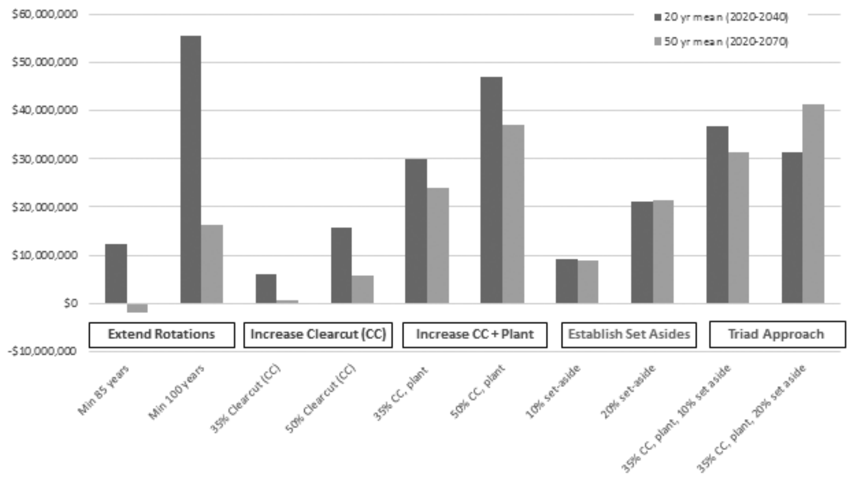


Mean annual timber harvest volume.

The modeled scenarios indicate changes in total timber harvests (and revenue) coupled with increased costs associated with the planting scenarios will result in overall total costs for implementing these NCS relative to the BAU (*Figure 12*). The 100min scenario accrued the most costs over the first 20 years due to high opportunity costs associated with reduced harvests. When the analysis was extended to 50 years, scenarios that involved planting faced the highest costs. Of course, those higher costs resulted in greater amounts of carbon being sequestered on the stump and harvested wood products, thereby reducing the break-even carbon price that a landowner may be willing to receive to implement a specific practice (*Figure 13*). When assessing the GHG mitigation cost from this perspective, it is clear that most forest management NCS practices can be implemented at a cost of \$10–20/tCO_2e, which is relatively inexpensive compared to most non-NCS opportunities.

Figure 12. Mean Cost Relative to Baseline

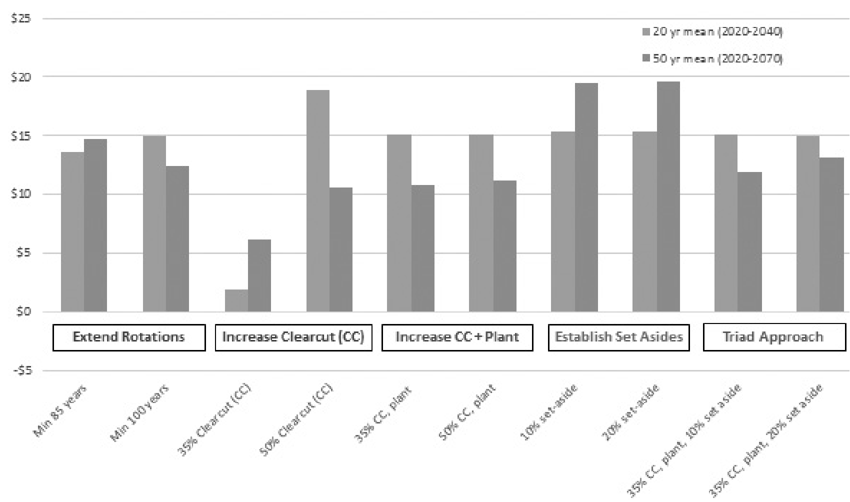
($/yr)



Mean total annual mitigation cost relative to BAU.

Figure 13. Mean Break Even Carbon Price

($/$tCO_2e$)



While our results are largely presented at the nine million acre study level, the Landis-modeling framework also allows one to assess impacts at a species and habitat level. Some of these aspects are summarized in *Table 5.* As presented above, total timber harvest was lower under all forest management scenarios relative to the baseline (BAU min50) 2010–2060, ranging from less than 0.5% lower under the 35% clearcut with or without planting to 13% lower under extended rotation to a minimum age of 100 years. However, the forest management scenarios varied widely in the impact on the ecosystem services we considered. Spruce-fir carbon increased under all scenarios, except 35% clearcut without planting. As with total aboveground carbon, planting after clearcutting increased spruce-fir carbon. Late successional (LS) forest for both spruce-fir (SF) and northern hardwood (NH) forest declined under Min 100 but increased with the addition of a 10% forest set-aside. LS results under the 35% clearcut scenarios varied, but lynx foraging habitat increased under all three. Lynx habitat decreased with extended rotation (Min 100) or 10% forest set-aside.

Table 5. Comparison of select forest NCS model outputs ca. 2060 under a subset of forest management strategies and RCP 2.6, including mean break even carbon price, and relative difference (compared to BAU min50) in total harvest, spruce-fir total aboveground carbon, late successional spruce-fir (SF) or northern hardwood (NH) forest, and lynx foraging habitat.

Scenario	Break even carbon price ($/tCO$_2$)	Total harvest 2010–2060	Spruce-Fir C	LS forest Change		Lynx habitat Change
				SF	NH	
Min 100 years	$12	−13%	33%	−8%	−13%	−25%
10% set-aside	$20	−7%	10%	4%	4%	−3%
35% CC	$6	−0.4%	−4%	−12%	4%	33%
35% CC + plant	$14	−0.3%	117%	9%	−7%	487%
35% CC + plant + 10% set-aside	$12	−8%	118%	−4%	0%	427%

3.1.2.2 Afforestation and avoided conversion

As discussed above, the afforestation and avoided forest conversion estimates were derived outside of the Landis model and encompass the *entire* State of Maine. Afforestation and restoration of areas that were determined to be forested historically, but not reduce agricultural production or low to high intensity development was estimated to be feasible on about 360,000 acres of land across the state (Cook-Patten, *et al.,* 2020). The average afforested stand was estimated to sequester 2.1 tCO$_2$e/ac/yr, thereby yielding a total of 760,000 tCO$_2$e/yr in additional carbon sequestration. Implementing this NCS across Maine was estimated to cost about $22.8 million/yr, or $30/tCO$_2$e.

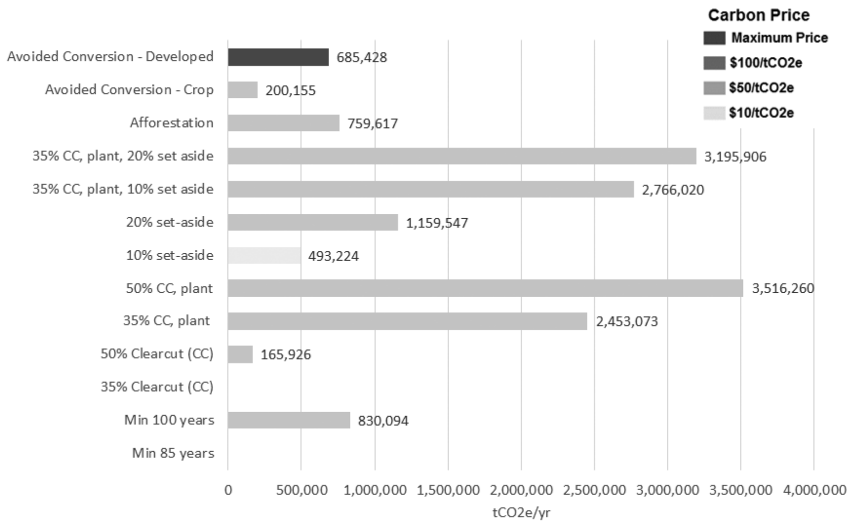
Incentivizing forest landowners to avoid converting their land to other uses has a wide range of costs depending on where the forest under threat is located in the state and what it is expected to be converted to. Following the historical trend that about 2,000 acres per year of forest is converted to agriculture in the state, we estimated that this could be avoided at a cost of about $21/tCO$_2$e, thereby sequestering an average of 200,000 tCO$_2$e/yr over the next 50 years. The cost of avoided conversion to developed land was much higher due to the expected land value associated with that land use. As a result, it could cost about $700/tCO$_2$e to keep the 6,500 acres of forest threatened by development every year as forests in perpetuity.[17] If there was a willingness to pay this amount, then about 685,000 tCO$_2$e/yr could be sequestered on average over the next 50 years by these 'protected' areas.

3.1.2.3 Summary of core modeled results

The 50 year average estimates of key results from all the forest NCS practices evaluated are summarized in *Figure 14.* The figure shows that many of the top mitigation options are expected to come from increasing clearcuts and planting and/or permanent set-asides. In addition, afforesting marginal pasture and cropland could also provide additional mitigation in addition to the improved forest management. We find that the average break-even carbon prices for most forest NCS practices are in the range of $10–$20/tCO$_2$e. Additionally, if landowners could collectively change forest management across the 9.1 million acres in northern Maine from BAU to 50% clearcut followed by planting in addition to afforesting marginal land *and* reducing conversion of forests to cropland across the state, we estimate that it could yield about 4.5 MtCO$_2$e/yr in additional carbon sequestration at a cost of $64 million/yr or $14/tCO$_2$e.

[17] N.B., because an additional 8,500 acres of 'new' land is threatened by conversion each year, the total amount of land that needs to be protected increases over time. As a result, over 420,000 acres of forest area could potentially be spared from conversion under this approach by 2070.

Figure 14. Total Maine Forest NCS Mitigation
(tCO_2e/yr)



Total Maine forest NCS mitigation potential (tCO_2e/yr), 2020–2070 annual average, RCP 2.6.

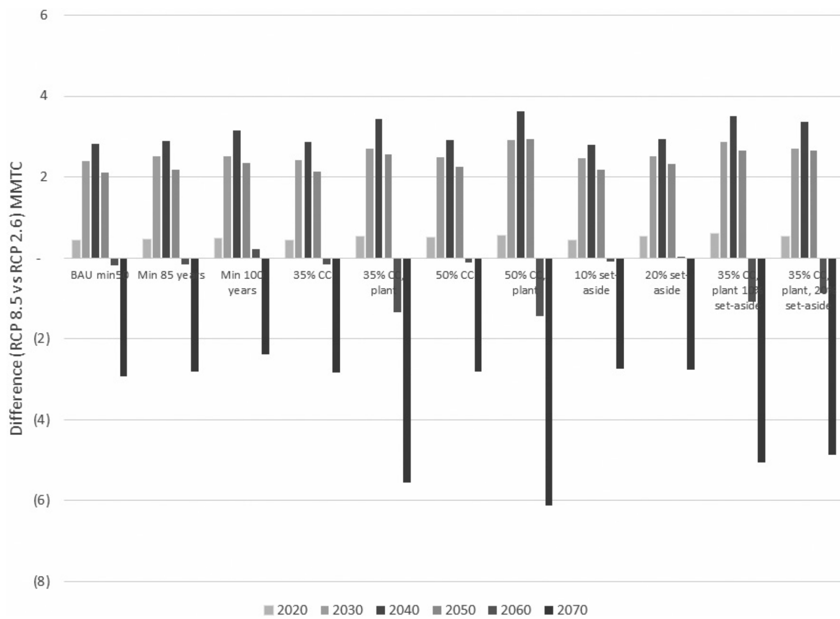
(Note: the avoided conversion and afforestation scenarios cover the entire state, while the other scenarios only include 9.1 million acres of managed forest in northern Maine.)

3.1.3 Sensitivity Analysis

3.1.3.1 Climate change impacts sensitivity

Total forest carbon was generally higher under the high emission scenario (RCP 8.5) across all management scenarios, until 2050 (*Figure 15*). Beginning with the 2050–2060 interval (blue bar, *Figure 15*), there was a reversal in trends under RCP 8.5 that resulted in a negative net difference between RCP 8.5 and RCP 2.6. Across all scenarios, this difference increased 2060–2070 (dark blue bar, *Figure 15*).

Figure 15.



Difference in MMTC, across scenarios, for aboveground carbon per interval between RCP 8.5 and RCP 2.6. A positive difference indicates that total forest carbon stock was higher in a given interval (*e.g.,* 2010–2020) under RCP 8.5.

Table 6 summarizes the key differences between RCP 2.6 and RCP 8.5 estimates based on a 50 year annual mean over 2020–2050. The analysis indicates that the most sensitive indicators are total forest carbon and total mitigation cost. Scenarios that specified more clearcuts and/or planting appear to be more sensitive to climate impacts, which makes sense as this approach accelerates forest succession. Mean harvest volume only differed by 1% between the two RCPs, which was by design in our modeling exercise.

Table 6. Key RCP 8.5 model estimates and difference from RCP 2.6 scenarios, 2020–2070 mean.

Scenario	Total Forest Carbon Above Baseline (tCO_2e/yr)		Total Harvest (gt/yr)		Total Cost (mil $/yr)		Break-even carbon price ($/$tCO_2e$)	
	RCP 8.5	% Diff	RCP 8.5	% Diff	RCP 8.5	% Diff	RCP 8.5	% Diff
Min 85 years	−12,935	−29%	9,573,938	1%	−$1.8	−4%	$15	−2%
Min 100 years	856,688	3%	8,189,758	1%	$16.6	2%	$12	0%
35% Clearcut (CC)	−66,115	−5%	9,388,191	1%	$0.6	18%	$6	−5%
50% Clearcut (CC)	170,936	3%	8,986,382	1%	$6.0	1%	$10	−6%
35% CC, plant	2,290,789	−7%	9,397,854	1%	$24.2	0%	$11	3%
50% CC, plant	3,317,819	−6%	9,006,471	1%	$37.3	0%	$11	3%
10% set-aside	501,816	2%	8,746,120	1%	$9.2	2%	$19	−1%
20% set-aside	1,315,509	13%	7,728,575	0%	$22.7	7%	$19	−5%
35% CC, plant, 10% set aside	2,631,673	−5%	8,718,366	1%	$31.6	1%	$12	4%
35% CC, plant, 20% set aside	3,073,542	−4%	7,795,875	1%	$41.6	1%	$14	4%
Afforestation	735,443	0%	9,264,829	1%	$22.1	0%	$30	0%
Avoided Conversion—Crop	100,086	0%	9,264,829	1%	$2.1	0%	$21	0%
Avoided Conversion—Developed	341,358	0%	9,264,829	1%	$239.9	0%	$703	0%

3.1.3.2 Economic benefits and costs sensitivity

The revenue and costs associated with timber harvests and planting can vary over time and space. As a result, we conducted a sensitivity analysis that adjusted the stumpage price and planting costs that landowners may face under different stand and market conditions by a factor of ±25% compared to our core assumptions. As expected, changing stumpage prices had a linear effect on total cost and breakeven carbon prices for all scenarios that did not involve planting (*Table 7*). On the contrary, low/high stumpage prices had a relatively lower impact on costs for scenarios that also included planting. This is because planting trees contributes to a relatively large part of the total cost incurred by forests undertaking that practice. This finding is confirmed with the planting cost sensitivity analysis, which estimated that adjusting planting costs by 25% could lead to a 12% to 25% change in total costs in implementing those management practices.

Table 7. Change in forest NCS mitigation costs for stumpage price and planting sensitivity analysis.

Scenario	Total Cost (Mil $/yr)				Break-even carbon price ($/t$CO_2$e)			
	Low Planting	High Planting	Low Stumpage	High Stumpage	Low Planting	High Planting	Low Stumpage	High Stumpage
Min 85 years	0%	0%	−25%	25%	0%	0%	−25%	25%
Min 100 years	0%	0%	−25%	25%	0%	0%	−25%	25%
35% Clearcut (CC)	0%	0%	−25%	25%	0%	0%	−25%	25%
50% Clearcut (CC)	0%	0%	−25%	25%	0%	0%	−25%	25%
35% CC, plant	−25%	25%	0%	0%	−23%	23%	−2%	2%
50% CC, plant	−21%	21%	−4%	4%	−21%	21%	−4%	4%
10% set-aside	0%	0%	−25%	25%	0%	0%	−25%	25%
20% set-aside	0%	0%	−25%	25%	0%	0%	−25%	25%
35% CC, plant, 10% set-aside	−18%	18%	−7%	7%	−17%	17%	−8%	8%
35% CC, plant, 20% set-aside	−12%	12%	−13%	13%	−12%	12%	−13%	13%
Afforestation	−33%	33%	−33%	33%	−33%	33%	−33%	33%
Avoided Conversion—Crop	0%	0%	0%	0%	0%	0%	0%	0%
Avoided Conversion—Dev.	0%	0%	0%	0%	0%	0%	0%	0%

3.2 Agriculture

3.2.1 Model Baseline

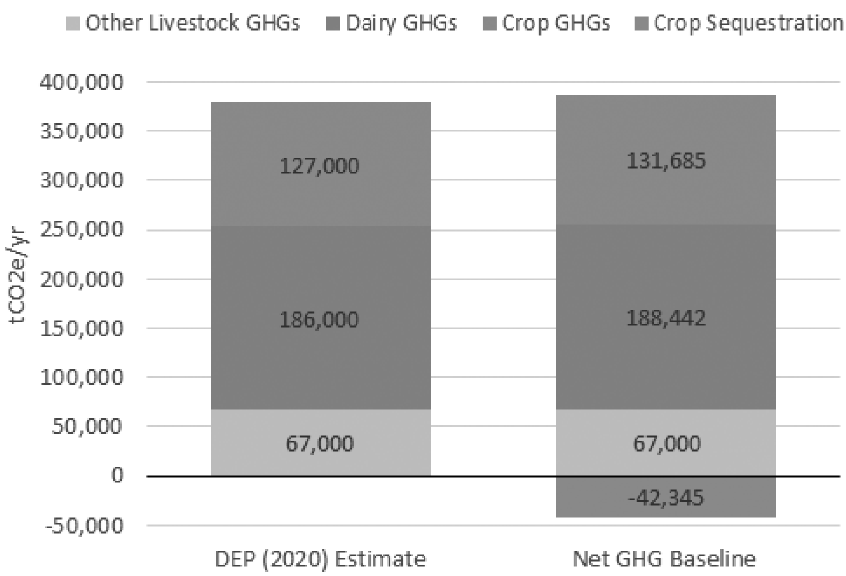
The agricultural sector model baseline estimates are listed in *Table 8.* We estimated that the 355,561 acres of major crops and 30,443 head of dairy cattle in the state collectively produced about $850 million in revenue per year, or about $246 million/yr in net revenue (*i.e.,* profit) once you take into account capital and operating expenses. These baseline farm enterprises emitted about 320,000 tCO_2e/yr of GHGs, but also sequestered about 42,000 tCO_2e/yr through activities such as no till and cover cropping.

Table 8. Key Maine agricultural sector model baseline estimates.

Crop	Area (acres)/ Head (cattle)	Revenue (Mil $/yr)	Cost (Mil $/yr)	Net Revenue (Mil $/yr)	Gross GHG (tCO_2e/yr)	Carbon Sequestration (tCO_2e/yr)	Net GHG (tCO_2e/yr)
Hay	175,231	$173.9	$56.5	$117.4	0	7,072	−7,072
Potato	50,211	$126.0	$69.4	$56.7	20,184	10,801	9,382
Blueberries	38,660	$81.3	$58.1	$23.1	12,513	0	12,513
Wheat	19,710	$16.6	$6.2	$10.5	20,445	4,220	16,225
Corn	32,571	$12.0	$18.7	−$6.7	39,297	14,406	24,891
Barley	19,710	$4.6	$7.3	−$2.7	3,625	4,220	−594
Vegetables	12,028	$266.0	$207.8	$58.2	18,998	1,626	17,373
Apples	7,441	$61.0	$44.4	$16.6	16,622	0	16,622
Crop Total	355,561	$741.5	$468.4	$273.0	131,685	42,345	89,340
Dairy	30,443	$108.6	$135.2	−$26.6	188,442	0	188,442
Major Ag Sector Total	355,561	$850.1	$603.6	$246.4	320,127	42,345	277,782

The baseline Maine agricultural sector GHGs and carbon sequestration are shown in *Figure 16.* When adding the 67,000 tCO_2e/yr of non-dairy livestock emissions to our estimates in *Table 8,* we estimated that gross GHGs are equal to about 387,127 tCO_2e/yr, while carbon sequestration from current NCS practices reduced the sector footprint by 42,345. For comparison, DEP (2020) estimates Maine's 2017 agricultural sector gross GHG emissions to be 380,000, or just 2% lower than our gross GHG estimate.

Figure 16.



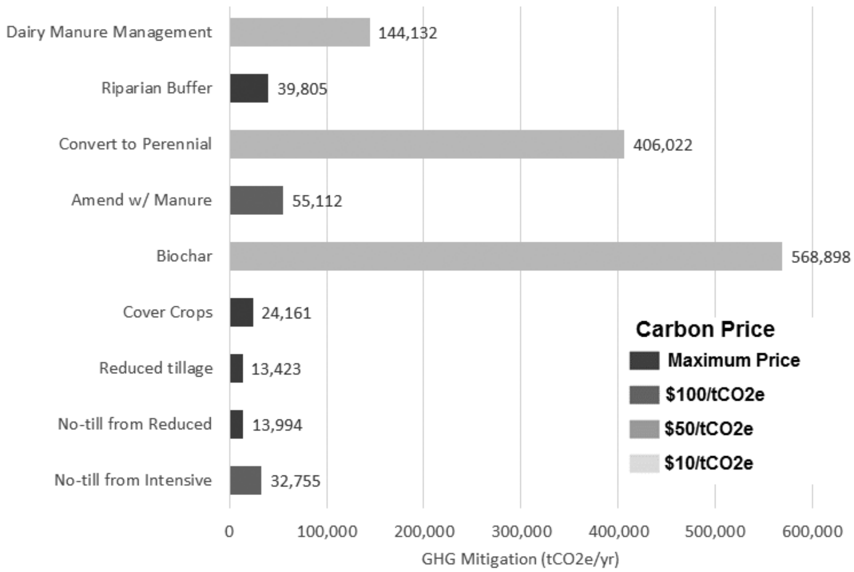
Maine DEP (2020) and modeled baseline agricultural sector GHG emissions.

3.2.2 Agriculture NCS practice results

Applying our core (*i.e.,* 'medium') agricultural sector model assumptions about mitigation potential, yield change, and practice costs, we estimate that there is wide variation in potential from implementing agricultural NCS in Maine (*Figure 17*). According to our results, the largest mitigation potential comes from the application of biochar, which could yield nearly 570,000 tCO_2e/yr, followed by permanent conversion from managed cropland and pasture to non-harvested perennial grass (363,255 tCO_2e/yr). Both of these could be implemented at relatively low cost as well, in the range of \$25–\$34/tCO_2e (*Table 9*). The large mitigation potential is primarily a factor of two things. First, both of these practices have relatively high per acre carbon sequestration rates. Second, the two NCS practices apply to a wide range of crops, including hay, which makes up a large proportion of Maine's total crop area.

Many of the other practices considered for this study yielded relatively low total mitigation or were relatively costly. Cover crops and reduced intensity tillage practices yielded between 13,423 and 32,755 tCO_2e/yr due to low area applicability and low rates of carbon accumulation (0.1 to 0.4 t/ac/yr) on a per acre basis. However, we note that our study only focused on the climate mitigation and yield impacts of implementing these practices, while they are likely to produce additional co-benefits such as improved soil health and water quality.

Figure 17. Total Maine Agriculture NCS Mitigation
(tCO_2e/yr)



Total Maine agriculture NCS mitigation potential (tCO_2e/yr).

The Maine agricultural NCS model estimates by specific crop are summarized in *Table 9.* This table highlights how the overall carbon sequestration potential of some agricultural management practices is limited by the small amount of land in crop production. Furthermore, it highlights that mitigation has the potential to come from a wide range of crops.

Table 9. Maine agricultural NCS practice estimates by crop.

NCS Practice	Hay	Potato	Blue-berry	Wheat	Corn	Barley	Veg.	Apples	Dairy	Total
Annual Mitigation (tCO_2e/yr)										
No-till from Intensive	0	0	0	8,968	14,820	8,968	0	0	0	32,755
No-till from Reduced	0	0	0	6,997	0	6,997	0	0	0	13,994
Reduced tillage	0	5,021	0	1,971	3,257	1,971	1,203	0	0	13,423
Cover Crops—non-legume	0	6,527	0	2,562	4,234	2,562	1,564	0	0	17,450
Cover Crops—legume	0	11,549	0	4,533	7,491	4,533	2,766	0	0	30,873
Cover Crops—mixed	0	9,038	0	3,548	5,863	3,548	2,165	0	0	24,161
Biochar	280,370	80,338	61,856	31,535	52,114	31,535	19,245	11,906	0	568,898
Amend w/Manure	27,161	7,783	5,992	3,055	5,049	3,055	1,864	1,153	0	55,112
Convert to Perennial	225,224	42,545	0	22,961	40,700	14,552	17,273	0	0	363,255
Dairy Manure Management	0	0	0	0	0	0	0	0	119,139	119,139
Riparian Buffer	28,789	5,302	0 476	1,629	384	836	0	0	37,418	
Annual Mitigation Cost (Mil $/yr)										
No-till from Intensive	$0.0	$0.0	$0.0	$1.7	$0.6	$0.7	$0.0	$0.0	$0.0	$3.0
No-till from Reduced	$0.0	$0.0	$0.0	$1.7	$0.0	$0.7	$0.0	$0.0	$0.0	$2.4
Reduced tillage	$0.0	$1.1	$0.0	−$0.1	$0.6	$0.5	$0.3	$0.0	$0.0	$2.3
Cover Crops—non-legume	$0.0	$3.2	$0.0	$2.8	$1.8	$1.6	$0.8	$0.0	$0.0	$10.0
Cover Crops—legume	$0.0	$3.2	$0.0	$1.3	$1.4	$1.3	$0.8	$0.0	$0.0	$7.9
Cover Crops—mixed	$0.0	$3.7	$0.0	$2.3	$2.0	$1.6	$0.9	$0.0	$0.0	$10.5
Biochar	$7.1	$2.0	$1.6	$0.8	$1.3	$0.8	$0.5	$0.3	$0.0	$14.5
Amend w/Manure	$2.4	$0.7	$0.5	$0.3	$0.4	$0.3	$0.2	$0.1	$0.0	$4.9
Convert to Perennial	$7.7	$1.8	$0.0	$0.7	$1.1	$0.7	$0.4	$0.0	$0.0	$12.4
Dairy Manure Management	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$2.6	$2.6
Riparian Buffer	$3.6	$0.7	$0.0	$0.1	$0.2	$0.1	$0.1	$0.0	$0.0	$4.6
Break-even Carbon Price ($/$tCO_2e$)										
No-till from Intensive	$0	$0	$0	$189	$41	$73	$0	$0	$0	$90
No-till from Reduced	$0	$0	$0	$243	$52	$94	$0	$0	$0	$168
Reduced tillage	$0	$218	$0	−$61	$198	$229	$218	$0	$0	$174
Cover Crops—non-legume	$0	$483	$0	$1,080	$415	$614	$483	$0	$0	$573
Cover Crops—legume	$0	$273	$0	$295	$189	$278	$273	$0	$0	$256
Cover Crops—mixed	$0	$412	$0	$641	$334	$462	$412	$0	$0	$434
Biochar	$25	$25	$25	$25	$25	$25	$25	$25	$0	$25
Amend w/Manure	$88	$88	$88	$88	$88	$88	$88	$88	$0	$88
Convert to Perennial	$34	$41	$0	$30	$28	$48	$24	$0	$0	$34
Dairy Manure Management	$0	$0	$0	$0	$0	$0	$0	$0	$22	$22
Riparian Buffer	$124	$124	$0	$106	$103	$132	$95	$0	$0	$122

All of these practices are presented as a single-focused implementation on a given parcel of land. In reality, some of these practices can be 'bundled' and applied simultaneously. In addition, the dairy manure management practices do not overlap with the crop practices. Thus, Maine farmers could collectively amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and construct and utilize anaerobic digesters to manage dairy manure waste. If these options were simultaneously implemented across all eligible farms, then Maine could expect to mitigate up to 786,000 tCO_2e/yr in agricultural GHG emissions or about double the sector's current annual emissions. This combined approach is estimated to cost $26.3 million/yr or about $34/$tCO_2e$. Future research will explore the technical and financial feasibility of creating different bundles of practices for agricultural NCS.

The dairy manure management estimates summarized above were based on the assumptions that Maine's dairy farms collectively implemented a mix of the five different dairy NCS practices under consideration (*Table 10*). Breaking out dairy by specific NCS practices , which were primarily different sized and types of anaerobic digesters (AD), reveals that the larger options (*i.e.,* complete mix AD and SLS) were the most cost effective, yielding break-even carbon prices of $6–$8/tCO_2e. However, these two practices would also need to rely on waste from several dairy farms. This is the case for the Summit Utilities Inc. anaerobic digester being constructed in Clinton, which is expected to collect waste from up to 17% of the state's dairy herd (Summit Utilities Inc., 2019). However, our results may be optimistic for Maine's dairy sector, which is often made up of small herds (*2017 Census of Agriculture,* 2019). As a result, widespread implementation will likely require extensive cooperation, capital investment, and potentially long waste hauling distances to achieve the scale of mitigation that we have estimated.

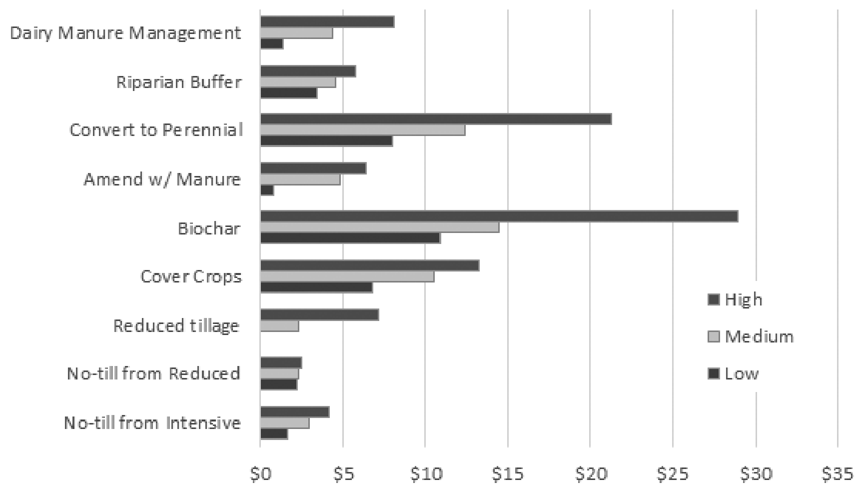
Table 10. Dairy manure management NCS summary

Estimate	Large Complete Mix Anaerobic Digester (AD) with electricity generation	Covered Lagoon/ Holding Pond AD with electricity generation	Solid-liquid separation (SLS)	Small Complete Mix AD with electricity generation	Plug Flow AD with electricity generation
Total constructed (no)	12	100	30	100	100
Total GHG Mitigation (tCO_2**e/yr**)	148,800	209,700	244,860	148,800	128,700
Total Mitigation Cost ($/yr)	$922,221	$9,329,591	$1,866,098	$5,290,110	$9,251,873
Break-even Carbon Price ($/$tCO_2$**e**)	$6	$44	$8	$36	$72

The model estimates were dependent on a wide range of assumptions about how NCS practices affect yield, cost, and mitigation potential.[18] As a result, we conducted a sensitivity analysis that tested the effect of our assessment when the 'core' (medium) assumptions were modified to a 'Low' and 'High' input cost and yield impact case. The analysis indicates that the mitigation costs were most sensitive for reduced tillage, biochar, conversion to perennial set asides, and manure management (*Figure 18, Figure 19*). However, biochar and manure management were still estimated to be relatively cheap, even under the 'high' cost case, and thus should not be ruled out even if actual costs are higher than our core assumptions. If we apply the same list of feasible practices discussed above across Maine's farms, then we estimate a Low total (break-even) cost of $17.4 mil/yr ($22/tCO_2e) and a High cost of $47.1 mil/yr ($60/tCO_2e). While this range is found to be higher than most of the forest NCS practices, it is still well within the range of other NCS and land-based mitigation studies (Fargione, *et al.,* 2018; Griscom, *et al.,* 2017; Roe, *et al.,* 2019) as well as the cost of implementing non-NCS options like renewable energy (Riahi, *et al.,* 2017).

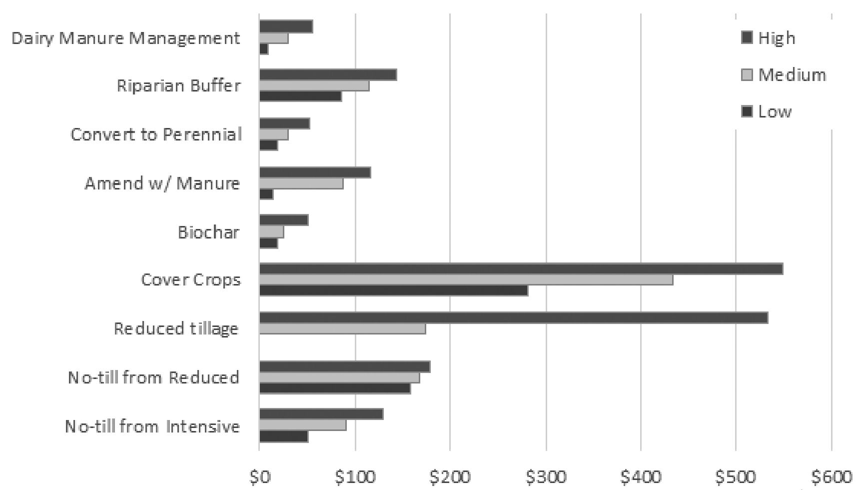
[18] N.B., for this analysis we opted to exclude a low and high mitigation sensitivity due to the extreme range in emissions scenarios published in the literature. We hope to explore this impact in a future analysis.

Figure 18. Total Ag GHG Mitigation Cost by Sensitivity Case
(Mil $/yr)



Total annual Maine agriculture NCS practice cost (mil $/yr) by sensitivity case.

Figure 19. Total Ag GHG Mitigation Break-even Price by Sensitivity Case
($/$tCO_2e$)



Total annual Maine agriculture NCS practice break-even carbon price ($/ tCO_2e) by sensitivity case.

4. Summary & Conclusions

This study sought to estimate the financial costs and GHG mitigation benefits of implementing a range of NCS practices across Maine's farms and forests. A summary of the key findings are listed in *Table 11.* Based on this assessment, we found that the following five practices for each of the forestry and agriculture sectors provided the most mitigation potential in Maine at relatively low cost.

Forestry:

1. 50% clearcut area + planting

Agriculture:

1. Amend soil with biochar

Forestry:

2. 35% clearcut + 20% set aside
3. 35% clearcut + 10% set aside
4. 35% clearcut + planting
5. Afforest marginal crop and pasture

Agriculture:

2. Convert to perennial grasses
3. Dairy manure management
4. Amend soil with manure
5. Plant riparian buffers

The results in *Table 11* present the impacts if specific practices were implemented on their own. However, in some instances, a subset of NCS practices can be implemented simultaneously, either on the same farm/stand or in separate areas, which will be explored in more detail in a future analysis. On the forestry side, collectively changing forest management across 9.1 million acres in northern Maine to 50% clearcut followed by planting in addition to afforesting marginal land and reducing conversion of forests to cropland across the state could yield about 4.5 $MtCO_2e$/yr in additional carbon sequestration at a cost of $64 million/yr or $14/$tCO_2e$. In terms of agriculture, Maine farmers could collectively amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and construct and utilize anaerobic digesters to manage dairy manure waste, thereby mitigating up to 786,000 tCO_2e/yr in GHG emissions or about double the sector's current annual emissions. This combined approach for the agricultural sector is estimated to cost $26.3 million/yr or $34/$tCO_2e$.

With respect to forestry, our analysis found that annual harvests were reduced by 5% or less compared to the BAU, thereby ensuring a steady timber supply even with an increase in forest carbon. The key exception is the scenario with the constraint that stands must be at least 100 years old to harvest. As harvests in most scenarios were close to BAU, there was also minimal risk of 'leakage' in the form of increased harvests and lost forest carbon outside of our study area. Our study also found that there are potential habitat tradeoffs with increased clearcuts and planting versus natural regeneration. Finally, we note that the average break-even carbon prices that we estimated for the sector are in the range of $10–$20/tCO_2e. These prices are relatively inexpensive compared to typical carbon prices for other sectors of economy and social cost of carbon estimates, thus indicating that application of NCS practices in Maine's forest sector could be a cost-effective option to help meet the state's greenhouse gas reduction goals.

Table 11. Summary of key findings for Maine NCS mitigation potential

Land-use Sector	NCS Practice	GHG Mitigation (tCO_2e/yr)	Mitigation Cost ($/yr)	Break-even Carbon Price ($/$tCO_2e$)	Total Applicable Area (acres or cows)
Forestry	BAU age (min 50)	0	$0.0	$0	9,100,000
	Min 85 years	−18,276	−$1.9	$15	9,100,000
	Min 100 years	830,094	$16.2	$12	9,100,000
	35% Clearcut (CC)	−69,900	$0.5	$6	9,100,000
	50% Clearcut (CC)	165,926	$5.9	$11	9,100,000
	35% CC, plant	2,453,073	$24.1	$11	9,100,000
	50% CC, plant	3,516,260	$37.1	$11	9,100,000
	10% set-aside	493,224	$9.0	$20	9,100,000
	20% set-aside	1,159,547	$21.3	$20	9,100,000
	35% CC, plant, 10% set-aside	2,766,020	$31.4	$12	9,100,000
	35% CC, plant, 20% set-aside	3,195,906	$41.3	$13	9,100,000
	Afforestation	759,617	$22.8	$30	360,000
	Avoided Conversion—Crop	200,155	$4.1	$21	95,300
	Avoided Conversion—Developed	685,428	$481.8	$703	327,800
Agriculture	No-till from Intensive	32,755	$3.0	$90	71,990
	No-till from Reduced	13,994	$2.4	$168	39,419
	Reduced tillage	13,423	$2.3	$174	134,229
	Cover Crops	24,161	$10.5	$434	134,229
	Biochar	568,898	$14.5	$25	355,561
	Amend w/Manure	55,112	$4.9	$88	355,561
	Convert to Perennial	406,022	$12.4	$30	241,346
	Riparian Buffer	39,805	$4.6	$115	21,309
	Large Complete Mix AD	150,997	$0.9	$6	30,443
	Covered Lagoon/Holding Pond AD	212,797	$4.1	$19	30,443
	Solid-liquid separation (SLS)	129,565	$1.9	$15	30,443
	Small Complete Mix AD	150,997	$5.4	$36	30,443
	Plug Flow AD	76,305	$9.4	$123	30,443

For Maine agriculture our results point to a high mitigation potential from amending soil with biochar, converting cropland and pasture to perennial grasses, and constructing anaerobic digesters for dairy manure management. There is abundant literature from throughout the globe on the potential effect of biochar on reducing GHG emissions, but it is less proven at the commercial level, especially in conditions such as Maine. In addition, converting land to perennial grasses could potentially take cropland out of production, thereby reducing the amount of locally sourced food available to Mainers. Dairy management relies on the investment in digesters, which require financial capital. Despite these potential uncertainties, Maine's agricultural sector has the potential to reduce its within-sector emissions or even be net-negative as a sector while enhancing the sustainability and health of Maine's farms and food systems.

We note that there are some important model limitations that could be addressed in future research applied to our forestry NCS assessment. First, the Landis-based model estimates were based on only a single 'run' for each scenario that quasi-randomly selected which stands to harvest and/or plant. Conducting multiple model runs for the same management scenario would provide additional insight on the level of uncertainty surrounding the carbon estimates. The second limitation is that the analysis only covered the northern half of the state. To provide a statewide context for our estimates, we incorporated carbon information derived from FIA data for areas outside our project study area (*Appendix C*). Encompassing the carbon dynamics of southern Maine to a degree equal to the efforts demonstrated here for northern Maine should be a priority for future research.

Our results show limited carbon sequestration of the agricultural NCS practices in Maine compared to forestry. Our model also only assessed their impact on yield and net GHG emissions and no other cobenefits such as the provision of other ecosystem services, improved climate change adaptation, and enhanced farm resilience. Further, locally collected data were often unavailable to inform our modeling approach, so many parameter values were drawn from regional estimates or extrapolated from growing systems with similarities to Maine as detailed in our methods description. Additional biophysical research specific to NCS practice application in Maine crops and cropping systems is needed to better understand local yield impacts and soil carbon sequestration dynamics. Further research could incorporate quantification of the potential co-benefits of NCS on aspects such as water quality and quantity and soil health. The analysis could also be extended to investigate interactions between the forestry and agricultural sectors.

Our analysis also assumed that the practices would be fully implemented across all eligible land. In reality, not every farmer and forest landowner will have the technical and financial resources, or the inclination in light of their own circumstances, to undertake some of these practices. For example, while we found biochar to be an extremely cost-effective opportunity for Maine's agricultural sector, particularly given the abundance of raw materials available to produce biochar, very few farmers are currently implementing this on their land in Maine. As a result, we are using interviews and focus groups to explore the potential technical, financial, social, and/or policy barriers and opportunities that stakeholders face in implementing the NCS practices presented in this report that may limit the ability to reach our estimated potential. These findings will be incorporated into future modeling efforts.

Finally, we offer two closing thoughts in light of this initial study. First, it is clear that while there is a tremendous body of knowledge in the literature upon which to draw to undertake these technical analyses, it is essential to support Maine decision-makers with Maine-based data and experience given the unique historical, biophysical, and socioeconomic character of Maine. Maine's spruce-forests are not like southern pine and Maine's potato production systems and markets are not like California. Second, most of these NCSs have important contributions to make to the urgent need to reduce greenhouse gas concentrations in the atmosphere, and at the same time they typically provide vital co-benefits that are often lumped into a term like ecosystem services. It should be noted, however, that most but not all are finite. We can increase carbon in forests and soils up to a point, but not forever. That makes their contributions between now and mid-century most critical for investment.

Appendix A. Detailed Results

Table 12. Maine forest NCS estimates for core (medium) analysis, 20 and 50 year means.

Scenario	Total Carbon Above Baseline (tCO_2e/yr)	Harvest Volume (gt/yr)	Mitigation Cost ($/yr)	Break-even Carbon Price ($/$tCO_2e$)
20 Year Mean (2020–2040)				
BAU age (min 50)	0	9,218,608	$0	$0
Min 85 years	977,442	8,293,587	$12,288,424	$14
Min 100 years	3,731,440	5,034,894	$55,578,455	$15
35% Clearcut (CC)	322,382	8,758,310	$6,114,819	$2
50% Clearcut (CC)	904,263	8,042,478	$15,624,267	$19
35% CC, plant	2,094,584	8,752,861	$29,847,046	$15
50% CC, plant	3,255,452	8,046,626	$47,118,239	$15
10% set-aside	592,715	8,532,867	$9,109,711	$15
20% set-aside	1,370,633	7,631,017	$21,090,314	$15
35% CC, plant, 10% set-aside	2,536,070	8,103,470	$36,888,130	$15
35% CC, plant, 20% set-aside	3,121,529	7,240,923	$31,400,585	$15
Afforestation	735,443	9,218,608	$22,063,299	$30
Avoided Conversion—Crop	100,086	9,218,608	$2,058,912	$21
Avoided Conversion—Developed	341,358	9,218,608	$239,925,645	$703
50 yr mean (2020–2070)				
BAU age (min 50)	0	9,332,668	$0	$0
Min 85 years	−18,276	9,475,356	−$1,895,530	$15
Min 100 years	830,094	8,115,025	$16,175,762	$12
35% Clearcut (CC)	−69,900	9,291,435	$547,764	$6
50% Clearcut (CC)	165,926	8,887,980	$5,907,455	$11
35% CC, plant	2,453,073	9,301,018	$24,080,330	$11
50% CC, plant	3,516,260	8,911,726	$37,139,123	$11
10% set-aside	493,224	8,654,385	$9,010,648	$20
20% set-aside	1,159,547	7,728,575	$21,309,545	$20
35% CC, plant, 10% set-aside	2,766,020	8,630,582	$31,400,585	$12
35% CC, plant, 20% set-aside	3,195,906	7,708,553	$41,327,285	$13
Afforestation	759,617	9,332,668	$22,788,513	$30
Avoided Conversion—Crop	200,155	9,332,668	$4,117,478	$21
Avoided Conversion—Developed	685,428	9,332,668	$481,757,790	$703

Table 13. Maine agricultural NCS estimates by sensitivity case.

NCS Practice	Total Mitigation (tCO_2e/yr)	Total Cost (Mil $/yr)			Break-Even Price ($/$tCO_2e$)		
	Medium	Low	Medium	High	Low	Medium	High
No-till from Intensive	32,755	$1.70	$2.96	$4.22	$52	$90	$129
No-till from Reduced	13,994	$2.21	$2.36	$2.50	$158	$168	$178
Reduced tillage	13,423	−$1.91	$2.34	$7.15	−$142	$174	$532
Cover Crops	24,161	$6.80	$10.48	$13.28	$281	$434	$549
Biochar	568,898	$10.86	$14.48	$28.96	$19	$25	$51
Amend w/Manure	55,112	$0.81	$4.85	$6.44	$15	$88	$117
Convert to Perennial	406,022	$7.97	$12.38	$21.24	$20	$30	$52
Riparian Buffer	39,805	$3.41	$4.57	$5.73	$86	$115	$144
Dairy Manure Mgmt.	144,132	$1.42	$4.33	$8.14	$10	$30	$56

Appendix B. Detailed Input Data

Maine forest systems

Table 14. Landis baseline area by species, 2010.*

Species	Area (acres)
Red Maple	2,933,457
Balsam Fir	2,915,428
Yellow Birch	2,287,363
Red Spruce	2,244,374
Sugar Maple	1,933,383
Northern White Cedar	1,386,127
Paper Birch	1,264,980
American Beech	967,934

Table 14. Landis baseline area by species, 2010.*—Continued

Species	Area (acres)
Eastern Hemlock	479,583
Black Spruce	462,059
White Ash	449,635
Eastern Whi[t]e Pine	449,049
White Spruce	326,810

*Acres sum to more than the 10 million acres in total area covered by Landis because any given 30mpixel in the model can have anywhere from 1 to 13 species present.

Maine cropping systems

The following section includes additional information on each of the agricultural enterprise systems and detailed budgetary information. For all of the enterprises, costs were adjusted to 2017 dollars based on the Producer Price Index (PPI) to account for inflation, and revenue is based on a 5-yr (2012–2017) average of the commodity price in Maine (Crop Values Annual Summary, 2020).

Apples

The financial budget for an apple system is calculated based on bearing fruit acres and was created based on economic information from a Cornell University study (Schmit, *et al.,* 2018).

Table 15. Apple orchard budget

Component	Per bearing fruit acre
Revenue	
Yield (lbs)	30243.5
Price	$0.31
Estimated Revenue	$8,196.00
Variable Costs	
Labor	$2,855.00
Chemical Inputs	$1,052.00
Insurance, Utilities, Interest, and professional/technical services	$541.00
Equipment expenses (fuel, oil, trucking, maintenance, leasing)	$481.00
Miscellaneous Expenditures	$630
Total Variable Costs	$5,559.00
Fixed Costs	
Real estate costs (repair, taxes, and leasing)	$407.00
Total Costs	**$5,966.00**
Net Revenue	**$2,230.00**
Return over Variable Cost	**$2,637.00**

Barley

According to the 2017 USDA NASS Census of Agriculture, 15,115 acres of barley were grown for grain (*2017 Census of Agriculture,* 2019). The financial budget for a typical barley cropping system assumes a farm of 26 planted acres. Costs were adapted from data from the USDA Economic Research Service for the Northeast region and is partly based on USDA's Agricultural Resource Management Survey (*Commodity Costs and Returns,* 2020).

Table 16 summarizes the key revenues and costs for a typical Maine barley cropping system.

Table 16. Barley farm budget.

	Total	Per planted acre
Revenue		
Number of acres	26	
Yield	(bu)	1248 48
Price	($/bu)	$3.87
Primary product grain	$4,825.60	$185.60

Table 16. Barley farm budget.—Continued

	Total	Per planted acre
Secondary product silage/straw/grazing	$871.55	$33.52
Annual Revenue	**$5,697.15**	**$233.25**
Variable costs		
Seed	$741.59	$28.52
Fertilizer [a]	$1,313.84	$50.53
Chemicals	$57.95	$2.23
Custom services	$699.20	$26.89
Fuel, lube, and electricity	$426.49	$16.40
Repairs	$504.51	$19.40
Other variable expenses [b]	$33.87	$1.30
Interest on operating inputs	$39.39	$1.51
Total Variable Costs	**$3,816.85**	**$146.80**
Fixed costs		
Hired labor	$54.44	$2.09
Opportunity cost of unpaid labor	$1,398.64	$53.79
Capital recovery of machinery and equipment	$1,651.27	$63.51
Opportunity cost of land	$2,281.23	$87.74
Taxes and insurance	$146.26	$5.63
General farm overhead	$337.43	$12.98
Total Fixed Costs	**$5,869.28**	**$225.74**
Total Costs	**$9,686.12**	**$372.54**
Net Revenue	**−$3,988.98**	**−$139.29**
Net Revenue over Variable Costs	**$1,880.30**	**$86.45**

[a] Cost of commercial fertilizers, soil conditioners, and manure.
[b] Cost of purchased irrigation water and straw baling.

Blueberries

Lowbush blueberries are clonal perennial shrubs that tolerate marginal, poorly drained sites but most commercial production takes place on freely drained and often sandy soils, most commonly under acidic soil conditions. They are managed on a 2 year cycle that utilizes mowing or (less commonly these days) burning in the non-production year to maximize floral initiation, fruit set, yield, and ease of mechanical harvest during the production year. About 70% of blueberry plants' biomass is found underground in rhizomes, which enables their recovery from biannual mowing or burning (Files, *et al.,* 2008). An average of 14 gallons of diesel fuel per acre are required for mowing, whereas 80 gallons of diesel fuel per acre is required for burning. Other important field operations and inputs include rental of honeybees for pollination during production years, use of N-P-K fertilizers, applications of sulfur (often applied at a concentration of 1,000 lbs/acre) (Files, *et al.,* 2008) to lower pH and manage weeds, application of herbicides, fungicides, and insecticides, and irrigation on an as-needed basis during both production and non-production years (Yarborough, 2012).

According to former Extension wild blueberry specialist Dave Yarborough, opportunities for enhanced carbon sequestration in this crop may be limited because "wild blueberries do not store much biomass as plants are pruned every other year and there is a slow decomposition of the cut stems. Prior to the 1970's, plant[s] were burned with #2 fuel oil and so we had a much higher carbon emission in the past but now most are mowed; so most of the carbon benefits have been accrued in past years with this change in practice." [19] However, use of organic mulches including living mulches, as well as use of cover crops in lowbush blueberry systems, represent areas of theoretical promise in which new research is currently being conducted.[20]

The financial budget for a typical blueberry cropping system was adapted from an enterprise budget prepared by the University of Maine Cooperative Extension (*Blueberry Enterprise Budget,* 2016) and reflects the following assumptions: a medium yield, conventional farm of 58 acres. *Table 17* summarizes the key revenues and costs for a typical Maine blueberry cropping system.

[19] D. Yarborough, personal communication, January 27, 2020.
[20] L. Calderwood, personal communication, January 9, 2020.

Table 17. Lowbush Blueberry Farm Financial Budget.

	Total	($/Acre)	($/lb)
Revenue			
Number of Acres (Crop)	58.06		
Yield (lbs)	258,089		
Yield (lbs./Acre)	4,445.21		
Price ($/lb)	0.47		
Annual Revenue	**122,024.43**	**2,101.70**	**0.47**
Variable Costs			
Pruning (burning and mowing)	$7,234	$125	$0.03
Weed Control	$7,471	$129	$0.03
Fertilization	$7,710	$133	$0.03
Pollination	$15,435	$266	$0.06
Pest Monitoring	$531	$9	$0.00
Insect Control	$2,198	$38	$0.01
Disease Control	$4,099	$71	$0.02
Irrigation	$0	$0	$0.00
Sulfur (pH)	$0	$0	$0.00
Harvest (raking and mechanical)	$36,711	$632	$0.14
Packing and Marketing	$0	$0	$0.00
Interest on Capital	$2,571	$44	$0.01
Blueberry Tax	$3,354	$58	$0.01
Total Variable Costs	**$87,315**	**$1,504**	**$0.34**
Total Costs	**$87,315**	**$1,504**	**$0.34**
Net Revenue	**$34,709**	**$598**	**$0.13**

Corn

According to the 2017 USDA NASS Census of Agriculture, 7,237 acres of corn were grown for grain and 25,344 acres were grown for corn silage (*2017 Census of Agriculture,* 2019). Silage corn is planted at soil temperatures above 50 °F, typically takes 70–95 days to grow to maturity, and yields 18–30 tons per acre of 30% dry matter feed.[21] No-till (NT) and reduced-tillage (RT) practices are applicable to this crop, and biochar and set-aside programs may be as well. After harvest, silage corn is typically stored for fermentation in bunkers or silos. The financial budget is adapted from an enterprise budget prepared by the University of Maine Agricultural and Forestry Experimental Station (Hoshide, *et al.,* 2004) and assumes a 160 acre farm. *Table 18* summarizes the key revenues and costs for a typical Maine silage corn cropping system.

Table 18. Silage Corn Farm Financial Budget.

	Total	Per Acre	Per Bu
Revenue			
Number of Acres	160		
Grain Corn Yield (bu)	16,000	100	
Price ($/bu)	$3.69		
Annual Revenue	**$59,008**	**$368.80**	**$3.69**
Variable Costs			
Seed	$5,918	$36.99	$0.37
Fertilizer	$14,434	$90.21	$0.90
Lime	$2,677.433	$16.73	$0.17
Chemicals	$5,382	$33.64	$0.34
Labor	$8,121	$50.75	$0.51
Diesel Fuel and Oil	$2,853	$17.83	$0.18
Maintenance and Upkeep	$5,221	$32.63	$0.33
Supplies	$2,207	$13.79	$0.14
Insurance	$73	$0.46	$0.00
Utilities	$441	$2.76	$0.03
Rent or Lease	$2,759	$17.24	$0.17

[21] R. Kersbergen, personal communication, Spring 2018.

Table 18. Silage Corn Farm Financial Budget.—Continued

	Total	Per Acre	Per Bu
Drying	$4,264	$26.65	$0.27
Interest	$1,501	$9.38	$0.09
Total Operating Expenses	**$55,851**	**$349.07**	**$3.49**
Fixed Costs			
Depreciation and Interest	$33,493	$209.33	$2.09
Tax and Insurance	$2,444	$15.28	$0.15
Total Ownership Expenses	$35,938	$224.61	$2.25
Total Annual Cost	$91,789	$573.68	$5.74
Net Farm Income (NFI)	−$32,781	−$204.88	−$2.05
Return over Variable Cost (ROVC)	**$3,157**	**$19.73**	**$0.20**

Dairy

The dairy production cycle begins with the birth of a calf, which induces milk production. Milk is harvested for a 10–12 month period, which overlaps with the first seven months of the next nine month gestation period. The last two months prior to calving are usually a dry period provided for the health of the cow.

Overall a mature dairy cow produces a calf every 12 to 14 months. Mature cows are replaced or culled from the herd at a rate of about 25% of a milking herd per year. Approximately 50% of new female calves are kept (sometimes sent elsewhere to be raised) for replacement, and reach the age of first calving at about 24 months, while the remaining excess calves are sold for veal or beef production (*CAFO Permit Guidance Appendix B: Animal Sector Descriptions,* 2003). Management-intensive rotational grazing (MIRG) is often considered an environmental best-practice (Undersander, *et al.,* 1993). The financial budget for a typical dairy system is adapted from an enterprise budget prepared by the University of Maine Agricultural and Forestry Experimental Station (Hoshide, *et al.,* 2004) and assumes a coupled dairy and hayfield farm with 66 cows. The values in the budget are per cow, rather than per acre. *Table 19* summarizes the key revenues and costs for a typical Maine dairy cropping system.

Table 19. Dairy Farm Budget.

	Total	Per Cow	Per Cwt
Revenue			
Number of Cows	66	—	—
Annual Milk Shipment (cwt)	10,413	157.77	—
Milk Receipts	$1,643,983,614	$18.08	$0.93
Crop and Hay Revenue	$42,266,367	$0.46	$0.02
Livestock Revenue	$90,905,490	$1.00	$0.05
Total Revenue	**$1,777,155,471.00**	**$19.55**	**$1.00**
Variable Costs *Labor Expenses*			
Family	$0	$0.00	$0.00
Hired	$112,710,312	$1.24	$0.06
Subtotal	**$112,710,312.00**	**$1.24**	**$0.06**
Purchased Feed Expenses			
Dairy Forage	$0	$0.00	$0.00
Dairy Concentrate	$440,928,072	$4.85	$0.25
Subtotal	**$440,928,072.00**	**$4.85**	**$0.25**
Livestock Expenses			
Breeding Fees	$20,524,023	$0.23	$0.01
Veterinary and Medicine	$43,745,013	$0.48	$0.02
Bedding	$24,595,506	$0.27	$0.01
DHIA Expenses	$7,591,077	$0.08	$0.00
Livestock Insurance	$15,473,718	$0.17	$0.01
Subtotal	**$111,929,337.00**	**$1.23**	**$0.06**

Table 19. Dairy Farm Budget.—Continued

	Total	Per Cow	Per Cwt
Crop and Pasture Expenses			
Seeds	$33,675,642	$0.37	$0.02
Chemicals	$24,887,070	$0.27	$0.01
Fertilizer	$23,408,424	$0.26	$0.01
Lime	$19,982,547	$0.22	$0.01
Other	$52,356,564	$0.58	$0.03
Subtotal	**$154,310,247.00**	**$1.70**	**$0.09**
Maintenance and Equipment Expenses			
Fuel and Oil	$61,457,526	$0.68	$0.03
Machinery Repairs	$124,810,218	$1.37	$0.07
Subtotal	**$186,267,744.00**	**$2.05**	**$0.10**
Deduction Expenses			
Milk Marketing	$15,057,198	$0.17	$0.01
Hauling and Trucking	$66,684,852	$0.73	$0.04
Subtotal	**$81,742,050.00**	**$0.90**	**$0.05**
Interest (5.4% on ½ of total operating expense)	**$29,372,969.57**	**$0.32**	**$0.02**
Total Variable Costs	***$1,117,260,731.57***	***$12.29***	***$0.63***
Fixed Costs *Annual Overhead Expenses*			
Property Tax	$81,939,897	$0.90	$0.05
Farm Insurance	$82,085,679	$0.90	$0.05
Dues and Professional Fees	$10,600,434	$0.12	$0.01
Utilities	$66,247,506	$0.73	$0.04
Miscellaneous	$155,632,698	$1.71	$0.09
Subtotal	**$396,506,214.00**	**$4.36**	**$0.22**
Annual Depreciation and Interest Expenses			
Land	$84,147,453	$0.93	$0.05
Buildings	$268,009,794	$2.95	$0.15
Machinery and Equipment	$174,417,750	$1.92	$0.10
Subtotal	**$526,574,997.00**	**$5.79**	**$0.30**
Livestock Herd Expenses			
Cows (Milking and Dry)	$108,753,372	$1.20	$0.06
Heifers	$45,890,091	$0.50	$0.03
Calves	$17,264,754	$0.19	$0.01
Dairy Bulls	$780,975	$0.01	$0.00
Subtotal	**$172,689,192.00**	**$1.90**	**$0.10**
Total Fixed Costs	**$1,095,770,403.00**	**$12.05**	**$0.62**
Total Annual Cost	**$2,213,031,134.57**	**$24.34**	**$1.25**
Net Farm Income (NFI)	***−$435,875,663.57***	***−$4.79***	***−$0.25***
Return over Variable Cost (ROVC)	***$659,894,739.43***	***$7.26***	***$0.37***

Hay

Hay is the most harvested crop in Maine by acreage. Grasslands are not a native ecosystem type in Maine, and without human intervention in the form of periodic mowing, early successional woody species including alders, birches, and poplars will invade, beginning the process through which, left to its own devices, the land will transition back to forest. It is possible that reversion of some hayfields to forest could be beneficial from an NCS standpoint. The financial budget for a typical hayfield cropping system is adapted from an enterprise budget prepared by the University of Maine Agricultural and Forestry Experimental Station (Hoshide, *et al.,* 2004) and assumes that 200 acres of hay is grown. *Table 20* summarizes the key revenues and costs for a typical Maine hayfield cropping system.

Table 20. Conventional and Coupled Medium-Large Haylage.

	Total	Per Acre	Per Ton
Revenue			
Number of Acres	200		

Table 20. Conventional and Coupled Medium-Large Haylage.—Continued

	Total	Per Acre	Per Ton
Haylage Yield (tons)	1,200	6	
Price ($/ton)	$165.40		
Total Revenue	**$19,8480.00**	**$992.40**	**$165.40**
Variable Costs			
Seeds	$0.00	$0	$0
Fertilizer	$8,607.51	$43.04	$7.17
Lime	$2,758.82	$13.79	$2.30
Chemicals	$0.00	$0.00	$0.00
Labor	$10,023.28	$50.12	$8.35
Diesel Fuel and Oil	$4,014.08	$20.07	$3.35
Maintenance and Upkeep	$4,062.36	$20.31	$3.39
Supplies	$2,758.82	$13.79	$2.30
Insurance	$91.04	$0.46	$0.08
Miscellaneous Rent or Lease	$3,448.52	$17.24	$2.87
Storage and Warehousing	$275.88	$1.38	$0.23
Other Expenses	$1,379.41	$6.90	$1.15
Interest	$736.60	$3.68	$0.61
Total Variable Costs	**$38,156**	**$190.78**	**$31.80**
Fixed Costs			
Depreciation and Interest	$24,410	$122.05	$20.34
Tax and Insurance	$1,944	$9.72	$1.62
Total Fixed Costs	**$26,354**	**$131.77**	**$21.96**
Total Annual Cost	**$64,510**	**$322.55**	**$53.76**
Net Farm Income (NFI)	***$133,970***	***$669.85***	***$111.64***
Return over Variable Cost (ROVC)	***$160,324***	***$801.62***	***$133.60***

Numbers may not sum due to rounding.

Potato

Potatoes are second to hay in acres harvested in Maine. Growers selling to the processing market are generally under contract with the buyer who can have considerable influence on what growing practices are employed. Growers for the processing market generally receive bonuses for potato size and quality, ability to store the crop until processing, and for highest yield.[22] Most growers are using a 1:1 rotation with one year of potatoes and one year of a much less valuable cash crop like a grain or an unharvested cover crop. Some growers are using a 2:1 rotation with a longer "off" period from potatoes.[23] Potato cropping involves key vulnerable periods with respect to potential soil erosion and loss of soil organic matter. Potatoes take about three weeks to emerge after planting, leaving the soil susceptible to erosion during this time.[24] Soils are also generally uncovered and susceptible after potato harvest, as well as following fall tillage in the preceding rotation crop.[25] The multiple tillage/cultivation passes inherent to potato planting and hilling are harmful for soil organic matter and aggregation (*i.e.,* good soil structure), and despite the adoption of one-pass hilling by some growers, potato cropping systems remain by necessity tillage-intensive. Nurse cropping (Jemison, 2019), use of organic amendments (Mallory & Porter, 2007), and transition to longer rotations represent key opportunities to improve soil health in Maine potato cropping systems. The financial budget for a typical potato cropping system assumes the farm is 320 acres that grows 160 acres each of potatoes and corn in rotation. *Table 21* summarizes the key revenues and costs for a typical Maine potato cropping system.

[22] J. Jemison personal communication, February 2018.
[23] N. Lounsbury, unpublished data, January 23, 2020.
[24] J. Jemison personal communication, February 2018.
[25] Lounsbury, unpublished data, January 23, 2020.

Table 21. Potato Farm Budget.

	Potato (cwt)	Corn (bu)	
Revenue			
Number of acres	160	160	
Yield/acre	240	100	
Yield	38,400	8,960	
Unit Price	$10.46	$3.69	
Annual Revenue	**$401,664**	**$33,044.48**	
Total Revenue	**$19,8480.00**	**$992.40**	**$165.40**
	Total	Per Acre	Per Cwt
Variable Costs			
Seed	$57,463	$179.57	$1.21
Fertilizer	$45,534	$142.29	$0.96
Lime	$4,884	$15.26	$0.10
Chemicals	$41,711	$130.35	$0.88
Labor	$58,728	$183.53	$1.24
Diesel Fuel and Oil	$19,486	$60.89	$0.41
Maintenance and Upkeep	$29,710	$92.84	$0.63
Supplies	$14,918	$46.62	$0.31
Insurance	$12,300	$38.44	$0.26
Miscellaneous			
Utilities	$8,857	$27.68	$0.19
Custom Hire	$0	$0.00	$0.00
Rent or Lease	$16,553	$51.73	$0.35
Freight and Trucking	$3,930	$12.28	$0.08
Storage and Warehousing	$6,857	$21.43	$0.14
Other Expenses	$1,324	$4.14	$0.03
Interest	$8,900	$27.81	$0.19
Total Variable Costs	**$331,156.06**	**$1,034.86**	**$6.99**
Fixed Costs			
Depreciation and Interest	$104,264	$325.82	$1.60
Tax and Insurance	$6,767	$21.15	$0.10
Total Fixed Costs	**$111,031.38**	**$346.97**	**$1.70**
Total Annual Cost	**$442,187.44**	**$1,381.84**	**$8.69**
Net Farm Income (NFI)	***$18,484.56***	***$57.76***	***$1.03***
Return over Variable Cost	***$129,515.94***	***$404.74***	***$2.73***

Numbers may not sum due to rounding.

Diversified vegetable

The financial budget for a typical diversified vegetable cropping system assumes a 150 acre farm with 120 acres in woodlot, 10 acres in annual vegetable production, 10 acres in cover crops, and 10 acres in animal pasture. We assume that the farm grows beans, bell peppers, cucumbers, peas, pumpkins, sweet corn, squash, and tomatoes. This assumption is based on expert consultation and data from the 2017 USDA Census of Agriculture (*2017 Census of Agriculture,* 2019). The crops are grown in five hundred 100′ rows. *Table 22* summarizes the key revenues and costs for a typical Maine diversified vegetable cropping system.

Use of biochar is thought to be minimal in Maine at present,[26] but because diverse rotations that often include numerous field operations per season are common, there exist many opportunities to incorporate organic amendments including biochar into diversified vegetable systems. Use of mulches is common in these systems, and particularly in the case of organic mulch, represents an additional means of improving soil health (*Conservation Practice Standard: Mulching,* 2017). Conservation set-aside programs, where a portion of the land is put into conservation uses, are also feasible in these systems.

[26] S. O'Brian, unpublished data, Fall 2019.

Table 22. Diversified vegetable farm budget.

Cost Component	Mean Veg (100′ row)	Total Veg part of farm (500 rows)	Total/veg ac
Revenue	**$442.35**	**$221,174**	**$ 22,117.43**
Variable Costs	$234.48	$117,238	$11,723.78
Fixed Costs	$111.05	$55,524	$5,552.38
Mixed Veg Total Costs	**$345.52**	**$172,762**	**$17,276.16**
Return over variable costs	***$207.87***	***$103,936***	***$10,393.64***
Return over total costs	***$96.83***	***$48,413***	***$4,841.26***

Wheat

According to the 2017 USDA NASS Census of Agriculture, 262 acres of winter wheat were grown in Maine (*2017 Census of Agriculture,* 2019). The financial budget for a typical wheat cropping system was adapted from an enterprise budget created by the University of Maine Cooperative Extension (Kary, *et al.,* 2011). We assume the farm is 90 acres and produces 45 acres each of wheat and straw.

Table 23 summarizes the key revenues and costs for a typical Maine wheat cropping system.

Table 23. Wheat budget.

	Unit	Unit/Acre	Revenue/Unit	Revenue/Acre
Revenue				
Wheat	bu.	45	$15.42	$693.88
Straw	sq. bale	45	$3.34	$150.34
Annual Revenue				**$844.21**
Variable Costs *Material Expenses*				
Wheat Seed	lb	120	$0.51	$61.68
Manure	ton	5	$12.85	$64.25
Chilean Nitrate	ton	0.05	$868.63	$43.43
Lime	ton	0.2	$20.56	$4.11
Subtotal				**$168.75**
Miscellaneous Expenses				
Grain Drying	bu.	45	$0.34	$15.27
Leased Land	acre	0.25	$51.40	$12.85
Extra	%	5.00%	N/A	$14.99
Interest	%	4.73%	N/A	$8.60
Subtotal				**$51.71**
Field Operation Expenses				
Primary Tillage	pass	1	$6.61	$6.61
Secondary Tillage	pass	2	$4.81	$9.62
Manure Spreading	pass	1	$23.91	$23.91
Fertilizer Spreading	pass	1	$3.14	$3.14
Lime Spreading	pass	0.2	$3.14	$0.63
Planting Wheat	pass	1	$5.54	$5.54
Combining	pass	1	$31.97	$31.97
Hauling Wheat	pass	1	$2.08	$2.08
Baling Straw	pass	1	$6.18	$6.18
Hauling Straw	pass	1	$2.05	$2.05
Subtotal				**$91.71**
Total Variable Costs				**$312.17**
Total Costs				***$312.17***
Net Revenue				***$532.04***

Natural Climate Solutions for Agriculture

Emissions factor estimates for agricultural NCS practices used in our model, accompanied by relevant citations and notes, are outlined in *Table 24* and *25.* Additional input assumptions that we applied for the dairy manure management practices are listed in Table 26. Information and literature reviews concerning NCS practices and their applicability to growing systems in Maine is contained in the following sections of text corresponding to each included NCS practice and cropping system.

Table 24. Baseline and NCS emissions factor reduction estimate for major crops applicable NCS practices.

Crop	Emissions factor (Mg CO_2e ac^{-1} yr^{-1})	Citation/Notes
Baseline values		
Potato	2.11	Poore & Nemecek, 2018
Lowbush blueberry	0.32	Percival & Dias, 2014
Wheat	0.47	Adom, *et al.,* 2012
Corn grown for silage	0.66	Adom, *et al.,* 2012
Barley	[27] 0.47	Adom, *et al.,* 2012
Vegetables	2.21	Poore & Nemecek, 2018
Apples	2.23	Poore & Nemecek, 2018; Karlsson, 2017
Reduction due to NCS practice application		
Change to NT from intensive tillage	0.46	USDA COMET Planner (Swan, *et al.,* 2020)
Change to NT from RT	0.36	USDA COMET Planner
Change to RT from intensive tillage	0.10	USDA COMET Planner
Use of cover crop (rye)	0.13	USDA COMET Planner
Use of cover crop (red clover)	0.23	USDA COMET Planner
Use of cover crop (oats and peas mix)	0.18	USDA COMET Planner
Biochar application	[28] 1.6	Ciborowski, 2019
Amend with manure	0.16	USDA COMET Planner
Convert to permanent perennial grass set-aside	1.29	Paustian, *et al.,* 2019
Permanent riparian border on marginal land	1.69	National Council for Air and Stream Improvement & U.S. Forest Service Northern Research Station, n.d.

Table 25. Baseline and NCS emissions factor reduction estimates for dairy manure management practices.

Manure management practice	Emissions factor factor (tCO_2e cow^{-1} yr^{-1})	Citation/Notes
Baseline value		
One dairy cow	6.19	Maine DEP [29]
Reduction due to NCS practice application		
Large (up to 2,500 cows) Complete Mix Anaerobic Digester with electricity generation	4.96	AgSTAR Livestock Anaerobic Digester Database (EPA, 2020), median value of applicable digesters located in northern states [30]
Covered Lagoon/Holding Pond Anaerobic Digester	6.99	AgSTAR Livestock Anaerobic Digester Databas[e], mean of applicable digesters located in northern states
Soild-liquid separation (SLS)	8.16	(ICF International, 2013)
Small (300 cows) Complete Mix Anaerobic digester with electricity generation	4.96	AgSTAR Livestock Anaerobic Digester Database, median value of applicable digesters located in northern states
Plug Flow Anaerobic digester with electricity generation	4.29	AgSTAR Livestock Anaerobic Digester Database, median value of applicable digesters located in northern states

[27] Assuming the same emissions for growing barley as a rotation crop as winter wheat for animal feed, due to similarities in equipment use and nitrogen fertility; Beegle, D. (2017). *Estimating Manure Application Rates* [University]. Penn State Extension. *https://extension.psu.edu/estimating-manure-application-rates*.

[28] Assuming a one-time application of 5.9 Mg/ac with benefits for 20 years.

[29] Unpublished data obtained through personal communication with Maine Department of Environmental Protection, July 2020.

[30] We included in this analysis data from any digester in a northern state using dairy manure as a primary animal/farm type, with size limited to digesters serving a maximum of 10,000 head of dairy cows. Northern states included CT, IA, ID, IL, IN, MA, ME, MI, MN, NE, MT, NY, OH, OR, PA, SD, VT, WA, WI, and WY. No data were available for ND, NH, NJ, and RI, which would otherwise have been considered applicable. Median values are reported in some cases to avoid biases in mean estimates resulting from skewed data distributions.

Table 26. Input assumptions for Maine dairy manure management practices. Estimates are based on data published in the EPA AgSTAR Database (EPA, 2020), ICF (2013), and USDA EQIP Cost Sheets (*Maine Payment Schedules,* 2020; USDA NRCS, 2014).

Estimate	Large complete mix anaerobic digester with electricity generation	Covered lagoon/ holding pond anaerobic digester	Solid-liquid separation (SLS)	Small complete mix anaerobic digester with electricity generation	Plug flow anaerobic digester with electricity generation
Farm herd size (dairy cows)	2,500	300	1,000	300	300
GHG mitigated per farm (tCO_2e/yr)	16,000	2,097	8,162	1,920	2,883
GHG mitigated per cow (tCO_2e/head/yr)	4.96	6.99	8.16	4.96	4.29
Annualized Capital Costs ($/yr)	$96,564	$72,793	$34,894	$49,545	$75,983
Operations and Maintenance Cost ($/yr)	$158,136	$33,557	$27,309	$24,697	$37,877
Energy Sold ($/yr)	$177,848	$13,054	$0	$21,342	$21,342
Total Cost Less Energy ($ farm/yr)	$76,852	$93,296	$62,203	$52,901	$92,519
Total Cost Less Energy ($ cow/yr)	$31	$311	$62	$176	$308

No-till cropping (NT)

No-till cropping practices address the amount, orientation,[31] and distribution of crop and other plant residue on the soil surface year-round. Crops are planted and grown in narrow slots or tilled strips established in the untilled seedbed of the previous crop (*Residue and Tillage Management, No Till,* 2016). This practice includes maintaining most of the crop residue on the soil surface throughout the year, commonly referred to as no-till. The common characteristic of this practice is that the only tillage performed is a very narrow strip prepared by coulters, sweeps, or similar devices attached to the front of the planter.

Benefits to soil include increasing organic matter, improving soil tilth, and increasing productivity as the constant supply of organic material left on the soil surface and in the soils as roots is decomposed by a healthy population of earthworms and other soil macro- and microorganisms. Operations and maintenance for this practice includes evaluating the crop-residue cover and orientation for each crop to ensure the planned amounts, orientation, and benefits are being achieved. Weeds and other pests must be monitored to ensure pest populations do not exceed thresholds.

According to the 2017 USDA NASS Census of Agriculture, there were 21,676 acres of cropland in Maine reported to be implementing no-tillage practices, or 14% of all 152,796 acres of cropland in Maine that reported their tillage practices. For context, the USDA NASS Census of Agriculture found that Maine has a total of 472,508 acres of cropland, indicating that only 32% of the total crop area in the state reported any type of tilling practice (*2017 Census of Agriculture,* 2019). As a result, additional inference may need to be made to allocate tillage practices to the other 68% of cropland in the state, of which most could be no till (*e.g.,* blueberries, hay, *etc.*).

Reduced-till cropping (RT)

Reduced-till practice manages the amount, orientation, and distribution of crop and other plant residue on the soil surface and in the soils as roots year-round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting (*Residue and Tillage Management, Reduced Till,* 2016). This practice includes tillage methods commonly referred to as mulch tillage where a majority of the soil surface is disturbed by non-inversion tillage operations such as vertical tillage, chiseling, and disking, and also includes tillage/planting systems with relatively minimal soil disturbance. Mulch tillage includes the uniform spreading of residue on the soil surface; planning the number, sequence, and timing of tillage operations to achieve the prescribed amount of surface residue needed; and using planting equipment designed to operate in high residue situations.

RT cropping practice improves soil health by increasing organic matter, improving soil tilth, and increasing productivity as the constant supply of organic material left on the soil surface and in the soil is decomposed by a healthy population of earthworms and other soil macro- and microorganisms. Operations and maintenance for

[31] Orientation refers to the direction that crops are planted in a field, and can vary based on slope and direction.

this practice includes evaluating the crop residue cover and orientation for each crop to ensure the planned amounts, orientation, and benefits are being achieved.

According to the 2017 USDA NASS Census of Agriculture, there were 31,953 acres of cropland in Maine reported to be implementing reduced-tillage (but not no-till) practices, or about 20% of farmed acres in Maine with reported tillage practices (*2017 Census of Agriculture,* 2019).

Cover cropping

Cover cropping is growing a crop of grass, small grain, or legumes primarily for seasonal protection and soil improvement (*Cover Crop,* 2014). This practice is used to control erosion, add fertility and organic material to the soil, improve soil tilth, increase infiltration and aeration of the soil, and improve overall soil health. The practice is also used to increase populations of bees for pollination purposes. Cover and green manure crops have beneficial effects on water quantity and quality. Cover crops have a filtering effect on movement of sediment, pathogens, and dissolved and sediment-attached pollutants.

Operation and maintenance of cover crops include: controlling weeds by mowing or by using other pest management techniques, and managing for the efficient use of soil moisture by selecting water-efficient plant species and terminating the cover crop before excessive transpiration. Use of the cover crop as a green manure crop to recycle nutrients will impact when to terminate the cover crop to match the timing of the release of nutrients from the decomposing biomass with uptake by the following cash crop.

Cover crops can generate a variety of benefits and costs, both internal and external to the farm. The net effect of these impacts on farm-level profitability is a function of many factors and in a given case may be either negative or positive, though appropriate selection of cover cropping design can dramatically reduce the likelihood of negative outcomes (Clark & Sustainable Agriculture Research & Education Program, 2007).

According to the 2017 USDA NASS Census of Agriculture, there were 55,462 acres of cropland in Maine reported to be implementing cover cropping, or 12% of all acres of cropland in Maine (*2017 Census of Agriculture,* 2019).

Biochar Amendments

Biochar is a substance similar to charcoal, which can be used as a soil or growing media amendment. It is typically produced from biomass using pyrolysis technology where oxygen is either absent or depleted (K. Paustian, 2014). The pyrolysis process produces biochar as well as two additional materials, syngas and bio-oil that may have commercial value as energy sources. Biochars differ depending on the feedstock (starting material), temperature, and residence time. A wide variety of feedstocks can be used depending on location, cost, and availability.

Biochars have utility as a tool for waste management and soil remediation. Biochars may also mitigate greenhouse gas (GHG) emissions through carbon sequestration. Biochar addition to agricultural soils has gained much recognition in the last decade because it can have positive effects on crop yield and soil nutrient stocks, among other parameters (Ding, *et al.,* 2016). It should be noted, however, that yield improvements are not universal, and based on current data, are not expected in for our climate in major crops or systems including potato-grain (Jay, *et al.,* 2015), corn (Aller, *et al.,* 2018; Novak, *et al.,* 2019), orchards (Khorram, *et al.,* 2019; von Glisczynski, *et al.,* 2016), and vegetables (Jeffery, *et al.,* 2017).

A number of studies and reviews have highlighted the potential benefits of utilizing biochar as a soil amendment. These have covered issues such as mitigation of global warming through application of stable carbon into soil, waste management, bioenergy production, soil health, and productivity (Kookana, *et al.,* 2011). However, full lifecycle assessments that include the effects of biochar amendment on non-CO_2 trace gasses and soil nutrient fluxes are few (Gurwick, *et al.,* 2013) and not necessarily applicable to our growing system. Perhaps the most relevant estimate for our systems comes from a Minnesota Pollution Control Agency report, which used a literature review approach to account for direct and indirect nitrous oxide emissions, methane sink removals, soil organic carbon, and greenhouse gasses from field removal and transit, calculating that biochar amended soils at a one-time application rate of 15 Mg ha^{-1} would sequester 0.85 Mg C ha^{-1} $year^{-1}$.[32] This value is in line with prior literature, which indicates a broad range of sequestration values from 0.2 to 5.3 Mg C ha^{-1} $year^{-1}$ (Eagle, *et al.,* 2013; Woolf, *et al.,* 2010). While this Minnesota estimate represents a useful starting place for the present analysis, it should be stressed given the range of possible outcomes and number of variables to

[32] P. Ciborwski, personal communication, June 16, 2020.

consider that field studies conducted in local soils, using biochar from locally applicable feedstocks, are greatly needed to verify applicability of literature estimates to our system and provide additional data. (Gurwick, *et al.,* 2013). The assumption of a one-time application with results annualized over 20 years is in line with how commercial-scale farmers might implement this practice in Maine.[33]

Most studies using biochars as soil amendments show that biochar can increase soil productivity, but some show decreased productivity (Maguire & Agblevor, 2010). This is likely due to the wide variety of biochars that can be produced and the variability among soils and cropping systems. Biochar can increase soil productivity through the application of nutrients (for some biochars and some nutrients), a liming effect for alkaline biochars, and through improvements in soil properties that includes aeration, moisture retention, and improved soil structure. Most minerals present in the feedstock are concentrated in the biochars produced, but much of the nitrogen and sulfur is lost during pyrolysis. Therefore, supplemental nitrogen will generally be needed when using biochars as a soil amendment. Wood biochars, for which locally available feedstock is abundant in Maine, often have particularly low nutrient concentrations.

Biochar can be applied by hand, or using widely available equipment including broadcast seeders and lime or manure spreaders at larger scales. To increase efficiency by limiting the number of field operations needed, biochar can be mixed with other amendments including lime and liquid manure prior to application. Biochar can be applied as a topdress amendment, broadcast and incorporated through subsequent tillage, or applied in surface or sub-surface bands. A potential tradeoff to consider is that biochar, especially when surface-applied in no-till or reduced-tillage systems, can bind to and diminish herbicide efficacy (Major, 2010). Additional research is needed to suggest tailored application rates most applicable to growing contexts in Maine.

It is unknown how many farmers in Maine are currently incorporating biochar into their farm systems. There is no centralized reporting system for biochar use, and some farmers produce their own biochar from their woodlots. However the overall figure for Maine at this time is likely to be very small.

Manure Management

Large dairy and hog farms with manure lagoons emit significant amounts of methane (CH_4), a potent greenhouse gas that can be mitigated through a suite of practices, including changes to agricultural land management. Manure management—how manure is captured, stored, treated, and used—has important implications for farm productivity and the environment (*Manure Management,* 2020). For context, about 88% of CH_4 emissions from livestock manure management in the US are generated from dairy (56%) and swine farms (32%) (*Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2017,* Chapter 5, Table 5–6, 2019). When applied according to the agronomic needs of crops, manure can improve productivity by reducing the need for commercial fertilizer while enhancing soil health. Manure management can also affect water quality primarily by leaching nutrients (*e.g.,* nitrogen and phosphorus) to groundwater and runoff resulting in eutrophication.

A single dairy cow weighs approximately 1,400 lbs and produces approximately 80 lbs of recoverable manure per day per 1,000 lbs of animal unit (*Animal Manure Management,* 1995), which works out to 112 lbs of recoverable manure per dairy cow per day. This translates to 40,880 lbs, or 18.5 metric tons, of manure produced per cow on an annual basis. On average, dairy manure produces about 0.023 m^3 of methane per kilogram of manure ($0.37'^3$ per lb) on a wet basis (Aguirre-Villegas, *et al.,* 2016), which translates to $15{,}126'^3$ of methane per cow per year, or approximately 6 lbs of CO_2-equivalent per year.

Most methane associated with manure is emitted during storage (Fangueiro, *et al.,* 2008). Maine farmers must store manure over the winter months because they are prohibited from spreading manure at that time (*Winter Spreading of Manure,* 2003). There are a number of manure management practices that can be employed to mitigate GHG emissions. These include placing impermeable covers on lagoons and liquid/slurry ponds; adding a solids separator to lagoon systems, which can reduce emissions by 19% or more (Aguirre-Villegas, *et al.,* 2016; Fangueiro, *et al.,* 2008); and adopting an anaerobic digester system (*e.g.,* a covered lagoon, complete mix, or plug flow system), which can reduce emissions by approximately 60% (Aguirre-Villegas, *et al.,* 2016; Amon, Kryvoruchko, Amon, *et al.,* 2006; Amon, Kryvoruchko, Moitzi, *et al.,* 2006). Farmers who install an anaerobic digester on their livestock operations can use manure to produce a biogas that can be burned to generate electricity. Digesters can also reduce greenhouse gas emissions from ma-

[33] J. Jemison, personal communication, Spring 2020.

nure storage and handling. The size of the digester will vary by the area being managed and can range from farm- to community-scale. For example, Summit Energy announced in May 2019 that they will construct a $20 million digester in Clinton, Maine, that will utilize waste from five dairy farms that make up 17% of the state's dairy production, and the company claims this will generate about 125,000 MMBtu of gas per year (Summit Utilities Inc., 2019).

To our knowledge, only one Maine dairy farm currently utilizes as anaerobic digester for manure management, the Fogler Dairy Farm in Exeter (*Stonyvale Farm (Fogler Farm) Anaeorobic Digester System,* n.d.). Other mitigation systems have varying applicability in Maine, depending on the size of the herd, which has implications for installment costs, and on the challenges posed by Maine's cold climate (ICF International, 2013). For example, freezing temperatures can impair the functioning of solids separators or inhibit the production of methane in digesters.

Manure Amendments

Manure used as a soil amendment can act as a fertilizer and can also improve the physical qualities of the soil including tilth, water infiltration and retention, and soil porosity (Risse, *et al.,* 2006). Most of these physical improvements are linked to an increase in soil organic matter. The addition of manure to soil can increase carbon sequestration (Koga & Tsuji, 2009), but it also increases nitrous oxide emissions (a potent greenhouse gas), especially when it is injected into soils rather than broadcast (Adair, *et al.,* 2019; Dittmer, 2018; Duncan, *et al.,* 2017). Increased carbon sequestration due to manure application may be offset by increased nitrous oxide emissions, at least on a global aggregate scale (Zhou, *et al.,* 2017). Thus, the environmental benefits of manure as a soil amendment may not include a reduction in greenhouse gas emissions. Nonetheless, the potential for manure amendment to reduce dependency on chemical fertilizers, use of a byproduct of animal production that would otherwise be considered waste, and increase climate resilience through improvements to soil health are important benefits from this practice that warrant consideration.

Manure amendment can help supply crop nutrient demand, but its nutrient composition varies (Brown, 2015; Chastain & Camberato, 2003). The average proportion of nitrogen-phosphorus-potassium in dairy manure is 11, 7, and 9 lbs per ton on a dry matter basis (Wilson, 2020). In general, plants require much more nitrogen than either phosphorus or potassium, and so applying manure to meet plant nitrogen needs will oversupply phosphorous and sometimes potassium. Further, most nitrogen in manure is stored in organic forms that are not plant-available and must be converted to inorganic forms through microbial processes influenced by the (carbon:nitrogen) ratio of the manure. The resulting variable rate of nutrient release makes timing manure application to coincide with plant fertility needs a challenge. The composition of the manure, nutritional demands of the crop, and the nutrient content and cropping history of the soil are all important considerations in determining amendment rates (Beegle, 2017; Koehler, 2020). Overapplication of fertility can result in negative consequences for water (Wilson, 2020) and air quality (Duncan, *et al.,* 2017).

Manure application methods vary depending on the liquid content of the manure. Both solid and liquid manure can be broadcast onto the surface of a field (and may be incorporated), while liquid manure can be injected (Rausch & Tyson, 2019; University of Minnesota Extension, 2018). Broadcasting solid or semi-solid manure with a spreader is perhaps the oldest and simplest method of application. Liquid manure is applied using liquid manure tankers pulled behind a tractor or mounted on a truck. Liquid manure can also be broadcast using irrigation equipment, either by sprinkler irrigation or by a draghose, tractor-mounted irrigation system (Rausch & Tyson, 2019). A drawback to the broadcasting method is the potential loss of inorganic and plant-available nitrogen to volatilization. This loss can be mitigated by incorporating the manure into the soil. Manure can be incorporated immediately upon broadcast or within a few days; the more quickly it is incorporated, the less ammonia is released to the atmosphere.

The injection method for liquid manure was developed to reduce odors and other issues related to the release of ammonia following the broadcasting of manure. It is also compatible with no-till systems. There are three injection methods: knife injection, in which vertical blades create 6–8″ vertical grooves that collect manure; sweep injection, which places a broad, horizontal band of manure underneath the surface soil; and disk or coulter injection, which uses a rolling disk or a coulter to create a vertical groove that collects manure (University of Minnesota Extension, 2018). Injection of manure greatly reduces ammonia volatilization, in some cases by nearly 100%, but it can increase nitrous oxide emissions by up to 152% (Dittmer, 2018; Zhou, *et al.,* 2017) and additionally result in increased nitrous oxide fluxes during winter freeze-thaw events (Adair, *et al.,* 2019).

Three factors that influence the cost of manure management are loading, transporting, and application. Each may require specialized equipment and have its own constraints. For example, loading is constrained to time periods when animals are not present (except in the case of an external storage structure). Transportation costs are influenced by the distance traveled, hauling capacity, and travel speed. Application is constrained by soil and plant conditions and requires specialized equipment (University of Minnesota Extension, 2018).

Manure may be stored, transported, and applied in three forms: solid, liquid and slurry. Solid manure is cheaper to transport due to its lower water content, and therefore can be transported farther. Liquid and slurry manure have the lowest loading costs, but they have high transport costs. Liquid manure, despite its high transport cost, is the cheapest to apply, especially when existing irrigation equipment is modified to broadcast manure (Massey & Payne, 2019). In general, manure is expensive to transport, and especially when it has a high liquid content; thus there are important economic tradeoffs between type of manure and hauling distance (Harrigan, 2001, 2011; Risse, *et al.,* 2006). A study of manure application in New York suggested that on average, farms were able to apply just under 240,000 gallons of liquid manure in a 10 hour day to fields that were on average 3.5 miles away. On average, about 15,000 gallons of manure were spread per application hour—approximately the amount required to supply one acre of corn with its total nitrogen needs for the growing season, if the manure is incorporated. On average, the estimated total annual cost of manure application was $105,000, or about $134 per cow (Howland & Karszes, 2012). Because it requires specialized equipment and more time to apply, injection is somewhat costlier than broadcasting (Hanchar, 2014), though one study indicated it only increased the cost by about 6% compared to broadcast application plus incorporation (Hadrich, *et al.,* 2010).

Crop and grassland conservation

Marginal cropland and pasture is often not profitable to farm in many years. As such, some farmers voluntarily retire cropland utilizing rental payments or easements. For example, the national Conservation Reserve Program (CRP) provides a yearly rental payment if farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality (Farm Service Agency, 2019). Contracts for land enrolled in the CRP are typically 10–15 years in length. The long-term goal of the program is to reestablish valuable land cover to help improve water quality, prevent soil erosion, and enhance wildlife habitat. Changes in vegetation and reduced soil disturbance are also likely to increase carbon sequestration and/or reduce GHG emissions as land is taken out of production.

According to the USDA, there were 7,744 acres in Maine enrolled in the Conservation Reserve Program as of September 30, 2017 (Farm Service Agency, 2017). These lands received a mean rental payment of $38/acre/yr for cropland and $18/acre/yr for grassland (Farm Service Agency, 2018). These values are relatively low compared to other parts of the US, indicating that there are limited opportunity costs of setting aside marginal land in Maine.

Additionally, the 2017 USDA Census of Agriculture reported that 484 farms in Maine had a conservation easement totaling 36,274 acres (*2017 Census of Agriculture,* 2019).

Riparian Buffer

Riparian buffers are vegetated areas adjacent to streams that differ from their surrounding land practices (*i.e.,* agriculture or forest land). In agricultural lands this usually involves planting trees, shrubs, and grasses 35′ to 100′ away from the stream boundary. Most literature suggests a three-stage approach to planting buffers (Dybala, *et al.,* 2019). The first zone closest to the stream should consist of large woody trees and shrubs that have traditionally coevolved with streams to withstand flooding. This zone provides aquatic shade, streambank stability, and dead wood and leaf litter nutrients for the stream. Zone 2 filters runoff and absorbs water borne pathogens/nutrients. It has similar vegetation as Zone 1 as it is mostly trees and shrubs. This zone can have larger trees with smaller trees and shrubs beneath. This zone can also be used for commercial harvest of non-traditional agriculture and commercial tree species like Christmas trees, nut crops, shade loving wildflowers, ginseng, red oak, and sugar maple. Zone 3 filters water and slows down runoff. This zone should consist of tall grasses and is the last zone adjacent to working cropland and pastureland.

Riparian buffers in agricultural land have large potential benefits for landowners and downstream communities. Riparian zones have a relatively large carbon sequestration potential that can also offset emissions from traditional agricultural practices. Furthermore, they filter nutrients and collect sediments, which can improve water quality (Zhang, *et al.,* 2010). Riparian buffers can also provide local habitat and biodiversity benefits.

Key costs to implement riparian buffers include planting, maintenance, and opportunity costs. Agricultural land directly adjacent to waterways is often less productive then the landowner's average farmland so the opportunity cost of retiring crop land is typically lower in buffer zones relative to the most productive areas of the farm (Daigneault, *et al.,* 2017). There is estimated to be approximately 21,000 acres of potential riparian buffer zone land in Maine agriculture (Cook-Patton, *et al.,* 2020). The costs of implementing riparian buffers in Maine are listed in *Table 27.*

Table 27. Detailed riparian buffer costs

Item	Min	Med	Max
Establishment Costs ($/ac) *First 2/3 Stages of Trees and Shrubs, tree dominated buffer. Assumed 80% trees, 20% shrubs.*			
Tree Saplings	$386.49	$463.78	$541.08
Shrub Saplings	$91.67	$110.00	$128.33
Tree Labor + Mats + Shelters	$297.30	$356.76	$416.22
Shrub Labor + Mats + Shelters	$61.94	$74.32	$86.71
Tree shelter + mats	$594.59	$713.51	$832.43
Shrub mats	$61.94	$74.32	$86.71
Shipping and Handling for tree mats and shelters	$49.55	$59.46	$69.37
Shipping and Handling for Shrub mats	$4.95	$5.95	$6.94
Total Stage 1 and 2 Establishment Cost	$1,548.42	$1,858.11	$2,167.79
3rd stage, grasses.			
Planting	$5.23	$42.23	$79.24
Seeds	$52.30	$204.44	$356.58
Site Preparation	$9.41	$36.40	$63.39
Fertilizer/Lime	$15.69	$47.46	$79.24
Mowing or Herbicide	$5.23	$50.16	$95.09
Total Stage 3 Establishment Cost	$87.86	$380.70	$673.53
Total Establishment Cost			
Stage 1, 2, and 3 Establishment Cost	$1,636.28	$2,238.81	$2,841.33
Maintenance Costs ($/ac)			
Replanting (assuming 80% survival rate)	$58.57	$81.58	$104.60
Stage 1 & 2 Mowing and/or Herbicide	$39.64	$79.28	$118.92
Stage 3 Mowing	$6.28	$18.83	$31.38
Stage 1, 2, and 3 Maintenance Cost	$104.49	$179.69	$254.89
Total Riparian Buffer Costs and Benefits			
Total Riparian Buffer Cost ($/ac)	$1,740.77	$2,418.50	$3,096.22
Annualized Costs over 20 years ($/ac/yr)*	$139.68	$194.07	$248.45
Annual Average Carbon Sequestration (tCO_2e/ac/yr)	1.23	1.69	2.13
Break-Even Carbon Price ($/$tCO_2e$)	$114	$115	$117

*Costs annualized over 20 years using a discount rate of 5%.

Table 28. Range of agricultural NCS GHG mitigation factors from literature (tCO_2e/ac/yr)*

NCS Practice	Min	Median*	Max
No-till from Intensive	0.01	0.46	0.89
No-till from Reduced	0.00	0.36	0.70
Reduced tillage	0.00	0.10	0.19
Cover Crops	−0.15	0.18	1.06
Biochar	1.10	1.60	2.82

Table 28. Range of agricultural NCS GHG mitigation factors from literature ($tCO_2e/ac/yr$) *—Continued

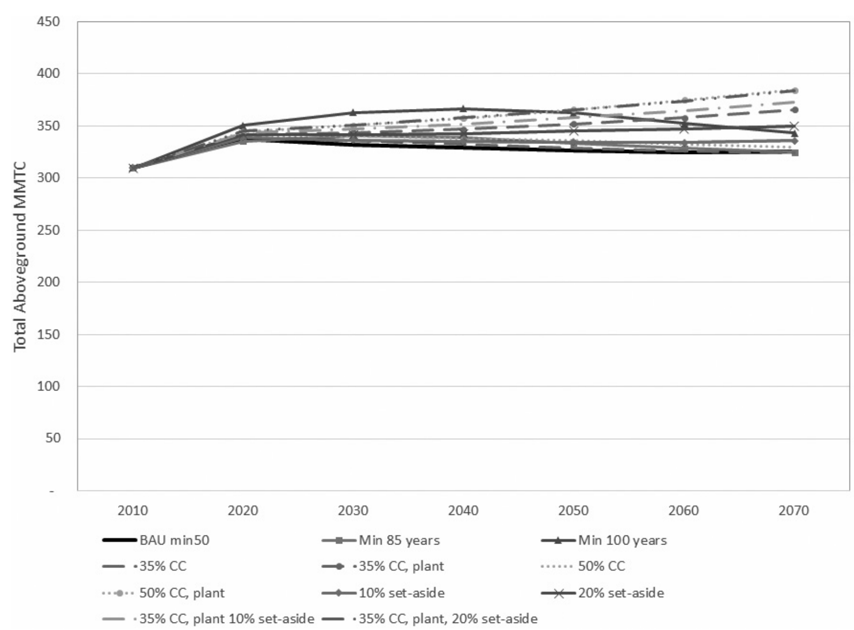
NCS Practice	Min	Median *	Max
Amend w/Manure	−0.13	0.16	0.60
Convert to Perennial	0.65	2.31	3.47
Riparian Buffer	1.74	2.20	2.64
Dairy Manure Management	1.94	4.73	6.68

* Only median (medium) values were used for this analysis.

Appendix C. Statewide extrapolation of forest carbon estimates

To incorporate the potential additive effects of the current forest carbon stock and future forest growth in areas outside our project study area we used US Forest Service Inventory and Analysis plot data to estimate (1) live forest carbon ca. 2010, and (2) average 10 year change in forest carbon. The live forest carbon ca. 2010 was 177 MMTC and the average 10 year change was 23.6 MMTC/yr based on all ~1,700 plots outside our project study area. We added these values to the simulated predictions for our study area to derive a statewide estimate of total aboveground forest carbon 2010–2070 (*Figure 20*). It is important to note that using this process, implicitly assumes no change in forest management on commercial forestlands outside our project study area, nor accounts for the potential effects of climate change on forest productivity.

Figure 20.



Total forest carbon stock (MMTC) for all of Maine, including 7.5 million acres outside of the Landis model study area, modeled from 2010 to 2070.

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Inside cover: Howland Research Forest, Dave Hollinger, USDA Forest Service.

Partners in this United States Climate Alliance project are the State of Maine Governor's Office of Policy Innovation and the Future; the U.S. Department of Agriculture Climate Hub; the Northern Institute of Applied Climate Science; The Nature Conservancy in Maine; Maine Farmland Trust; Maine Climate Table; American Farmland Trust; and Wolfe's Neck Center of Agriculture & the Environment.

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SUBMITTED STATEMENT BY HON. CHERI BUSTOS, A REPRESENTATIVE IN CONGRESS FROM ILLINOIS

[*https://bustos.house.gov/wp-content/uploads/2019/08/Rural-Green-Partnership-1.pdf*]

[August 6, 2019]

Combatting Climate Change: An Opportunity for Rural America *

From agriculture to outdoor recreation, rural economies across the United States depend on a stable climate and consistent weather patterns. Combatting climate change is both a necessity in rural America and also an opportunity to reverse the economic headwinds which are widening the gap between rural communities and their urban counterparts. The unique opportunities for rural America stem from its vast land resources: 71% of U.S. territory (excluding Alaska) is privately-owned rural land[1] where carbon can be sequestered in soils, vegetation and forests; where biobased and renewable products—fuels, plastics and other renewable materials—can be grown and produced; where captured carbon dioxide can be stored deep underground or utilized in other ways; where wind farms and solar fields can be built on a large scale; and where a plethora of technical training schools like community colleges, tribal colleges, land-grant universities, union-registered apprenticeship programs and technical training colleges can prepare workforces that will grow rural economies while addressing climate change.

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* **Editor's note:** there is an accompanying news release (*https://bustos.house.gov/bustos-announces-rural-green-partnership-to-combat-climate-change-and-spur-economic-growth/*) and video (*https://www.dropbox.com/s/t9tmc1votajbnrj/Rural%20Green_1.mp4?dl=0*) that have been retained in Committee file.

[1] USDA, *NRCS National Resources Inventory Summary Report,* September, 2018, p. 2–1.

Goal

To capitalize on these opportunities, we propose a Rural Green Partnership—a set of policies that work with Federal, local and state governments, local businesses, unions, producers, NGOs and other stakeholders to lower greenhouse gas (GHG) emissions in every economic sector of rural America and spur economic growth.

Rural Green Partnership Framework

Five principles will guide Rural Green Partnership climate policies:

(1) Expand and improve conservation programs that are respected and well known to farmers, and explore new markets for ecosystem services that establish economic incentives to adopt conservation practices that increase resilience, sequester more carbon in soil, crops and forests, prevent erosion and can be scaled up quickly and efficiently.

(2) Invest in rural infrastructure that will form the foundation of new green economic growth: including faster broadband speeds so farmers can take advantage of GPS for precision agriculture, an expanded grid, green infrastructure and carbon dioxide pipelines to transport captured carbon to locations where it can be stored or utilized.

(3) Leverage zero and low interest loans, tax credits and grants to incentivize new clean energy development and innovations that drive down GHG emissions.

(4) Increase basic and applied research funding for farming practices and sustainable land uses, clean energy technologies, energy storage, energy efficiency and carbon dioxide capture, storage and utilization as well as extension efforts and technical assistance to ensure that government research outcomes are transferred effectively to stakeholders.

(5) Foster green workforce development at union and registered apprenticeship programs, community colleges, tribal colleges, technical training centers and other colleges and universities across rural America.

Rural Green Partnership Policies

The following sections outline policies to reduce GHG and increase clean energy opportunities in rural America across the five economic sectors that comprise total U.S. emissions:[2] * agriculture, electricity, transportation, commercial & residential and industry. Policies will also increase carbon dioxide removals via land use and forestry practices.

Agriculture, Land Use and Forestry

Agriculture contributes 9% of U.S. GHG emissions[2]—the least of all economic sectors. In the last 30 years, however, land use and forestry (LUF) activities in the United States have removed greater amounts of carbon dioxide from the atmosphere than they have generated. In 2017, for example, LUF offset nearly 11% of total U.S. GHG emissions.[3] Moreover, the largest and most cost-effective potential sink for drawing down significant carbon dioxide emissions still remains the nation's soils and forests—rural America's greatest asset. Rural Green Partnership policies for agriculture will therefore focus on increasing soil organic carbon through soil health strategies that help farmers and ranchers manage risk by increasing long-term resiliency and adaptation to proliferating extreme weather events. For forestry, Rural Green Partnership policies will rely on sustainable management, reforestation and uses of forest products. Specifically, the Rural Green Partnership will:

- Increase funding and number of acres available for Federal assistance to incentivize adoption and maintenance of proven, science-based, precision agriculture and conservation management farming practices that increase soil carbon, reduce runoff and optimize fertilizer inputs as part of systemic farm management. This work can be done through existing Natural Resources Conservation Service (NRCS), Farm Service Agency (FSA), other Federal programs or re-envisioned Federal assistance.
- Expand the number and availability of conservation technical experts capable of offering customized, one-on-one conservation advice to agricultural producers.

[2] Data on greenhouse gas emissions by sector from EPA: *https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions*.

* **Editor's note:** the footnote reference "2" should have been set as an endnote as it is used multiple times in this document.

[3] EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions*.

- Streamline the process to sign up for NRCS/FSA programs.
- Facilitate widespread data collection to aid hyper-localized management strategies that increase carbon sequestration and increase resilience for the various geographies in the U.S.
- Incentivize integrated crop/livestock operations to maximize the soil carbon sequestered in croplands.
- Expand grants, loans and tax incentives for farm and ranch operations that improve energy efficiency, energy generation and drive down GHG emissions through technologies like methane digestors.
- Increase applied agricultural R&D (research and development) for crop breeding, precision agriculture, soil health practices, extension yield trials, and other on-farm conservation research that mitigates risk and increases resilience.
- Guarantee broadband access for farms, homes and small businesses to ensure that data related to best management practices is readily available.
- Incentivize sustainable forestry practices that sequester carbon while creating new markets for biomass to heat and power homes and business.
- Expand sustainable forestry practices such as pre-commercial thinning, establishing forest stewardship plans and developing fire resilient Wildland Urban Interfaces that reduce the incidence and intensity of fires and CO_2 emissions, and further increase resources available for reforestation after catastrophic loss.

Electricity

The electricity sector comprises 28% of total U.S. annual GHG emissions. Despite this, 64% of U.S. electricity is generated from fossil fuels, while 19% comes from nuclear and 17% from renewables. Wind comprises just 7% of the total and solar a mere 1.6%. When accounting for GHG emissions, coal accounts for 27% of electrical production yet close to ⅔ of carbon dioxide emissions. Rural Green Partnership policies for the electricity sector anticipate a future dominated by clean and net-zero energy that also works to reduce GHG emissions from fossil fuel sources. Policies for this sector will:

- Support the immediate and widescale deployment of carbon capture, utilization and storage (CCUS) technologies on existing fossil fuel energy facilities to significantly reduce GHG emissions.
- Expand R&D for direct air capture (DAC) carbon dioxide technologies that can be deployed in rural America.
- Expand R&D to overcome barriers to wider adoption for intermittent renewables (including the integration of battery storage) in order to further drive down costs.
- Ensure the continued safety and operation of the existing nuclear fleet and the research, demonstration and deployment of advanced nuclear reactors.
- Extend and increase renewable (solar, wind and biogas) tax credits that enable rural businesses, including farms, to adopt cleaner technologies, reduce costs and raise income.
- Invest in and support community colleges, tribal colleges, technical schools, union and registered apprenticeship programs, colleges and universities that engage in workforce development programs for renewables and provide on-farm assistance for renewable deployment.
- Make available investment tools to municipalities, communities and extension services who form partnerships to build and deploy renewables locally.
- Modernize and expand the electrical grid to facilitate the greater utilization and deployment of renewable sources and keep costs low for consumers.
- Provide assistance to rural municipalities and cooperatives that are looking to bundle demand flexibility, energy efficiency and rate design to ensure economic viability and achieve GHG emissions.

Transportation

At 29% of total U.S. GHG emissions,[2] transportation is now the leading emitting sector. Light-duty vehicles account for 60% of emissions within transportation, while medium- and heavy-duty trucks account for 23% of the sector. To cut emissions and increase economic activity in rural America, the Rural Green Partnership focuses on the use of biofuels which have significantly lower lifecycle GHG emissions than gasoline and can save consumers money at the pump. For example, soybean biodiesel has a 57% reduction,[4] and corn ethanol has a 19–48% reduced lifecycle GHG emissions compared to gasoline, with estimated reductions of approximately 70% when specific conservation practices are implemented. Moreover, increasing consumption of biofuels would increase stability for farmers while boosting rural economies and providing a catalyst for continuous economic sustainability. Targeted biofuels policies would:

- Expand use of biofuels (including ethanol, biodiesel, advanced and other biofuels) that reduce GHG emissions by strengthening, expanding or optimizing existing fuel standards and/or creating new fuel standards (Renewable Fuel Standard, High-Octane Fuel Standard, Low-Carbon Fuel Standard).
- Limit the expansive use of small refinery waivers that undermine the Renewable Fuel Standard and increase GHG emissions.
- Extend biodiesel and second-generation biofuel producer tax credits.
- Incentivize land use practices, such as cover crops and no till farming, to sequester more carbon, improve soil health and further improve the lifecycle GHG benefits of biofuels.
- Create incentives for automobile manufacturers to produce vehicles designed and warranted for higher blends of ethanol, such as E30–E85 to help meet new efficiency and GHG emissions reduction standards.
- Incentivize states to support fueling stations that install E15 to E85 pumps.

In addition, transportation policies should expand opportunities for electric vehicles (EV) and hybrid electric vehicles (HEV) in rural America. Because rural communities often generate significant business by providing service to interstate highway travelers (hotels, restaurants, gas stations), programs should not only focus on increasing U.S. EV sales (in 2017, these were still only a little over 1% of total car sales), but also should assist rural businesses in installing EV charging infrastructure to facilitate interstate EV travel. To facilitate EV/HEV sales and infrastructure development, policies will:

- Make Federal funds available (low interest loans or grants) to increase EV charging stations across rural America.
- Maintain and expand the EV tax credit for lower income purchasers by making it available at the point of purchase.
- Make investment tax credits available for EV/HEV auto manufacturers and businesses that manufacture EV/HEV parts in rural America.
- Provide grant funds for community colleges, technical schools, union and registered apprenticeship programs, colleges and universities that engage in workforce development programs for EV technicians and electrical workers.

Finally, public transit is an important way to increase commerce and drive down GHG emissions in rural America. Rural Green Partnership policies will:

- Invest in high speed rail service to link rural communities with urban job centers and markets.
- Support rural transit services that facilitate access to jobs, schools and services across rural America.

Commercial & Residential

Approximately 11% of total U.S. GHG emissions come from homes and commercial businesses (not including industry). Rural households typically face a higher energy burden than their urban and suburban counterparts. Low-income rural households are especially hard-hit, with an energy burden triple that of higher income families.[5] Rural housing stock is typically older and less energy efficient. On average, energy efficiency upgrades can reduce energy burden by up to 25% in rural communities.[6] Rural Green Partnership priorities for this sector would:

- Expand energy efficiency and renewable energy programs for homes and buildings (new programs and retrofits).
- Help rural energy co-operatives expand innovative programs to increase beneficial electrification programs in rural America.

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[4] EPA Office of Transportation and Air Quality, July, 2016. *https://www.epa.gov/sites/production/files/2016-07/documents/select-ghg-results-table-v1.pdf.*

[5] Ross, *et al.,* 2018. *The High Cost of Energy in Rural America: Household Energy Burdens and Opportunities for Energy Efficiency* (Prepared by ACEE) *https://aceee.org/sites/default/files/publications/researchreports/u1806.pdf.*

[6] *Ibid.*

- Increase R&D for supporting more distributed energy systems and integrated energy efficiency measures.
- Incentivize methane emission capture standards from landfills and the efficient recycling and use of food waste.
- Provide loans and grants for energy efficiency at wastewater treatment plants throughout rural America.

Industry

Industrial processes produce goods and raw materials that are essential to our economy yet contribute to roughly 22% of annual GHG emissions. Many industrial plants that manufacture chemicals, vehicles and equipment, food products, pulp and paper, iron and steel, petroleum and biofuels are located throughout rural America and are the economic backbone of many of these communities. This is the only economic sector expected to significantly increase GHG emissions in the next decade, so creative policy solutions will be needed to help rural manufacturers cut GHGs while supporting economic growth. The Rural Green Partnership will:

- Implement zero and low interest loans for CCUS infrastructure projects that transport carbon dioxide from industrial sources to locations in rural areas where it can be used or permanently stored in geologic sinks.
- Facilitate permitting for CCUS infrastructure and storage reservoir assessments.
- Increase R&D funding and prizes for innovative, scalable uses of carbon dioxide that will lead to new businesses in rural America.
- Offer investment tax credits for industries that use carbon dioxide and reduce emissions.
- Introduce tax incentives to encourage industries to switch from higher CO_2 emission fuel sources to zero or low CO_2 emission fuel sources.
- Establish tax incentives, loans and grants for the development and use of biobased and sustainable forestry products that lower GHG emissions.
- Provide a federally-backed match to all Small Business Innovation Research (SBIR) recipients that receive funding for the production of sustainably sourced biobased or recycled products.
- Provide tax incentives, grants and technical assistance for rural business that invest in industrial energy efficiency.

Conclusion

Rural America continues to acutely experience the negative effects of climate change. This year alone, farmers across the heartland have faced record flooding and weather events that jeopardize both personal health and economic livelihoods. At the same time, rural communities could contribute significantly to clean energy utilization and more sustainable land use practices. The Rural Green Partnership focuses on economic growth through mitigation of and adaptability to the effects of climate change. Importantly, it gives rural America a front and center seat at the climate change table while respecting the unique needs and interests of the 19% of the population that call rural America home. Significantly lowering future GHG emissions is achievable, and rural America is primed to lead the way.

SUBMITTED LETTER BY HON. KIM SCHRIER, A REPRESENTATIVE IN CONGRESS FROM WASHINGTON

ROBERT BONNIE,
Deputy Chief of Staff for Policy and Senior Advisor on Climate,
United States Department of Agriculture,
Washington, D.C.

Dear Mr. Bonnie:

Congratulations on your recent reappointment to the U.S. Department of Agriculture. I am writing to invite you to visit Washington's 8th Congressional District for a roundtable meeting with farmers, growers, and local stakeholders to discuss climate policy and agriculture with a specific focus on ensuring Federal policy supports the productivity of lands and the economic resiliency of our rural communities.

Recent town halls and time spent with farmers and growers in my district have shown me they share the urgent need for action on climate change. They are the leading stewards of the land and are on the frontlines facing the impacts of climate change. Droughts, fires, and floods are affecting their livelihoods. Farmers are also driving much of the on-the-ground innovation and leading efforts to embrace and share climate smart practices. We must recognize, support, and bolster contributions from farmers and ensure they have a place at the table in Federal policy. That includes open and honest discussion on any immediate and downstream impacts Federal policy may have on agriculture stakeholders.

In Washington State, we have a proud farming heritage that goes back multiple generations. Washington's climate, rich soils, and large-scale irrigation make it one of the most productive growing regions in the world, enabling farmers to produce over 300 different crops each year. We are the nation's top producing state for apples, pears, and cherries—many of which are grown in Washington's 8th Congressional District. Our growers produce top-quality fruits that are in high demand around the globe, with roughly ⅓ of our crops exported each year.

As the only Member from the Pacific Northwest on the House Agriculture Committee, I am honored to be a voice for the farmers and growers in the region. I look forward to working together to ensure the values and contributions of our agriculture community are recognized and ensu[r]ing their voices are heard in ongoing policy discussions on climate change and agriculture.

Sincerely,

Hon. KIM SCHRIER,
Member of Congress.

SUBMITTED LETTERS BY HON. JIMMY PANETTA, A REPRESENTATIVE IN CONGRESS FROM CALIFORNIA

LETTER 1

September 22, 2020

Hon. NANCY PELOSI,
Speaker,
U.S. House of Representatives,
Washington, D.C.;

Hon. MITCH MCCONNELL,
Majority Leader,
U.S. Senate,
Washington, D.C.;

Hon. KEVIN MCCARTHY,
Minority Leader,
U.S. House of Representatives,
Washington, D.C.;

Hon. CHARLES SCHUMER,
Minority Leader,
U.S. Senate,
Washington, D.C.

Dear Majority Leader McConnell, Minority Leader Schumer, Speaker Pelosi, and Minority Leader McCarthy:

We, the undersigned organizations and members of the Forest Climate Working Group, are writing today to express our strong support for the bipartisan REPLANT Act (S. 4357 and H.R. 7843), which would enable the U.S. Forest Service to address the millions of acres of National Forests in immediate need of reforestation and keep up with future demands.

The Forest Climate Working Group (FCWG) is our country's only forest-climate coalition that represents every aspect of U.S. forests from government agencies, landowners, forest products, outdoor recreation, conservation and wildlife groups, academics, and carbon finance experts. Together, we represent diverse and bipartisan stakeholders that are committed to advancing scientifically informed forest policy that incorporates forests, forest products and natural working lands solutions as a key part of climate change mitigation. Reforesting National Forests through the REPLANT Act will yield significant climate mitigation benefits by sequestering carbon in growing trees, while creating jobs in rural communities and protecting America's water supplies.

America's 193 million acres of National Forests are at a crossroads. They are a critical part of our daily lives, providing clean drinking water, supporting jobs and the economy, naturally capturing carbon from the atmosphere, and supporting our outdoor heritage. National Forests are the single most important source of water in the United States, providing water to 66 million people in 3,400 communities, including cities.

Yet, our National Forests are facing new challenges that we need to address. These public lands are being rapidly and intensely damaged by extreme wildfire, drought, and pests supercharged by a changing climate. We must speed up the process of reforesting millions of acres of degraded forestland to restore its ability to collect and filter drinking water, naturally capture carbon dioxide, generate wood and related forest jobs, and provide for wildlife and recreation. In some National Forests this is a "now or never" chance to reforest burned over areas that are not reforesting on their own. Without action, we risk losing these forests forever.

The REPLANT Act will address this crisis by modernizing the Reforestation Trust Fund (16 U.S.C. § 1606a) which was established by Congress in 1980 to reforest our National Forests. The Reforestation Trust Fund is funded by reliable, plentiful tariffs on designated wood products. There is just one catch: due to an outdated $30 million cap, most of these tariff revenues are unavailable for addressing ever-increasing critical reforestation needs.

This bipartisan legislation, introduced by Senators Udall, Portman, and Stabenow and Representatives Panetta, Simpson, Schrier, and LaMalfa, will remove this outdated cap, enabling the Forest Service to address almost 8 million of acres of National Forests in need of reforestation,[1] which includes 1.3 million acres of forests in need of immediate treatment. This 1.3 million acre priority list is growing by approximately 200,000 acres each year because funding has not kept up with even the most urgent reforestation needs. Through the REPLANT Act, the Forest Service will be able to treat these priority lands and plant or naturally regenerate more than 1.2 billion trees over the next decade alone, creating nearly 49,000 jobs.

Now more than ever, America is turning to our public lands for physical, spiritual, economic and environmental renewal. By recently passing the Great American Outdoors Act, Congress made significant, strategic investments in repairing these lands. The REPLANT Act builds on this momentum by ensuring we can reforest millions of acres of National Forests and enjoy their benefits for generations. We urge you to prioritize and pass this vital legislation.

Sincerely,

1. American Forest Foundation
2. American Forests
3. Binational Softwood Lumber Council
4. California Forestry Association
5. EFM
6. Forest Landowners Association
7. Forest Stewards Guild
8. Green Diamond Resource Company
9. Hancock Natural Resource Group
10. Land Trust Alliance
11. Michigan State University, Department of Forestry
12. Molpus Woodlands Group
13. National Alliance of Forest Owners
14. National Association of Conservation Districts
15. National Association of Forest Service Retirees
16. National Association of State Foresters
17. National Association of University Forest Resources Programs
18. National Wildlife Federation
19. New England Forestry Foundation
20. Open Space Institute
21. Pinchot Institute for Conservation
22. Port Blakely Timber
23. PotlatchDeltic
24. Rayonier
25. Society of American Foresters
26. Sonen Capital
27. Spatial Informatics Group—Natural Assets Laboratory (SIG–NAL)
28. Sustainable Forestry and Land Retention Network
29. Sustainable Forestry Initiative
30. The Climate Trust
31. The Forestland Group
32. The Nature Conservancy
33. The Trust for Public Land
34. The Westervelt Company
35. University of Kentucky, Department of Forestry
36. Weyerhaeuser
37. WoodWorks—Wood Products Council

LETTER 2

September 30, 2020

Hon. NANCY PELOSI,
Speaker,
U.S. House of Representatives,
Washington, D.C.;

Hon. KEVIN MCCARTHY,
Minority Leader,
U.S. House of Representatives,
Washington, D.C.

Dear Speaker Pelosi and Minority Leader McCarthy:

We write to express strong support for the REPLANT Act (H.R. 7883), a bill that would enable the U.S. Forest Service to address the millions of acres of public lands in urgent need of reforestation and to keep up with future demands. This bipartisan legislation, introduced by Representatives Panetta, Simpson, Schrier and LaMalfa and Senators Udall, Portman and Stabenow will lift the cap placed on the Reforestation Trust Fund, enabling the Forest Service to replant and regenerate 1.2 billion trees every decade across America's National Forests. This is projected to create

[1] USFS field staff report 1.378 million acres need reforestation as of 2019. Geospatial analyses suggest even greater need for reforestation than the data reported by USFS field staff. The USFS Rapid Assessment of Vegetation Condition after Wildfire (RAVG) dataset suggests that potential acreage could be as much as three times greater (*https://data.fs.usda.gov/geodata/rastergateway/ravg/index.php*). A recent estimate by The Nature Conservancy suggests total reforestation need on USFS land could reach 7.7 million acres (Fargione, *et al.,* 2018 and updated analysis in press Cook-Patton, *et al.,* 2020).

nearly 49,000 forestry-related jobs, inject economic vitality into gateway communities, and support the broader outdoor recreation economy.

Prior to the pandemic, the outdoor recreation economy was generating $778 billion in gross economic output annually and was growing faster than the GDP. The sector provides millions of green, sustainable jobs that cannot be outsourced or exported. Many of these jobs are located in rural towns that look to the outdoor recreation economy as a way to strengthen their communities. For this industry to keep growing, the nation must have access to healthy public lands. This is truer than ever, due to Americans being eager to experience the outdoors as they look for ways to safely manage through the pandemic. The REPLANT Act's investment in our industry's core infrastructure—public lands and waters—will allow our gateway towns to get back to what they do best: support Main Street entrepreneurs, put people back to work, and allow Americans to benefit from time spent outside.

The REPLANT Act will also deliver important long-term value. Over the long haul, the outdoor recreation sector and our gateway communities depend on a healthy climate and healthy places to play in order to remain viable. Right now, America's 193 million acres of National Forests are being damaged much more rapidly and intensely by extreme wildfire, drought, and pests supercharged by a changing climate. The REPLANT Act will address this crisis this by modernizing the Reforestation Trust Fund and provide it with the needed funds to catch up and keep up with growing reforestation needs.

The Forest Service already has prioritized more than 1.3 million acres of land for reforestation to repair disturbances such as severe wildfire. This waiting list is growing by approximately 200,000 acres each year because funding has not kept up with rising reforestation needs. Moreover, given the increasing intensity of wildfires and their severe impact on forest soils and landscapes, more and more of these impacted forests will be lost forever unless we invest in Reforestation Trust Fund resources to bring them back.

The resulting severe impacts on the outdoor recreation sector would frustrate economic and job recovery, unduly limit public recreation use of public lands, and hamper future economic growth. In contrast, the REPLANT Act will bolster outdoor recreation and economic growth across the country; add 1.2 billion trees on 4.1 million acres of our National Forests each decade; create thousands of green jobs, primarily in rural communities hardest hit by COVID–19; capture millions of metric tons of carbon dioxide; and protect drinking water supplies for millions of Americans.

At this challenging moment in our history, America is turning to our public lands for physical, spiritual, economic, and environmental renewal. The Great American Outdoors Act, which was recently signed into law, shows that Congress is ready to make strategic investments in repairing our public lands—investments that will put Americans back to work and better meet the needs of the public. To continue building on this momentum, we need the REPLANT Act. We strongly urge you to advance the REPLANT Act to secure the lasting recreation and economic value of our National Forests for generations to come.

Sincerely,

REI Co-op
Patagonia
Burton
Columbia
The North Face
Big Agnes
Petzl
Renee Thompson Designs
Ruffwear
Salewa
Western Spirit Cycling
Rooted, Grounded, Renewed
Alpine Shop, Ltd.
Outdoor Industry Association
California Outdoor Recreation Partnership
American Horse Council
International Snowmobile Manufacturers Association
Arcteryx
Keen
Hydro Flask
Klean Kanteen
Jones Snowboards
NEMO Equipment
L.L Bean
Peak Designs
Mountain Shades/Optic Nerve
Tahoe Mountain Sports
Yakima Products
22 Designs
The Conservation Alliance
Outdoor Recreation Roundtable
American Sportfishing Association
Specialty Equipment Market Association
National Association of RV Parks and Campgrounds

cc: House Agriculture Committee *Chairman* COLLIN C. PETERSON and *Ranking Member* K. MICHAEL CONAWAY.

LETTER 3

November 10, 2020

Hon. NANCY PELOSI,
Speaker,

Hon. MITCH MCCONNELL,
Majority Leader,

U.S. House of Representatives,
Washington, D.C.;

Hon. KEVIN MCCARTHY,
Minority Leader,
U.S. House of Representatives,
Washington, D.C.;

U.S. Senate,
Washington, D.C.;

Hon. CHARLES SCHUMER,
Minority Leader,
U.S. Senate,
Washington, D.C.

Dear Speaker Pelosi, Minority Leader McCarthy, Majority Leader McConnell, and Minority Leader Schumer:

Our businesses, which collectively employ nearly 70,000 people, generate more than $26B in revenue annually, and represent a spectrum of industries and perspectives, share a common commitment to climate solutions that will foster resilience for our communities, our national economy, and our planet. We recognize the particularly vital role that forests play as a natural asset that efficiently stores and manages carbon. In that context, we are writing to urge action before the end of this Congress on the bipartisan **REPLANT Act** (H.R. 7843/S. 4357), a bill that would address the critical reforestation backlog in America's National Forests and **catalyze 49,000 jobs** over the next decade.

American businesses recognize the existential threat posed by climate change and are helping to lead the way to a better future with dynamic, market-based changes to reduce our carbon footprint and invest in in natural carbon solutions. Actions by the business community, while critical, must be complemented by Congressionally-led public policy actions. Enhancing America's forest resources is a necessary component of that public response. America's forests and forest products already capture and store 15 percent of our nation's carbon emissions each year, with the potential for substantially increased sequestration through targeted reforestation efforts.

The REPLANT Act will dramatically increase the pace of reforestation on America's 193 million acres of National Forests—providing the resources to regenerate **1.2 billion trees** per decade and **remove almost 758 million metric tons of carbon dioxide equivalent** over their lifetimes.

The Forest Service has identified more than 1.3 million acres of National Forest awaiting reforestation due to disturbances such as severe wildfire. This waiting list is growing by approximately 200,000 acres each year as funding has not kept up with rising reforestation needs. Moreover, as severe wildfires and disease increase across the country, more and more forests will be lost forever without Reforestation Trust Fund resources to bring them back. The REPLANT Act will respond to accelerated forest losses by removing the 40 year old cap on the Reforestation Trust Fund providing essential funding, billions of trees and create and support approximately 49,000 jobs.

Beyond its positive climate impacts, the REPLANT Act will provide significant additional community benefits as well. Forests provide clean drinking water for more than 50 percent of all Americans. They clean our air and help reduce respiratory diseases such as asthma. They support fish and wildlife habitat, forest recreation opportunities, and the broader outdoor economy. The REPLANT Act is a win-win solution that addresses the full spectrum of these needs.

We strongly support the REPLANT Act and urge Congress to pass it this year.

Sincerely,

[Salesforce.com, inc.]

[Sazerac Company, Inc.]

[Recreational Equipment, Inc.] [Independent Stave Company, Inc.]

[Sierra Nevada Brewing Co.] [Robinson Stave Mill and East Bernstadt Cooperage]

cc: House Agriculture Committee *Chairman* COLLIN C. PETERSON and *Ranking Member* K. MICHAEL CONAWAY; Senate Agriculture Committee *Chairman* PAT ROBERTS and *Ranking Member* DEBBIE STABENOW.

LETTER 4

November 24, 2020

Hon. MITCH MCCONNELL,
Majority Leader,
U.S. Senate,
Washington, D.C.;

Hon. CHARLES SCHUMER,
Minority Leader,
U.S. Senate,
Washington, D.C.;

Hon. NANCY PELOSI,
Speaker,
U.S. House of Representatives,
Washington, D.C.;

Hon. KEVIN MCCARTHY,
Minority Leader,
U.S. House of Representatives,
Washington, D.C.

Dear Majority Leader McConnell, Speaker Pelosi, Democratic Leader Schumer, and Republican Leader McCarthy:

On behalf of the undersigned organizations, which together represent millions of hunters and anglers all across America, we would like to express our thanks for your important conservation achievements thus far in the 116th Congress, and to urge action before adjournment to pass the REPLANT Act (S. 4357 and H.R. 7843). This bipartisan legislation provides a critically needed response to the damage that wildfires and other disasters continue to inflict on our National Forests, the vital fish and wildlife habitats these lands host, and the local recreation economies they support.

Public lands, and specifically our nation's network of National Forests, are home to a truly remarkable array of game and nongame wildlife populations, and they provide irreplaceable hunting, fishing, and other public recreation access. These resources, however, have suffered from devastating forest losses from the increasing number and severity of wildfires and from the destructive impacts of severe storms, drought, disease, and insect infestation. Inadequate funding to address these losses has resulted in a backlog of unmet reforestation need in the National Forests; the U.S. Forest Service has identified more than 1.3 million acres that may never recover without replanting or regeneration assistance, and other estimates of the need are far higher, even as the backlog grows by some 200,000 acres annually. Lands at risk include forest and riparian habitats essential for key fish and wildlife populations, and just as essential for the future of outdoor recreation in a host of public land-dependent communities.

The REPLANT Act will reverse these unsustainable losses by removing the outdated funding cap on the Reforestation Trust Fund, which has remained fixed at just $30 million per year for the past 4 decades, despite exponentially growing needs throughout the National Forest System. Enactment will bring the resources to maintain the outdoor recreation value of these vital public lands and to eliminate the reforestation backlog in National Forests within 10 years. At the same time, it will create and support an estimated 49,000 reforestation jobs, establish an additional 1.2 billion trees per decade, and sequester an estimated 75 million metric tons of carbon per decade, with corresponding benefits to wildlife communities everywhere.

The REPLANT Act is a win-win opportunity to enhance stewardship and resource management of our National Forests, and to ensure their ongoing resource values for local communities and for America's sportsmen and women. With deep appreciation for your commitment to our nation's fish and wildlife, our public lands, and our outdoor economy, we strongly support this important legislation and ask that you do all you can to secure passage without delay.

Sincerely,

American Woodcock Society
Archery Trade Association
Boone & Crockett Club
California Waterfowl
Campfire Club of America
Congressional Sportsmen's Foundation
Conservation Force
Council to Advance Hunting and the Shooting Sports
Dallas Safari Club
Delta Waterfowl
Houston Safari Club
Izaak Walton League of America
Masters of Foxhounds Association
Mule Deer Foundation National Association of Forest Service Retirees
National Deer Association
National Shooting Sports Foundation
National Wild Turkey Federation
National Wildlife Federation
North American Grouse Partnership
Orion: The Hunter's Institute
Pheasants Forever
Pope and Young Club
Public Lands Foundation
Quail Forever
Ruffed Grouse Society
Texas Wildlife Association
Theodore Roosevelt Conservation Partnership
Whitetails Unlimited
Wild Sheep Foundation
Wildlife Forever
Wildlife Management Institute
Wildlife Mississippi

SUBMITTED QUESTIONS

Response from Jim Cantore, Senior Meteorologist, The Weather Channel, Atlanta, GA

Questions Submitted by Hon. Jimmy Panetta, a Representative in Congress from California

Forests and Climate Change

Question 1. Mr. Cantore, I appreciate your efforts to connect the dots between climate change and billion-dollar natural disasters like the record-breaking wildfires that my district experienced just a few months ago.

While wildfires are natural and beneficial in certain contexts, the fires we have been experiencing across the American West are laying claim to the very forestland we rely on to sequester 10% of our nation's emissions.

In California alone, we lost an unprecedented 4.4 million acres to wildfires last year, about 4% of our entire state, with over 640,000 of those acres in my district.

Reforestation efforts, like those supported by my REPLANT Act, which increases funding for the Reforestation Trust Fund, can help us reclaim the incomparable value of forests as carbon sinks while also helping protect our communities from mudslides and other disastrous after-effects.

In addition to ecologically-sound post-fire reforestation, we must also do a better job of protecting existing forests, particularly old-growth forests, from future fire risk.

Mr. Cantore, from your perspective as a meteorologist, can you elaborate on the climate-related benefits of better protecting existing forests and increasing the pace and quantity of reforestation efforts? What happens if don't take these steps?

Answer. Healthy forests are good for the natural environment and ecosystem. In addition to carbon storage, forests serve as wildlife habitats, supply fiber and wood products and are enjoyed for the recreational activities they provide. As you mention, we rely on our forests to sequester roughly 10% of the country's emissions. It is important we do not minimize or lose this important role forests play because the more CO_2 in the atmosphere the more warming and subsequent negative impacts. Extreme heat and drought, which is increasing across portions of the country, especially the western U.S., including California, can cause stress and reduce forest productivity and even increase tree mortality. It is important to preserve and restore our nation's forests, because without good maintenance and preventive measures we could continue to see the erosion of quality and quantity of our great forests, allowing the negative effects such as large wildfires, mudslides and loss of habitat to continue. REPLANT Act also adds native species back to their natural environment faster. What I can't tell you is when we can string several average or above average water/snow years together here (also needed for a healthy forest).

Question 2. Mr. Cantore, when we talk about reforestation, we also need to talk about climate-forward forestry, which means planting the right tree in the right place. Do you have any thoughts to share on how we can be smarter about planting trees, including climate-ready species that are better suited to climate changes?

Answer. Planting native species has always been a great practice. We have seen what adding non-native trees and plants can do in the wrong areas: like aiding the 2007 Harris fire in San Diego and covering the southeast in invasive kudzu that was brought in for erosion control. That said, my knowledge of certain species of trees and their ability to flourish in certain regions of the country is limited as a meteorologist. I will say, however, climate projections should be considered when choosing where and when to plant certain tree species. Some areas of the country may become more prone to drought, for example, so trees that are better at thriving through times of low water would be a smarter choice.

Forestry Workforce

Question 3. Mr. Cantore, research has shown that each $1 million invested in forest restoration and reforestation has the potential to support as many as 40 jobs.

As Congress looks ahead to an infrastructure package, I firmly believe we must invest Federal resources in workforce development in forestry sector.

That's why I introduced the Save Our Forests Act, which would provide funding to address chronic staffing shortages at the U.S. Forest Service. Increasing staff capacity in our Federal forests will not only help prevent fires but it will also help create the capacity needed to implement climate solutions in our Federal forests and the wildland-urban interface.

Mr. Cantore, based on your experience covering and studying natural disasters and their aftermath, do you think bolstering the forestry workforce will help create and sustain more resilient forests that are better able to sequester carbon?

Answer. Unfortunately, I don't know enough about the forestry workforce and their role in creating resilient forests to answer directly. I can, however, speak broadly on the topic of natural disasters. It has been my experience that the more resources, funding, and attention focused toward prevention and education can help mitigate losses after a natural disaster and potentially lead to a quicker return to normal. We have seen examples of communities building intelligently around floodplains to minimize infrastructure loss during heavy rain events. And better building codes have shown to make an incredible difference in reducing damage after severe weather and hurricanes. Marshland and forests can be natural barriers to many things and any attempt to shrink these beneficial ecosystems is further harm to our planet, in my opinion.

Response from Pamela N. Knox, Director, University of Georgia Weather Network; Agricultural Climatologist, UGA Cooperative Extension, Athens, GA

Questions Submitted by Hon. Chellie Pingree, a Representative in Congress from Maine

Question 1. One thing my bill, the Agriculture Resilience Act, focuses on is additional technical assistance and training on climate resilience and reducing emissions-not just for farmers, but also for the NRCS professionals and extension agents who work with them. Given your previous work with the Southeast Climate Hub, how would that additional support improve adoption of some of the climate-smart practices we discussed at the hearing?

Answer. Thank you for tackling this important question. The additional support provided by your bill would improve adoption of climate-smart practices in several ways. First, by sponsoring targeted research on methods for applying smart irrigation and other climate-smart management practices, the bill will help scientists to provide specific, actionable methods for reducing the use of water and agricultural chemicals that farmers can take and utilize on their farms. This will benefit the farmers economically as well as reduce emissions of greenhouse gases. It will also improve the health of surrounding ecosystems and communities by improvements in air and water quality. Second, the support would foster the use of workshops, publications, and field visits to allow direct transmission of the applied research to those who work with producers "on the ground", including extension agents and

NRCS professionals. Providing "hands-on" experience is a more targeted and useful approach to providing technical assistance than just publications, although those also have their place in providing information to farmers. Third, in that process of interaction, farmers would also be able to guide future development of useful methods of farm management that would be driven by the most important needs of the farm communities. As people who are actually doing the daily work of farming, they are best equipped to know what management strategies are workable and economically valuable as well as sustainable. That will ensure the best use of the funds and other resources provided by the Agriculture Resilience Act to directly benefit both agricultural producers and the larger community through improvements in climate resilience.

Question 2. One of the issues you mentioned in your testimony is a great interest of mine—reducing greenhouse gas emissions by reducing food waste. Can you elaborate on how food waste contributes to climate change and where you see opportunities to reduce food waste throughout the supply chain?

Answer. As you have pointed out, food waste contributes significantly to greenhouse gas emissions. This occurs in a variety of ways. When food is produced and then thrown away unused, all of the water, chemicals, fuel, and soil nutrients that went into the production of that food are essentially discarded too, resulting in unnecessary emissions of greenhouse gases, loss of available water, and reduced productivity of the soil. That will have to be supplemented in future crops on those fields, resulting in additional inputs of fuel, water, and chemicals that will also contribute to greenhouse gas emissions. Transportation of that food costs time and fuel to bring the food from the field to the factories or markets where they are processed or purchased for consumption. That transportation also adds to the emission of greenhouse gases through the use of fuel to power the trucks and trains needed for moving the products through the system. When food waste is discarded, either at the factory level or in individual kitchens, it is often placed into landfills where it decays anaerobically into methane, one of the most powerful greenhouse gases in its ability to add to global warming. Landfills are the third largest human-related source of methane emissions in the United States, and so reductions in landfill emissions by eliminating or decreasing food waste would contribute significantly to reductions in greenhouse gas emissions overall.

Fortunately, there are a number of methods available to use the food waste before it decays. This includes the use of digesters which convert the methane into usable fuel, feeding of food waste to livestock, and composting on municipal and individual scales, which reduce the output of methane. Encouraging factories to adopt lower-waste methods for processing the food and consumers to make better use of their food so that less is thrown out are also opportunities for reducing the impact of food waste on climate change.

Question 3. In your testimony, you made the point that farmers who own their land have the greatest incentive to improve their soil health. However, a huge number of producers, particularly young people and farmers of color, don't own the land they farm. In your view, how can we improve land access for these farmers? How can our policies better incentivize renters to make long-term investments in soil health if they're not sure they'll be the ones who reap the rewards?

Answer. To encourage the improvement of agricultural soils, we need to take a two-pronged approach. First, we need to encourage landowners to participate in efforts to increase carbon sequestration on their land by providing monetary or other incentives to encourage their tenants to practice carbon-smart techniques for improving their soils through the use of no-till agriculture, cover crops, and other regenerative practices. Landowners should be given the means of communicating how to do this to their tenants and rewarding those tenants who are best able to practice this, for example, by bonuses for excellent land use, lower rents, or multi-year leases that encourage smarter use of the land over numerous years.

Second, tenant farmers should be given access to information about climate-smart practices such as smart irrigation to reduce unneeded water use and fuel for pumping. They should also be provided with information from extension agents, NRCS specialists, and others on how to use inputs like chemicals efficiently to reduce overuse and to minimize their inputs, which will increase the amount of money they make on each crop. Access to broadband internet services is an important part of making the best use of their land, but it also requires knowledge acquired through training and education to see how these sustainable techniques work in practice. Access to affordable soil moisture sensors and other weather information will allow them make the best use of the information they have. Programs to encourage producers to purchase their own land such as low-cost loans should also be considered.

Question Submitted by Hon. Salud O. Carbajal, a Representative in Congress from California

Question. All our public forests are an incredible carbon sink, especially our intact temperate rainforests along the West Coast and in Alaska. While some carbon is stored in long lived wood products, far more is lost to the atmosphere as the result of logging and soil disturbance. I believe that legislation such as the Roadless Area Conservation Act, and other protective policies and legislation are necessary in our climate fight. According to the best available science, what are some key policy opportunities to elevate the role our forests play storing and sequestering carbon?

Answer. The Roadless Area Conservation Act and other legislation are important steps towards protecting and maintaining our immense and valuable forests across the United States, especially those in the western U.S. that are less touched by human activities than those in the eastern U.S. This protection is important not only because of the incredible amounts of carbon that they store, but also to maintain valuable ecosystem diversity and water quality of streams flowing through the forests. We can elevate the role of forests in sequestering carbon by first recognizing that the best way to reduce emission of greenhouse gases is not to emit it in the first place. That means reduction in the widespread clearcutting of forests in favor of more targeted harvesting of trees that reduces soil disturbance and preserves ecological diversity and water quality. Preservation of older and more diverse forests is an important part of that solution. It also means a reduction in the uses of forest products like paper so that fewer trees are needed, including a shift to other sustainable products like bamboo or hemp. Policies should also encourage improved management of forest lands to decrease the threat of wildfires, which release huge amounts of carbon into the atmosphere along with pollutants like soot when they occur. That would also reduce the health and property risks to vulnerable populations living near those forests.

Once trees are harvested, they should be quickly replaced by other trees to help absorb the carbon released by the trees that were removed. Restoration and replacement of degraded forests will also improve their ability to absorb excess carbon; in fact, some studies suggest that those processes could provide almost a third of the mitigation needed to counteract climate change by 2030. Extending our knowledge of wise management of forests to other countries would also help with greenhouse gas emissions overall, since wood use for fuel and clearing of tropical rain forests for food production are large contributors to greenhouse gas emissions around the world.

Questions Submitted by Hon. Jimmy Panetta, a Representative in Congress from California

Land Ownership and Climate

Question 1. Ms. Knox, you mentioned that producers who own their land, rather than rent it, reap greater benefits from taking steps to improve the health of their soils.

I completely agree—when farmers, ranchers, and foresters own their land, they not only have a greater incentive but also a greater capacity to invest in its long-term health.

In my district on the Central Coast, organizations like the Agriculture and Land-Based Training Association (ALBA) are working to help limited-resource minority farmers launch organic farming businesses.

Graduates of ALBA's training program now own and operate some of the most successful and ecologically conscious operations in my district.

Ms. Knox, Can you elaborate on the connection between land ownership and climate-smart agriculture?

Answer. As you point out, farmers, ranchers, and foresters that own their land have a greater incentive to protect it as well as invest in its long-term health. When you rent the land and don't own it, the increased value due to higher organic matter in soils, reduced erosion and loss of valuable topsoil, and water-holding capacity benefits the landowner much more than the farmer working the land, since the landowner can raise the rent in future years to capture the increased value of better soil fertility and structure. Little to none of the economic benefit is returned to the farmer who improved the soil in the first place. In some cases, the original farmer may be priced out of renting that land in future years, so any extra work he or she puts into improving the land can negatively affect their ability to rent those fields next year. If you own the land, then any benefits you get from practicing climate-smart management are returned directly to you in reduced need to add water and fertilizer in subsequent years, which increases the profitability of the harvests in later years. Many climate-smart techniques such as no-till production and smart irrigation also promote wiser and more judicious use of inputs like pumped irrigation water and agricultural chemicals like fertilizers, fungicides, and herbicides, which cost money both in direct purchases as well as in labor costs to apply them. This results in higher net income to the farmers since less money is paid out to protect the crops and supplement soil nutrient levels. Organic farming reduces the cost of man-made chemicals and also provides an economically valuable product that improves farmers' net profit as well as improves ecological diversity and soil fertility.

Question 2. Ms. Knox, Do you think USDA can better achieve its climate goals by creating more economic opportunities for minority farmers?

Answer. The USDA must achieve its climate goals by engaging with farmers at all scales to promote climate-smart approaches to farming. Engaging with minority farmers is an important part of that approach since many minority farmers have a strong interest in preserving their family farms for future generations. That requires excellent care of the farm characteristics such as soil fertility, water-holding capacity, and reductions in erosion to ensure the future productivity of their land. All of these approaches have the double benefit of both reducing emissions of greenhouse gases and improving the economic well-being of the minority farmers as well as their farmland. Additional methods such as the work promoted by organizations like the Agriculture and Land-Based Training Association (ALBA) to educate and encourage the development of organic farming businesses have the added advantage of providing minority farmers with highly profitable organic produce that maximizes their net income from selling their products.

Question Submitted by Hon. Glenn Thompson, a Representative in Congress from Pennsylvania

Question. In my district, we have a great example of an effort to tap private markets and private capital to capture and store carbon in our forests—which is also bringing new private money to rural, small family forest owners, helping them afford to stay on the land and manage it well.

Ms. Knox, what role do you see these private markets playing and how can we best leverage these opportunities to bring private sector support to rural America?

Answer. Private markets play an integral role as partners with agriculture and forestry in providing information, tools, and capital to producers working at all scales, from the largest commercial growers to the smallest family farms. They have the ability to react more quickly than many government agencies to disasters and changing market conditions that can affect the value of working forests. Private markets can help family forest owners by providing education and guidance on proper maintenance of their forest lots to maximize the value of the trees on those lots and determine appropriate timing for sales of the timber to maximize their profit overall. They can also help farmers replace harvested trees with new seedlings that will continue to absorb carbon from the atmosphere and provide future profit for those families. Private markets can also promote the wise use of forest products for low-carbon building materials in both residential and commercial buildings and the use of wood pellets for fuel. By putting private markets to use, we can provide a much wider array of targeted services to family forest owners than government agencies could do without their expertise.

Response from Zippy Duvall, President, American Farm Bureau Federation, Washington, D.C.

Question Submitted by Hon. Jimmy Panetta, a Representative in Congress from California

Role of Specialty Crops in USDA Climate Efforts

Question. I represent the Central Coast of California, also known as the Salad Bowl of the World. The farmers and farmworkers in my district grow over 100 specialty crops—you name it, we grow it—and they are part of a very rich agricultural history in the region.

Mr. Duvall, while you didn't specifically mention specialty crop producers in your testimony, I know that many of your members are specialty crop producers, and I am proud to represent many of those members on the Central Coast.

Have you engaged with your members in the specialty crop sector to ensure their views are being considered as Congress and USDA work to develop strategies to incentivize more climate-smart agriculture?

Answer. The American Farm Bureau Federation represents growers of every facet of agriculture, including specialty crops, as you noted. I agree that it is important their viewpoints are part of this conversation surrounding climate too and I can assure you they've had a voice both within our organization and beyond. Much of our climate work has been in conjunction with the Food and Agriculture Climate Alliance in which several organizations specifically representing specialty crop producers are members.

We believe Congress and USDA must take into consideration the diversity of American agriculture when crafting any climate policy. Existing carbon markets may not provide the same level of opportunity to all farmers, growers, ranchers, and foresters due to regional differences, crop and production types, total acreage under crop production, and farm size. Efforts should focus on reducing these barriers and providing a range of opportunities to ensure broad participation in climate-smart agricultural practices.

Question Submitted by Hon. Glenn Thompson, a Representative in Congress from Pennsylvania

Question. In my district, we have a great example of an effort to tap private markets and private capital to capture and store carbon in our forests—which is also bringing new private money to rural, small family forest owners, helping them afford to stay on the land and manage it well.

Mr. Duvall—what role do you see these private markets playing and how can we best leverage these opportunities to bring private-sector support to rural America?

Answer. Our mission at Farm Bureau is to build a sustainable future of safe and abundant food, fiber and renewable fuel for our nation and the world while ensuring the economic success of farmers, ranchers and rural communities. We are excited about opportunities like the one you mentioned. Investment in rural communities and keeping our families on the land is a priority for us. That is why Farm Bureau is at the table working with private industry and Congress to ensure that all opportunities are being presented to our landowners. We are exploring the best ways to leverage private markets but still must address any barriers to farmer participation. With this investment and voluntary, incentive-based initiatives, I am excited about the future.

Questions Submitted by Hon. Troy Balderson, a Representative in Congress from Ohio

Question 1. Thank you for being here, Mr. Duvall. The work and the relationship the American Farm Bureau—as well as the Ohio Farm Bureau back home—have with Ohio farmers is critical, so thank you for your work.

In data provided by the EPA and USDA, the American Farm Bureau calculates that U.S. greenhouse gas emissions from beef, swine, and dairy per unit have declined by 8, 18, and 25 percent, respectively, between 1990 and 2018.

Based upon some of the testimony we've heard here today, how do these figures fit into the broader narrative of U.S. agriculture being the primary culprit of climate change?

Answer. We certainly do not believe that U.S. agriculture is a culprit of climate change, but quite the opposite. We believe U.S. agriculture can be part of the solution. U.S. agriculture is just 10% of our overall greenhouse gas emissions. And our per unit GHGs have fallen, while production has increased. Nearly 100 million more acres would have been needed in 1990 to match 2018 production. In the last 30 years, we lost almost 30 million acres of cropland but on the remaining cropland our emissions flux has remained steady while we are producing 50 percent more per acre. We want to build upon this strong foundation of innovation and climate-smart practices and are looking for partners to continue to improve.

Question 2. The EPA attributes 15 percent of global greenhouse gas emissions to the United States, with China at 30 percent. Based upon the Netflix video "Kiss the Ground", in which Mr. Brown appears, I get the impression that the way American farmers use their land is doing more harm than good.

Mr. Duvall, how has the AFBF worked with farmers to increase their use of environment-benefiting technology on their land and how successful would you say these efforts have been?

Answer. U.S. agriculture has a great sustainability story to tell, thanks to the ways we have embraced technology and innovation and adopted modern conservation practices. Farmers everywhere want to protect our natural resources and keep our land productive for generations to come, and we are always looking for ways to do better. Unfortunately, American farmers haven't always gotten credit for our efforts, and that's partly on us because we haven't been great at telling that story. Historically, we weren't engaged in the conversation—especially when it comes to climate change—and yet we expected the public to somehow know what we were doing and the advancements we've achieved.

Here are a few of the great strides U.S. farmers and ranchers have made reducing our environmental footprint and protecting our natural resources:

- U.S. agriculture is just 10% of our overall greenhouse gas emissions.

- Ag's per unit GHGs have fallen, while production has increased. Nearly 100 million more acres would have been needed in 1990 to match 2018 production.
- 140 million acres (15% of all farmland) are enrolled in USDA conservation programs. That's equal to the total land area of California and New York combined.
- In 2018 alone, the use of ethanol and biodiesel reduced GHG emissions by 71 million metric tons. That's the equivalent of taking 17 million cars off the road.
- In a 5 year period, U.S. farmers and ranchers have put in 132% more renewable energy sources including geothermal, solar panels, windmills, hydro systems and methane digesters.

At the American Farm Bureau Federation, we want U.S. farmers and ranchers to be recognized as the leaders they are when it comes to climate-smart solutions. That's what led us to join with other U.S. ag groups, as well as food, forestry and environmental groups in founding the Food and Agriculture Climate Alliance (FACA).

Response from Gabe Brown, Co-Owner/Operator, Brown's Ranch, Bismarck, ND

Question Submitted by Hon. Chellie Pingree, a Representative in Congress from Maine

Question. I appreciated your reference to the PRIME Act at the hearing. I've been working on improving meat and poultry processing infrastructure for many years. I view this as a part of the climate conversation not just because producers often have to drive their animals hundreds of miles to reach the nearest facility, but also because it's a part of our food system where greater resilience is sorely needed. Can you talk a little about how having a local processing option fits into your regenerative operation? What more can Congress do to increase processing options?

Answer. In order to sell our pastured proteins, they must be inspected for retail sale. Processors that have their facilities inspected are few and far between. We knew that in order to sell our products, we needed to invest in a slaughter plant and then patronize that plant. In 2014 a group of us started a co-op called Bowdon Meat Processors. It is a cooperative that is open for anyone to have animas processed there. Congress can allow meat that is processed at state-inspected facilities the ability to be sold anywhere in the U.S. This would allow producers to patronize their local processors but yet they would have access to more markets. This would also help to provide food security in cases where large processors are closed, such as that which occurred during the [COVID]–19 pandemic.

Question Submitted by Hon. Glenn Thompson, a Representative in Congress from Pennsylvania

Question. In my district, we have a great example of an effort to tap private markets and private capital to capture and store carbon in our forests—which is also bringing new private money to rural, small family forest owners, helping them afford to stay on the land and manage it well.

Mr. Brown—what role do you see these private markets playing and how can we best leverage these opportunities to bring private sector support to rural America?

Answer. Government needs to realize that the current farm program is not working. Farmers and ranchers assume all of the risk for very marginal returns. We need more capital investment in agriculture. There are a number of private markets that are looking to purchase carbon to offer to industry/businesses for carbon offsets. Congress needs to allow and encourage the expansion of these markets. Farmers and ranchers need to be paid for the ecological services they provide. I am working with a fund that is investing money in farms and ranches that are using regenerative practices which will significantly enhance both farm profitability and ecosystem function. Congress needs to encourage and support regenerative practices.

Response from Michael Shellenberger, Founder and President, Environmental Progress, Berkeley, CA

Question Submitted by Hon. Glenn Thompson, a Representative in Congress from Pennsylvania

Question. In my district, we have a great example of an effort to tap private markets and private capital to capture and store carbon in our forests—which is also bringing new private money to rural, small family forest owners, helping them afford to stay on the land and manage it well.

Mr. Shellenberger—what role do you see these private markets playing and how can we best leverage these opportunities to bring private-sector support to rural America?

Answer. The most important role for the private-sector in farming is to increase yields on existing farmland. Doing so lowers the amount of land used for farmland, which allows ecosystems and forests that store carbon to return. U.S. farmers have been wildly successful at increasing yields, and we have some of the most innovative farmers in the world. Since the advent of tractors and combine harvesters, the amount of U.S. farmland has decreased by 25 percent, an area the size of California.

We should be wary of plans to grow small plots of forest on farmland when those forests are not contiguous. While small plots store some carbon, they can't be used as habitat by animals who require contiguous habitat. Free range meat production should also be avoided. Free range or pasture beef requires 14–19 times more land than industrial beef and releases 300 to 400 times more carbon emissions. Indoor chicken production also has land use and carbon benefits when compared to free range chicken.

The U.S. Federal Government, state governments, and private companies should continue to invest in research and development in innovative agricultural technologies that boost yields. Governments should also support the use of innovative technologies like GMOs, and private companies shouldn't prohibit those products in their stores out of wrongful environmental concerns.

For example, one technology that has struggled due to private business bans is AquAdvantage salmon, which are genetically modified salmon that are grown on land. Because they are grown on land, they pose a business opportunity to landowners in rural areas. These farmed fish grow twice as fast as wild salmon and require less feed. They are incredibly efficient at turning feed into consumer meat. While 8 pounds of feed is needed to harvest 1 pound of beef, only 1 pound of feed is needed to create 1 pound of AquAdvantage salmon. Fish farming takes pressure off of wild salmon, which, like many aquatic species, are facing immense pressure from overfishing. Despite these benefits, environmental groups oppose AquAdvantage salmon, which they believe will eventually enter the wild and displace wild salmon. It is unlikely AquAdvantage salmon will ever harm wild salmon since these farmed fish are not as fit as wild salmon and would struggle in the wild. These environmental groups have persuaded private companies such as Trader Joe's, Whole Foods, Costco, Target, and Kroger to not sell AquAdvantage salmon.

Question Submitted by Hon. Troy Balderson, a Representative in Congress from Ohio

Question. The IPCC (*Attachment 1*) released an assessment in 2018 which outlined their concerns if global temperatures increased by more than 1.5 °C from preindustrial levels. The report also concluded that major cuts across our global carbon output would need to be achieved in order to prevent this threshold from being crossed. The Institute for Energy Research released a report (*Attachment 2*) last month saying global emissions fell by seven percent in 2020.

Last year, *National Geographic* published an article (*Attachment 3*) that stated global emissions would need to decline by 7.6 percent each year through 2030 and beyond to prevent the IPCC's 1.5 °C level from being reached.

Mr. Shellenberger—given these conclusions, what's the most productive way for farmers in other countries to play their part? It sure feels like we're placing the majority of the burden of agriculture emissions on the American farmer, when all I've seen from folks back home is an increasing level of environmentally-conscience farming.

Answer. U.S. farmers deserve recognition for their efforts to boost yields and protect the environment. However, we should be wary of any farming practices that brand themselves as environmentally friendly but require more land or don't maximize yields. Minimizing the land needed for farming by maximizing yields is one of the most important environmental practices farmers can do.

Farming only produces ten percent of U.S. carbon emissions, so blaming farmers for climate change is not based in fact. But, there are ways to decarbonize farming without sacrificing yields. We can use clean energy, namely nuclear, to create fertilizer. Tractors and other machinery can be powered by electricity or hydrogen that comes from clean energy.

Likewise, farmers in other countries can best help the environment by boosting crop yields so that they can use less land for farming and allow forests and ecosystems to return. In some countries, yields can grow five-fold by modernizing. The U.S. should actively help countries boost their crop yields through existing foreign aid programs.

ATTACHMENT 1

[*https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf*]

Global Warming of 1.5 °C

An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

Summary for Policymakers *

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Introduction

This Report responds to the invitation for IPCC '. . . to provide a Special Report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policymakers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5 °C and for the comparison between global warming of 1.5 °C and 2 °C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated

* **Editor's note:** the full report is retained in Committee file and is available at: *https://www.ipcc.ch/sr15/download/#full*.

[1] Decision 1/CP.21, paragraph 21.

[2] The assessment covers literature accepted for publication by 15 May 2018.

language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the Report.

A. Understanding Global Warming of 1.5 °C[4]

A.1 Human activities are estimated to have caused approximately 1.0 °C of global warming[5] above pre-industrial levels, with a likely range of 0.8 °CC to 1.2 °C. Global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) (*Figure SPM.1*) {*1.2*}

A.1.1 Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87 °C (likely between 0.75 °C and 0.99 °C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely range*). Estimated anthropogenic global warming is currently increasing at 0.2 °C (*likely* between 0.1 °C and 0.3 °C) per decade due to past and ongoing emissions (*high confidence*). {*1.2.1, Table 1.1, 1.2.4*}

A.1.2 Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {*1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2*}

A.1.3 Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5 °C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {*3.3.1, 3.3.2, 3.3.3*}

A.2 Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are unlikely to cause global warming of 1.5 °C (*medium confidence*). (*Figure SPM.1*) {*1.2, 3.3, Figure 1.5*}

A.2.1 Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are unlikely to cause further warming of more than 0.5 °C over the next two to 3 decades (*high confidence*) or on a century time scale (*medium confidence*). {*1.2.4, Figure 1.5*}

A.2.2 Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer time scales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and to reverse ocean acidification (*medium confidence*) and will be required to minimize sea level rise (*high confidence*). {*Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2*}

A.3 Climate-related risks for natural and human systems are higher for global warming of 1.5 °C than at present, but lower than at 2 °C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the

[3] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, medium confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, very likely. This is consistent with AR5.

[4] See also Box SPM.1: Core Concepts Central to this Special Report.

[5] Present level of global warming is defined as the average of a 30 year period centred on 2017 assuming the recent rate of warming continues.

[6] This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {*1.2.1, Table 1.1*}

choices and implementation of adaptation and mitigation options (*high confidence*). (*Figure SPM.2*) {*1.3, 3.3, 3.4, 5.6*}

A.3.1 Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). (*Figure SPM.2*) {*1.4, 3.4, 3.5*}

A.3.2 Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate, they are larger if global warming exceeds 1.5 °C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5 °C, especially if the peak temperature is high (*e.g.,* about 2 °C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {*3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8 in Chapter 3*}

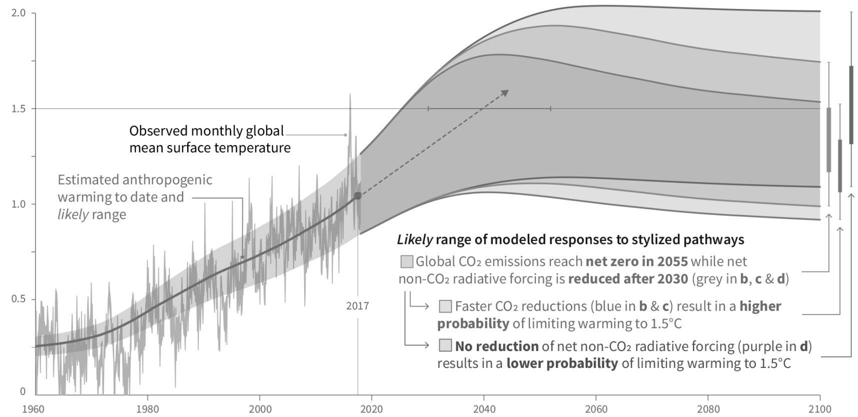
A.3.3 Adaptation and mitigation are already occurring (high confidence). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multilevel and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {*1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3*}

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5 °C

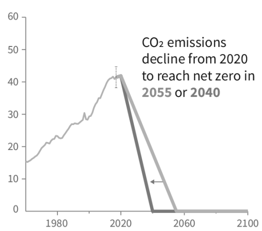
(a) Observed global temperature change and modeled responses to stylized anthropogenic emission and forcing pathways

Global warming relative to 1850–1900 (°C)

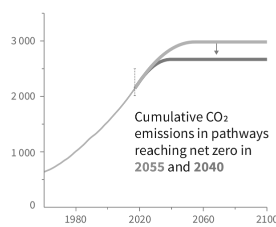
Figure SPM.1



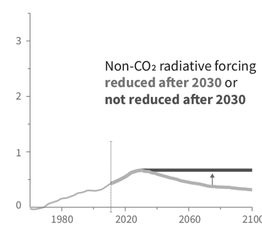
(b) Stylized net global CO_2 emission pathways
Billion tonnes CO_2 per year ($GtCO_2$/yr)



(c) Cumulative net CO_2 emissions
Billion tonnes CO_2 ($GtCO_2$)



(d) Non-CO_2 radiative forcing pathways
Watts per square metre (W/m²)



Faster immediate CO_2 emission reductions limit cumulative CO_2 emissions shown in panel (c).

Maximum temperature rise is determined by cumulative net CO_2 emissions and net non-CO_2 radiative forcing due to methane, nitrous oxide, aerosols and other anthropogenic forcing agents.

Panel a: Observed monthly global mean surface temperature (GMST, grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan-Way, and NOAA datasets) change and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively the central estimate and *likely* range of the time at which 1.5 °C is reached if the current rate of warming continues. The grey plume on the right of panel a shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd–66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {*1.2.1, 1.2.3, 1.2.4, 2.3, Figure 1.2 and Chapter 1 Supplementary Material, Cross-Chapter Box 2 in Chapter 1*}

B. Projected Climate Change, Potential Impacts and Associated Risks

B.1 Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5 °C,[8] and between 1.5 °C and 2 °C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {*3.3*}

B.1.1 Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5 °C supports the assessment that an additional 0.5 °C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5 °C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {*3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2*}

B.1.2 Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3 °C at global warming of 1.5 °C and about 4 °C at 2 °C, and extreme cold nights in high latitudes warm by up to about 4.5 °C at 1.5 °C and about 6 °C at 2 °C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {*3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3*}

B.1.3 Risks from droughts and precipitation deficits are projected to be higher at 2 °C compared to 1.5 °C of global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2 °C compared to 1.5 °C of global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence*). Heavy precipitation associated with tropical cyclones is projected to be higher at 2 °C compared to 1.5 °C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2 °C compared to 1.5 °C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2 °C than at 1.5 °C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2 °C compared to 1.5 °C of global warming (*medium confidence*). {*3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6*}

B.2 By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5 °C compared to 2 °C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depend on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {*3.3, 3.4, 3.6*}

B.2.1 Model-based projections of global mean sea level rise (relative to 1986–2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5 °C of global warming, 0.1 m (0.04–0.16 m) less than for a global warming of 2 °C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to ten million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {*3.4.4, 3.4.5, 4.3.2*}

B.2.2 Sea level rise will continue beyond 2100 even if global warming is limited to 1.5 °C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered at around 1.5 °C to 2 °C of global warming (*medium confidence*). (*Figure SPM.2*) {*3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3*}

[7] Robust is here used to mean that at least ⅔ of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

[8] Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

B.2.3 Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2 °C compared to 1.5 °C. The slower rate of sea level rise at global warming of 1.5 °C reduces these risks, enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems and infrastructure reinforcement (*medium confidence*). (*Figure SPM.2*) {*3.4.5, Box 3.5*}

B.3 On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5 °C of global warming compared to 2 °C. Limiting global warming to 1.5 °C compared to 2 °C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans (*high confidence*). (*Figure SPM.2*) {*3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3*}

B.3.1 Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5 °C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2 °C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires and the spread of invasive species are lower at 1.5 °C compared to 2 °C of global warming (*high confidence*). {*3.4.3, 3.5.2*}

B.3.2 Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1 °C of global warming, compared with 13% (interquartile range 8–20%) at 2 °C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5 °C compared to 2 °C (*medium confidence*). {*3.4.3.1, 3.4.3.5*}

B.3.3 High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and this will proceed with further warming. Limiting global warming to 1.5 °C rather than 2 °C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {*3.3.2, 3.4.3, 3.5.5*}

B.4 Limiting global warming to 1.5 °C compared to 2 °C is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5 °C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef ecosystems (*high confidence*). {*3.3, 3.4, 3.5, Box 3.4, Box 3.5*}

B.4.1 There is *high confidence* that the probability of a sea ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5 °C when compared to 2 °C. With 1.5 °C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2 °C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {*3.3.8, 3.4.4.7*}

B.4.2 Global warming of 1.5 °C is projected to shift the ranges of many marine species to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2 °C than those at global warming of 1.5 °C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5 °C (*high confidence*) with larger losses (>99%) at 2 °C (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2 °C or more (*high confidence*). {*3.4.4, Box 3.4*}

B.4.3 The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5 °C is projected to amplify the adverse effects of warming, and even further at 2 °C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, for example, from algae to fish (*high confidence*). {*3.3.10, 3.4.4*}

B.4.4 Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, dis-

[9] Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

ease incidence, and risk of invasive species (*medium confidence*) but are projected to be less at 1.5 °C of global warming than at 2 °C. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5 °C of global warming compared to a loss of more than 3 million tonnes for 2 °C of global warming (*medium confidence*). {*3.4.4, Box 3.4*}

B.5 Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5 °C and increase further with 2 °C. (*Figure SPM.2***) {***3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2***}**

B.5.1 Populations at disproportionately higher risk of adverse consequences with global warming of 1.5 °C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states, and Least Developed Countries (*high confidence*). Poverty and disadvantage are expected to increase in some populations as global warming increases; limiting global warming to 1.5 °C, compared with 2 °C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {*3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3*}

B.5.2 Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5 °C than at 2 °C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (high confidence). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5 °C to 2 °C, including potential shifts in their geographic range (*high confidence*). {*3.4.7, 3.4.8, 3.5.5.8*}

B.5.3 Limiting warming to 1.5 °C compared with 2 °C is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2 °C than at 1.5 °C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {*3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4*}

B.5.4 Depending on future socioeconomic conditions, limiting global warming to 1.5 °C compared to 2 °C may reduce the proportion of the world population exposed to a climate change-induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states could experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5 °C, as compared to 2 °C (*medium confidence*). {*3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4*}

B.5.5 Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5 °C than at 2 °C by the end of this century [10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5 °C to 2 °C (*medium confidence*). {*3.5.2, 3.5.3*}

B.5.6 Exposure to multiple and compound climate-related risks increases between 1.5 °C and 2 °C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5 °C to 2 °C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {*Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9*}

[10] Here, impacts on economic growth refer to changes in gross domestic product (GDP). Many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetize.

B.5.7 There are multiple lines of evidence that since AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2 °C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high risk between 1.5 °C and 2 °C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1 °C and 1.5 °C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5 °C and 2 °C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5 °C and 2.5 °C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1 °C and 2.5 °C for RFC5 (Large-scale singular events) (*medium confidence*). (*Figure SPM.2*) {*3.4.13; 3.5, 3.5.2*}

B.6 Most adaptation needs will be lower for global warming of 1.5 °C compared to 2 °C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5 °C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (medium confidence). {*Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5*}

B.6.1 A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (*e.g.,* ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (*e.g.,* coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (*e.g.,* efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, and community-based adaptation) and urban areas (*e.g.,* green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {*4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4*}.

B.6.2 Adaptation is expected to be more challenging for ecosystems, food and health systems at 2 °C of global warming than for 1.5 °C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5 °C (*high confidence*). {*3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3*}

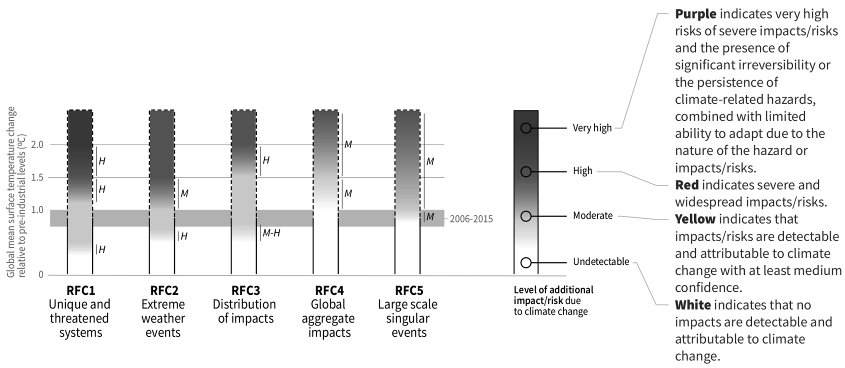
B.6.3 Limits to adaptive capacity exist at 1.5 °C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems and human health (*medium confidence*). {*Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5*}

How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

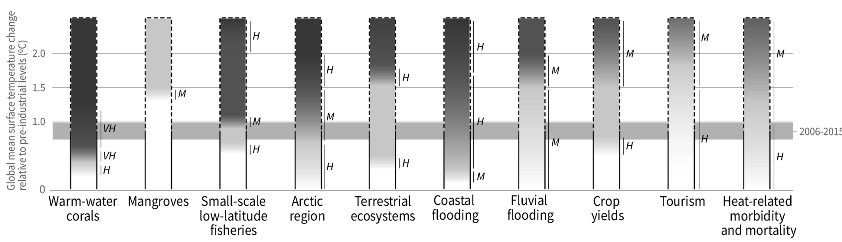
Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Figure SPM.2

Impacts and risks associated with the Reasons for Concern (RFCs)



Impacts and risks for selected natural, managed and human systems



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High, and *VH*=Very high.

Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. {*3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1, 5.5.3, 5.6.1, Box 3.4*}

RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots.

RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.

RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability.

RFC4 Global aggregate impacts: global monetary damage, global-scale degradation and loss of ecosystems and biodiversity.

RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets.

C. Emission Pathways and System Transitions Consistent with 1.5 °C Global Warming

C.1 In model pathways with no or limited overshoot of 1.5 °C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2 °C [11] CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5 °C show deep reductions that are similar to those in pathways limiting warming to 2 °C. (*high confidence*) (*Figure SPM.3a*) {*2.1, 2.3, Table 2.4*}

C.1.1 CO_2 emissions reductions that limit global warming to 1.5 °C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges and potential synergies and trade-offs with sustainable development. (*high confidence*) (*Figure SPM.3b*) {*2.3.2, 2.3.4, 2.4, 2.5.3*}

C.1.2 Modelled pathways that limit global warming to 1.5 °C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for 2 to 3 decades. Non-CO_2 emissions [12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5 °C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5 °C model pathways. (*high confidence*) (*Figure SPM.3a*) {*2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2*}

C.1.3 Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the preindustrial period, that is, staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the pre-industrial period are estimated to have reduced the total carbon budget for 1.5 °C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5 °C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {*1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material*}

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[11] References to pathways limiting global warming to 2 °C are based on a 66% probability of staying below 2 °C.

[12] Non-CO_2 emissions included in this Report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {*2.2.1*}

[13] There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5 °C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this Report.

[14] Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {*2.2.2*}

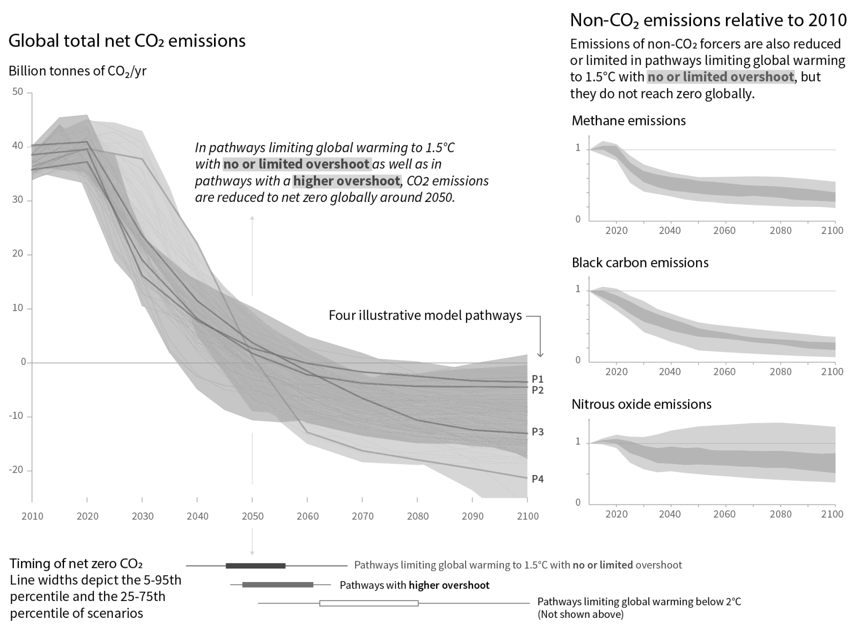
[15] These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

C.1.4 Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*) {*4.3.8, Cross-Chapter Box 10 in Chapter 4*}

Global Emissions Pathway Characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5 °C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in *Figure SPM.3b*.

Figure SPM.3a



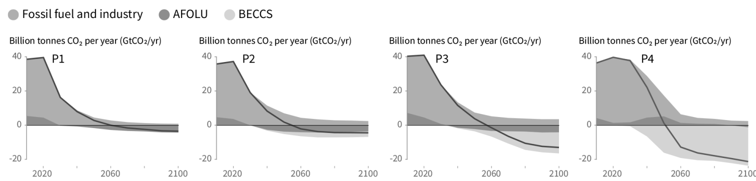
Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5 °C with no or limited (less than 0.1 °C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this Report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5 °C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2 °C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in *Figure SPM.3b*. {*2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11*}

Characteristics of Four Illustrative Model Pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5 °C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Figure SPM.3b

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
↳ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
↳ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
↳ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
↳ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
↳ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
↳ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
↳ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
↳ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
↳ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
↳ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
↳ of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km^2)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Characteristics of four illustrative model pathways in relation to global warming of 1.5 °C introduced in *Figure SPM.3a.* These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socioeconomic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry; agriculture, forestry and other land use (AFOLU); and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5 °C. Pathways P1, P2, P3 and P4 correspond to the LED, S1, S2 and S5 pathways assessed in Chapter 2 (*Figure SPM.3a*). {*2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Fig-*

ure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C.2 Pathways limiting global warming to 1.5 °C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {*2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5*}

C.2.1 Pathways that limit global warming to 1.5 °C with no or limited overshoot show system changes that are more rapid and pronounced over the next 2 decades than in 2 °C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5 °C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {*2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4*}

C.2.2 In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5 °C with no or limited overshoot (for more details see *Figure SPM.3b*) generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2 °C (*high confidence*). In 1.5 °C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2 °C pathways, particularly before 2050 (*high confidence*). In 1.5 °C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5 °C pathways with no or limited overshoot. In modelled 1.5 °C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2% interquartile range) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation. (*Figure SPM.3b*) {*2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2*}

C.2.3 CO_2 emissions from industry in pathways limiting global warming to 1.5 °C with no or limited overshoot are projected to be about 65–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2 °C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable biobased feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5 °C with no or limited overshoot (*high confidence*). {*2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2*}

C.2.4 The urban and infrastructure system transition consistent with limiting global warming to 1.5 °C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2 °C (*medium confidence*). Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5 °C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2 °C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2 °C of global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {*2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2*}

C.2.5 Transitions in global and regional land use are found in all pathways limiting global warming to 1.5 °C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5 °C with no or limited overshoot project a 4 million km^2 reduction to a 2.5 million km^2 increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km^2 reduction of pasture land, to be converted into a 0–6 million km^2 increase of agricultural land for energy crops and a 2 million km^2 reduction to 9.5 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land-use transitions of similar magnitude can be observed in modelled 2 °C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land-use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socioeconomic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {*2.4.4, Figure 2.24, 4.3.2, 4.3.7, 4.5.2, Cross-Chapter Box 7 in Chapter 3*}

C.2.6 Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5 °C compared to pathways without new climate policies beyond those in place today are estimated to be around 830 billion USD2010 (range of 150 billion to 1,700 billion USD2010 across six models[17]). This compares to total annual average energy supply investments in 1.5 °C pathways of 1460 to 3510 billion USD2010 and total annual average energy demand investments of 640 to 910 billion USD2010 for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5 °C pathways relative to 2 °C pathways. Annual investments in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015 (*medium confidence*). {*2.5.2, Box 4.8, Figure 2.27*}

C.2.7 Modelled pathways limiting global warming to 1.5 °C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3–4 times higher than in pathways limiting global warming to below 2 °C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5 °C mitigation pathways is limited and was not assessed in this Report. Knowledge gaps remain in the integrated assessment of the economy-wide costs and benefits of mitigation in line with pathways limiting warming to 1.5 °C. {*2.5.2; 2.6; Figure 2.26*}

C.3 All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1,000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5 °C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {*2.3, 2.4, 3.6.2, 4.3, 5.4*}

C.3.1 Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (high confidence). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {*2.3.4, 3.6.2, 4.3.2, 4.3.7*}

C.3.2 In pathways limiting global warming to 1.5 °C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2$

[16] The projected land-use changes presented are not deployed to their upper limits simultaneously in a single pathway.

[17] Including two pathways limiting warming to 1.5 °C with no or limited overshoot and four pathways with higher overshoot.

yr^{-1} in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2$ yr^{-1} and afforestation potential of up to 3.6 $GtCO_2$ yr^{-1} assessed based on recent literature (medium confidence). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (high confidence). (*Figure SPM.3b*) {*2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4*}

C.3.3 Pathways that overshoot 1.5 °C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5 °C by 2100, with larger overshoots requiring greater amounts of CDR (*Figure SPM.3b*) (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5 °C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {*2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11*}

C.3.4 Most current and potential CDR measures could have significant impacts on land, energy, water or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity, and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (*Figure SPM.3b*) {*2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3*}

C.3.5 Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (medium confidence). (*Figure SPM.4*) {*2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4*}

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D.1 Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] **in 2030 of 52–58 $GtCO_2eq$ yr^{-1} (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5 °C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO^2 emissions start to decline well before 2030 (*high confidence*). {***1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4*}

D.1.1 Pathways that limit global warming to 1.5 °C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq$ yr^{-1} in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq$ yr^{-1} range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3 °C by 2100, with warming continuing afterwards (*medium confidence*). {*2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2*}

D.1.2 Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5 °C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2 °C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {*1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4*}

[18] GHG emissions have been aggregated with 100 year GWP values as introduced in the IPCC *Second Assessment Report*.

D.1.3 The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5 °C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {*2.3.5, 4.4.5, 5.4.2*}

D.2 The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5 °C rather than 2 °C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {*1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1*}

D.2.1 Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5 °C or 2 °C and development goals that include poverty eradication, reducing inequalities, and climate action. (*high confidence*) {*Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1*}

D.2.2 The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5 °C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {*1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5*}

D.2.3 Mitigation and adaptation consistent with limiting global warming to 1.5 °C are underpinned by enabling conditions, assessed in this Report across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional dimensions of feasibility. Strengthened multilevel governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5 °C-consistent systems transitions. (*high confidence*) {*1.4, Cross-Chapter Box 3 in Chapter 1, 2.5.1, 4.4, 4.5, 5.6*}

D.3 Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5 °C, although trade-offs are possible (*high confidence*). {*1.4, 4.3, 4.5***}**

D.3.1 Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5 °C of global warming (*high confidence*). {*1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2*}

D.3.2 Adaptation to 1.5 °C global warming can also result in trade-offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {*4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3*}

D.3.3 A mix of adaptation and mitigation options to limit global warming to 1.5 °C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*). {*4.3.2, 4.3.3, 4.4.1, 4.4.2*}

D.3.4 Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low-carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5 °C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {*3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4*}

D.4 Mitigation options consistent with 1.5 °C pathways are associated with multiple synergies and tradeoffs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. (*high confidence*) (*Figure SPM.4*) {*2.5, 4.5, 5.4*}

D.4.1 1.5 °C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). Some 1.5 °C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), six (water) and 7 (energy access), if not managed carefully (*high confidence*). (*Figure SPM.4*) {*5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3*}

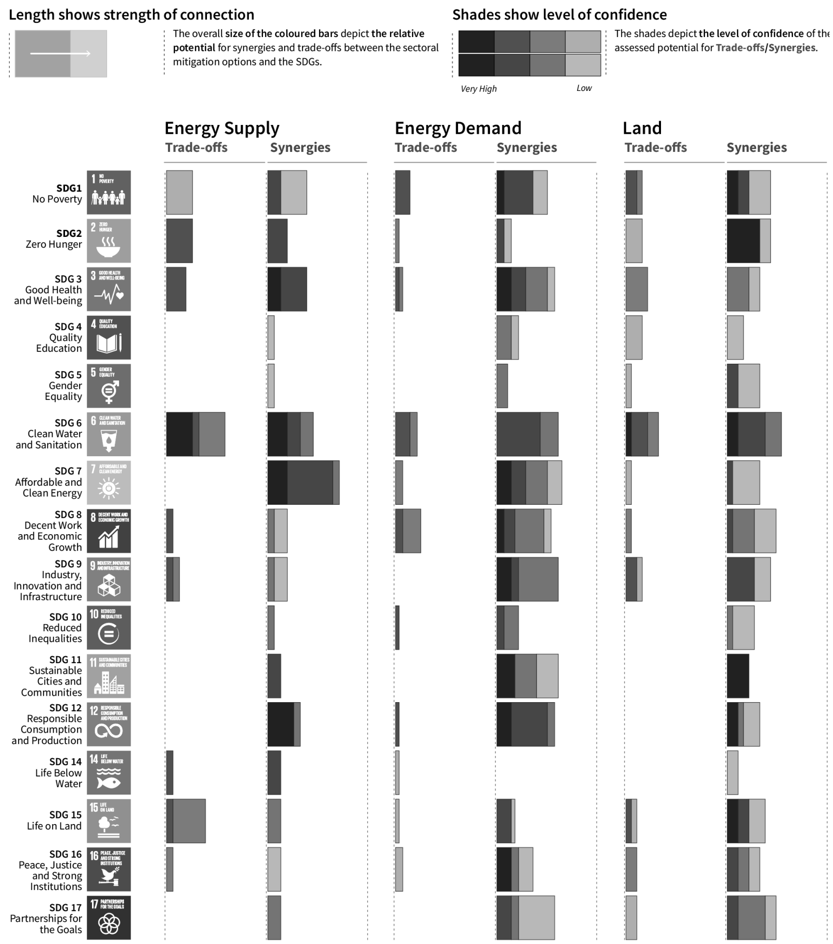
D.4.2 1.5 °C pathways that include low energy demand (*e.g.,* see P1 in *Figure SPM.3a* and *SPM.3b*), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways, sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5 °C (*high confidence*). (*Figure SPM.3b, Figure SPM.4*) {*2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4*}

Indicative Linkages Between Mitigation Options and Sustainable Development Using SDGs

(The Linkages Do Not Show Costs and Benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

Figure SPM.4



Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5 °C. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in *Table 5.2.* For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see *Table 5.2*) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have low confidence due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, carbon capture and storage (CCS) with bioenergy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets and reduced food waste, soil sequestration, livestock and manure management, reduced deforestation, afforestation and reforestation, and responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {*5.4, Table 5.2, Figure 5.2*}

Information about the net impacts of mitigation on sustainable development in 1.5 °C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5 °C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in *Figure SPM.4* is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D.4.3 1.5 °C and 2 °C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). (*Figure SPM.4*) {*5.4.1.3, Cross-Chapter Box 7 in Chapter 3*}

D.4.4 Mitigation consistent with 1.5 °C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {*5.4.1.2, Box 5.2*}

D.4.5 Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5 °C pathways. (*high confidence*) {*2.4.3, 5.4.2, Figure 5.5*}

D.5 Limiting the risks from global warming of 1.5 °C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {*2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6*}

D.5.1 Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges, including access to finance and mobilization of funds. (*high confidence*) {*2.5.1, 2.5.2, 4.4.5*}

D.5.2 Adaptation finance consistent with global warming of 1.5 °C is difficult to quantify and compare with 2 °C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5 °C than for 2 °C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and United Nations Framework Convention on Climate Change channels (*medium confidence*). More recently there is a growing understanding of the scale and increase in non-governmental organizations and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*). {*4.4.5, 4.6*}

D.5.3 Global model pathways limiting global warming to 1.5 °C are projected to involve the annual average investment needs in the energy system of around 2.4

trillion USD2010 between 2016 and 2035, representing about 2.5% of the world GDP (*medium confidence*). {*4.4.5, Box 4.8*}

D.5.4 Policy tools can help mobilize incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation, including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*). {*1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4, 4.4.5, 5.5.2*}

D.5.5 The systems transitions consistent with adapting to and limiting global warming to 1.5 °C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {*4.4.4, 4.4.5*}.

D.5.6 Education, information, and community approaches, including those that are informed by indigenous knowledge and local knowledge, can accelerate the wide-scale behaviour changes consistent with adapting to and limiting global warming to 1.5 °C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5 °C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {*1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5*}

D.6 Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5 °C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confidence*). {*Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3***}**

D.6.1 Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5 °C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {*5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5*}

D.6.2 The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {*5.5.1, 5.5.3, Figure 5.1*}

D.6.3 Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5 °C. (*high confidence*) {*2.3.1, 2.5.1, 2.5.3, 5.5.2*}

D.7 Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5 °C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {*1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5***}**

D.7.1 Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5 °C (*very high confidence*). {*1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3*}.

D.7.2 Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing, and cooperation on technology development and transfer can ensure participation, transparency, capacity building and learning among different players (*high confidence*). {*2.5.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3*}

D.7.3 International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5 °C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {*2.3.1, 2.5.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7*}.

D.7.4 Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5 °C, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {*1.4.2, 2.3.1, 2.5.1, 2.5.2, 2.5.3, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3*}

Box SPM.1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {*1.2.1.1*}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {*1.2.1.2*}

Global warming: The estimated increase in GMST averaged over a 30 year period, or the 30 year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30 year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {*1.2.1*}

Net zero CO_2 emissions: Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the pre-industrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {*2.2.2*}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {*2.2.2*}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this *Summary for Policymakers,* the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5 °C are classified as 'no overshoot'; those limiting warming to below 1.6 °C and returning to 1.5 °C by 2100 are classified as '1.5 °C limited-overshoot'; while those exceeding 1.6 °C but still returning to 1.5 °C by 2100 are classified as 'higher-overshoot'.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation and climate resilience.

[19] Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

ATTACHMENT 2

IER INSTITUTE FOR ENERGY RESEARCH.

[*https://www.instituteforenergyresearch.org/climate-change/global-carbon-dioxide-emissions-fell-7-percent-in-2020/*]

INSTITUTE FOR ENERGY RESEARCH

Commentary (*https://www.instituteforenergyresearch.org/type/commentary/*)

Global Carbon Dioxide Emissions Fell 7 Percent in 2020

By IER (*https://www.instituteforenergyresearch.org/about/ier-site-manager/articles*)

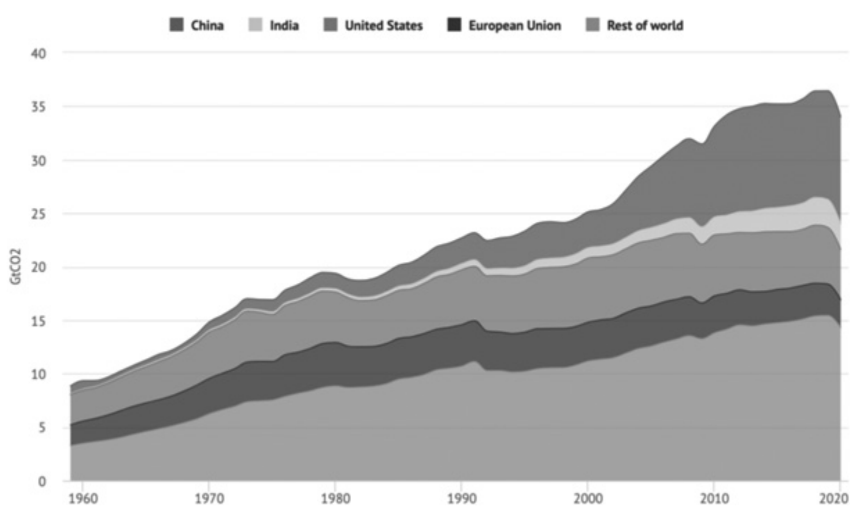
January 26, 2021

Due mainly to the lockdowns from the coronavirus pandemic, carbon dioxide emissions are estimated to have declined by *7 percent globally* [1] in 2020, while U.S. carbon dioxide emissions are estimated to have declined more—by *10.3 percent* [2]—to the lowest level since 1990, 3 decades ago. Despite China's carbon dioxide emissions falling during the first 4 months of 2020, they are expected to have increased as the country had an increase in its GDP of *2.3 percent* [3] in 2020, according to its National Bureau of Statistics—the only major economy to have its economy recover from the coronavirus pandemic. The *International Energy Agency's Birol* [4] agrees with this expected increase in China's carbon dioxide emissions in 2020.

The World

The seven percent [5] annual decline in global carbon dioxide emissions is the largest absolute drop in emissions ever recorded, and the largest relative fall since the second world war. Carbon dioxide emissions have fallen in most of the world's biggest emitters, the United States, the European Union, and India. This year has also seen the first fall in global emissions since a *1.3 percent drop in 2009,* [6] which was driven by the global financial crisis that started in 2008.

Global CO_2 Emissions from Fossil Fuels by Region, 1959–2020



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[1] *https://www.carbonbrief.org/global-carbon-project-coronavirus-causes-record-fall-in-fossil-fuel-emissions-in-2020*.

[2] *https://qz.com/1956081/the-pandemic-took-us-emissions-to-their-lowest-level-in-decades/*.

[3] *https://www.nytimes.com/2021/01/17/business/china-economy-gdp.html*.

[4] *https://www.reuters.com/article/us-china-emissions/chinas-co2-emissions-will-be-higher-in-2020-than-in-2019-says-ieas-birol-idUSKBN28510F*.

[5] *https://www.carbonbrief.org/global-carbon-project-coronavirus-causes-record-fall-in-fossil-fuel-emissions-in-2020*.

[6] *https://www.nature.com/articles/ngeo1022*.

Source: Carbon Brief.[7]

The decline in carbon dioxide emissions in the *EU27*[8] is expected to be 11 percent in 2020. Carbon dioxide emissions from oil, natural gas and cement are estimated to drop by 12 percent, three percent, and five percent, respectively. Consumption of both oil and natural gas, however, have been rebounding in recent years.

A 13-percent decline in emissions is predicted in the UK this year as a result of the extensive lockdown measures introduced in March, plus the second wave of the pandemic. The only country that is expected to have a larger drop in carbon dioxide emissions is France—by 15 percent.

Carbon dioxide emissions in *India*[9]—the world's third largest emitter—increased by just one percent in 2019 before the pandemic hit. This was a result of economic turmoil and strong hydropower generation. Despite a trend of growing emissions in India from oil and coal over the past decade—alongside moderate growth in natural gas and cement—the pandemic is expected to reduce carbon dioxide emissions by seven percent, ten percent, 2 percent and 15 percent, respectively, in 2020 in these four areas. 2020 is the first year in 4 decades in which emissions in India are expected to decline—a nine-percent overall reduction.

United States

The biggest drop in U.S. carbon dioxide emissions was in the transportation sector. For the first 9 months of 2020, carbon dioxide emissions in the transportation sector dropped *15 percent*[10]—similar to air and road passenger travel miles, which fell 15 percent below 2019 levels for the first 10 months of 2020. The *steep drop-off*[11] in air travel was the biggest contributor, with jet fuel consumption falling *68 percent*[12] at the peak of lockdowns in April and May. Gasoline (primarily from passenger vehicles) was down 40 percent in April and May and diesel (used in shipping and trucking) was down 18 percent. Jet fuel demand recovered somewhat bouncing back to around 35 percent below 2019 levels in December based on preliminary data. Diesel spurred by holiday deliveries returned to near 2019 levels in December.

Passenger travel bounced back quickly after travel restrictions were lifted in May and June in most regions. The first round of shelter-in-place orders led to a sharp decline in passenger vehicle travel (measured by vehicle-miles-traveled), dropping *40 percent*[13] at its peak in April. But travel recovered quickly by June (down only 13 percent) with a more gradual recovery through October (the last month of available data).

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[7] *https://www.carbonbrief.org/global-carbon-project-coronavirus-causes-record-fall-in-fossil-fuel-emissions-in-2020.*

[8] *https://europa.eu/european-union/about-eu/countries_en.*

[9] *https://www.carbonbrief.org/the-carbon-brief-profile-india.*

[10] *https://www.eia.gov/totalenergy/data/monthly/pdf/sec11_8.pdf.*

[11] *https://qz.com/1952203/are-people-traveling-by-air-again-despite-covid-19/.*

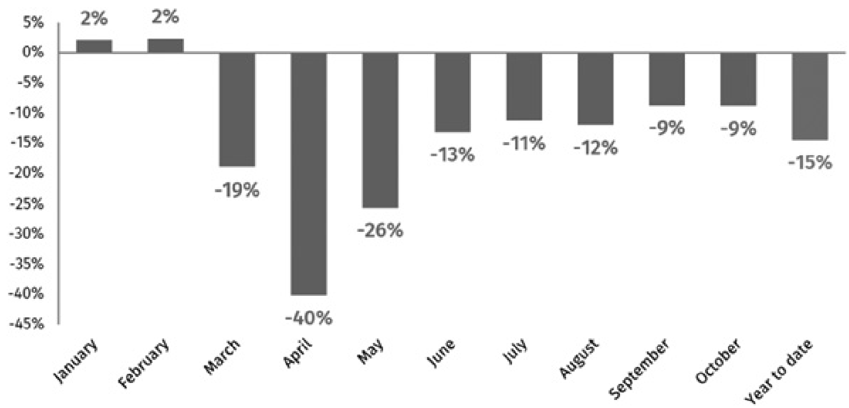
[12] *https://rhg.com/research/preliminary-us-emissions-2020/.*

[13] *https://rhg.com/research/preliminary-us-emissions-2020/.*

Figure 3

Change in Monthly Passenger Vehicle Miles Traveled, 2020 vs. 2019

Percent Change from 2019 Levels



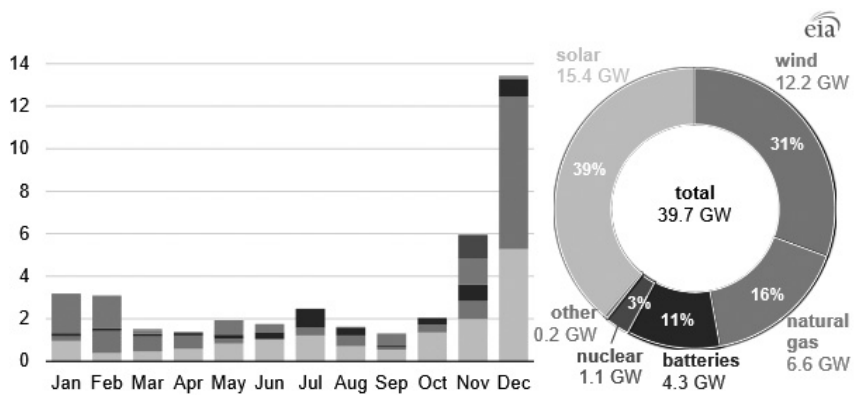
Source: Rhodium Group.[14]

In the U.S. electric power sector, carbon dioxide emissions dropped *12 percent*[15] for the first 9 months of the year. The pandemic hastened current trends, with coal use declining and natural gas and renewable energy increasing. Those trends are expected to continue with solar and wind power *accounting for 70 percent,*[16] 39 percent and 31 percent, respectively, of planned new power installations for 2021 and natural gas accounting for 16 percent, according to the Energy Information Administration (EIA). The new nuclear reactor at the Vogtle power plant in Georgia will account for three percent of the new capacity and batteries for 11 percent. Total new capacity announced by utilities for 2021 is almost 40 gigawatts.

Taxpayers will pay subsidies for the solar, wind, and battery capacity coming on line this year. According to EIA, the average capital cost for solar PV is *$1,331 per kilowatt.*[17] With 15.4 gigawatts of announced capacity, and an investment tax credit of 26 percent, taxpayers will pay $5.3 billion for the solar capacity subsidy in 2021. Battery technology also gets the same subsidy. With 4.3 gigawatts of announced battery capacity at an average cost of *$1,383 per kilowatt*[18] according to EIA, taxpayers will pay $1.55 billion in subsidies. Wind also gets a tax subsidy; it is on the amount of electricity production from the wind turbines and lasts for the first 10 years of their operation.

[14] *https://rhg.com/research/preliminary-us-emissions-2020/.*
[15] *https://www.eia.gov/totalenergy/data/monthly/pdf/sec11_9.pdf.*
[16] *https://www.eia.gov/todayinenergy/detail.php?id=46416&src=email.*
[17] *https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf.*
[18] *https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf.*

Planned U.S. Utility-Scale Electricity Generating Capacity Additions (2021)
gigawatts (GW)



Source: Energy Information Administration.[19]

China

China's *economy shrank 6.8 percent in the January–March*[20] period compared with 2019—the first contraction in nearly half a century as travel and business was nearly halted. Since then, the economy has improved steadily, finishing the year with growth of 6.5 percent in the last 3 months compared to the same period in 2019. Factories across China are filling overseas orders and cranes are busy at construction sites—this boom is expected to drive the economy in 2021.

When Wuhan was still under lockdown, China moved to get manufacturing up and running in other areas. The government provided long-haul buses to get workers from their home villages to factories after the Chinese New Year. State-owned banks extended special loans to factories, while many government agencies gave partial refunds of business taxes that had been paid before the pandemic.

Beijing also ramped up its infrastructure spending. With every major city in China already connected with high-speed rail lines, new lines were added to smaller cities and new expressways crisscrossed remote western provinces. Construction companies turned on floodlights at many sites so that work could continue around the clock.

Despite the trade war and tariffs, American and European companies turned to China for parts and goods when factories elsewhere struggled to meet demand. Factories within China turned to nearby suppliers to replace imports as transoceanic supply lines became less dependable.

Exports and infrastructure fueled much of the growth over the past year. China's exports grew *18.1 percent in December*[21] compared with the same month a year earlier, and were up 21.1 percent in November. Fixed-asset investment in everything from high-speed rail lines to new apartment buildings increased 2.9 percent last year.

The Chinese Academy of Social Sciences predicts that the country's economy would expand *7.8 percent in 2021.*[22] If it does, it would be China's strongest performance in 9 years. With that expansion, the world can expect increased carbon dioxide emissions as China *uses mainly fossil fuels to fuel its economy*[23] and is increasing their use at a breakneck speed.

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[19] *https://www.eia.gov/todayinenergy/detail.php?.*
[20] *https://www.nytimes.com/2020/04/16/business/china-coronavirus-economy.html.*
[21] *https://www.nytimes.com/2021/01/17/business/china-economy-gdp.html.*
[22] *https://www.nytimes.com/2021/01/17/business/china-economy-gdp.html.*
[23] *https://www.instituteforenergyresearch.org/international-issues/chinas-economy-is-based-on-fossil-fuels/.*

Birol, the head of the International Energy Agency, expects[24] China's oil demand to be slightly higher in 2020 than it was in 2019, and its natural gas demand to be much higher in 2020 compared to 2019. China has been and is being hit with an *extreme cold spell*[25] that will increase its heating fuel demand.

Conclusion

Most countries are expected to lower their carbon dioxide emissions in 2020 due to lockdowns caused by the coronavirus pandemic. The only exception is China, whose economy grew by 2.3 percent in 2020 and who is taking advantage of the downturn in manufacturing in other countries, increasing its exports tremendously by the end of 2020. It appears China is very serious about spurring its economic growth for its citizens' welfare and is using more energy—fossil energy—to do so.

ATTACHMENT 3

[*https://www.nationalgeographic.com/science/article/plunge-in-carbon-emissions-lockdowns-will-not-slow-climate-change*]

NATIONAL GEOGRAPHIC

NATIONAL GEOGRAPHIC

Power plants, industry, and other carbon-emitting activities kept on belching out greenhouse gases during the coronavirus-related lockdowns.
Photograph By Bartek Sadowski, *Bloomberg*/Getty Images.

Plunge in carbon emissions from lockdowns will not slow climate change

Emissions may be down, but carbon dioxide still piles up relentlessly in the atmosphere. It's more important than ever to find climate change solutions, experts say.

By ALEJANDRA BORUNDA

Published May 20, 2020

In May, the concentration of carbon dioxide in the atmosphere crept up to *about 418 parts per million.*[1] It was the highest ever recorded in human history and likely higher than at any point in the last 3 million years.

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[24] *https://www.reuters.com/article/us-china-emissions/chinas-co2-emissions-will-be-higher-in-2020-than-in-2019-says-ieas-birol-idUSKBN28510F.*

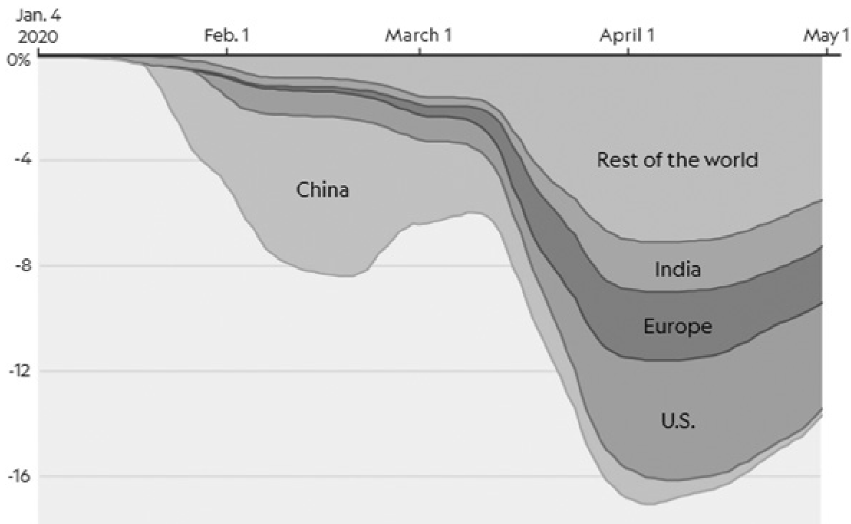
[25] *https://www.instituteforenergyresearch.org/.*

[1] *https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html.*

That record was broken in the midst of the coronavirus pandemic, even though the health crisis has driven one of the largest, most dramatic drops in CO_2 emissions ever recorded. During the peak of the global confinements in the first quarter of the year, daily emissions were about 17 percent below last year's, according to research published this week in *Nature Climate Change.*[2]

But even such big drops in carbon dioxide emissions will have *little impact on overall CO_2 concentration*[3] in the atmosphere, says *Richard Betts*[4]—a scientist at the U.K.'s Met Office—and that's what matters most for climate change.

Percentage change in global daily fossil CO_2 emissions, since Jan. 4, 2020



Ng Staff.
Source: Le Quéré, *et al. Nature Climate Change* (2020); Global Carbon Project.

The pandemic has disrupted life around the world, and stay-at-home orders have kept large swaths of the world at home for months now. But the disruption only results in a tiny drop in the overall concentration of CO_2 in the atmosphere because of how long the gas effectively lingers.

So that record concentration of 418 parts per million? That would have been just 0.4 parts per million higher without the virus-driven emissions drop, according to an analysis posted on climate science and policy website *CarbonBrief*[5] earlier in May.

Still, for energy and climate expert *Constantine Samaras,*[6] the message is clear: Just because this devasting pandemic has only a small impact on today's CO_2 levels doesn't mean the climate crisis is lost.

"A pandemic is the worst possible way to reduce emissions. There's nothing to celebrate here," says Samaras, of Carnegie Mellon University. "We have to recognize that, and to recognize that technological, behavioral, and structural change is the best and only way to reduce emissions."

What did we see with CO_2 emissions *vs.* concentrations?

During this unprecedented, deadly global event, millions of people who could stay at home did just that. Cars sat in driveways. Air travel ground to a halt. Manufacturing plants slowed or stopped. Public buildings shut their doors. Even construction slowed down. Nearly every sector of the energy-using economy reacted to the shock in one way or another.

[2] *https://www.nature.com/articles/s41558-020-0797-x.*
[3] *https://www.nationalgeographic.com/environment/article/global-warming-causes.*
[4] *https://www.metoffice.gov.uk/research/people/richard-betts.*
[5] *https://www.carbonbrief.org/analysis-what-impact-will-the-coronavirus-pandemic-have-on-atmospheric-co2.*
[6] *https://www.cmu.edu/cee/people/faculty/samaras.html.*

The result was one of the biggest single drops in modern history in the amount of carbon dioxide humans emit.

Over the first few months of 2020, global daily CO_2 emissions averaged about 17 percent lower than in 2019. At the moments of the most restrictive and extensive lockdowns, emissions in some countries hovered nearly 30 percent below last year's averages, says *Glen Peters,*[7] one of the authors of the *Nature Climate Change* analysis and a climate scientist at Norway's Center for International Climate Research.

China's emissions decreased by about a quarter in February. Other countries saw drops of a few percent in March and April, a team led by Tsinghua University's *Zhu Liu*[8] found in a *separate analysis.*[9] The effects, in some ways, are big—but in other ways, not big enough, he says.

"Only when we would reduce our emissions even more than this for longer would we be able to see the decline in concentrations in the atmosphere," he says. "We would probably need, like, a 20 percent reduction for the whole year—so every month, for the whole world, like April. But the world cannot suffer so long a lockdown."

The International Energy Agency estimates that by the end of 2020, global emissions will decline by *about eight percent*[10] compared to last year. That would work out to about 2.6 billion tons of carbon not added to the atmosphere. The Nature Climate Change team estimates that drop to be somewhere between four to seven percent, depending on the way lockdowns develop over the rest of the year. If people are driven back into their homes by rising COVID–19 infection rates, emissions could fall even more.

But that doesn't mean the carbon dioxide problem is solved, or even that there will be much positive effect on skies overfull with CO_2.

"Climate change is a cumulative problem," says Peters. "It's not like other pollution, where someone is putting something in the river and then they stop putting it in the river and [the] problem is solved. It's all our emissions in the past that matter."

Think of the atmosphere as a bathtub. Human-driven CO_2 emissions are like the water coming out of the tap. The ocean and land, which absorb or use up some of that CO_2, are the drain—but even when they're wide open, they can only let out half the water that comes in.

When a momentous event like this pandemic happens to push CO_2 emissions down, it's as if the bath's tap has been shut by 17 percent. But over 80 percent of the water is still gushing into the tub, so the water level in the tub will still rise. It might not fill quite as quickly as it did before, but it's definitely not draining completely.

In short, even though emissions have dropped, CO_2 is still going into the atmosphere and it will still accumulate there, just as it has since humans started burning vast amounts of fossil fuels.

"We treat the atmosphere like this big waste dump," says *Ralph Keeling,*[11] a scientist at the Scripps Institution of Oceanography whose lab runs the *Mauna Loa long-term monitoring project of atmospheric CO_2.*[12] "But when you throw something in the trash, it's still in the landfill. It's still out there. We can't just sweep it away."

What does this emissions drop mean for for climate?

Scientists have a pretty good idea of how much more atmospheric CO_2 will accumulate each year: about half as much as we pump up there (the other half gets absorbed by plants and the oceans). Each year, the average concentration gets higher. *In 2018, for example, concentrations rose by 2.5 parts per million,*[13] to an average of 407.4; 2019 averages have not yet been released, but a similar value is expected.

On top of this rising pattern—which depends primarily on how much humans emit—CO_2 concentrations go up and down during the seasons. They're highest in late spring each year, as plants around the Northern Hemisphere wake up from the winter and gobble up the carbon food, and lowest in early fall, as plants slow down for the coming winter (the Northern Hemisphere has so much more land and plants than the southern that it dominates the pattern).

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[7] *https://cicero.oslo.no/no/rapid-response-glen-peters.*
[8] *https://scholar.harvard.edu/zhu/home.*
[9] *https://arxiv.org/pdf/2004.13614.pdf.*
[10] *https://www.iea.org/news/global-energy-demand-to-plunge-this-year-as-a-result-of-the-biggest-shock-since-the-second-world-war.*
[11] *https://rkeeling.scrippsprofiles.ucsd.edu/.*
[12] *https://www.esrl.noaa.gov/gmd/obop/mlo/.*
[13] *https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/.*

Betts and his colleagues run a model that makes these predictions for the coming year. Their forecasts *are usually remarkably accurate.*[14] As soon as it became clear that coronavirus would suppress emissions this year, they realized that they could figure out exactly how much the drop would affect the overall concentrations of CO_2 in the atmosphere.

By the beginning of the pandemic, Betts's team had already predicted what atmospheric CO_2 was supposed to do in 2020. They forecast that in May, at the peak of the gas's annual seasonal cycle, its concentration would probably hover around 417 ppm (and sure enough, in early May the station saw a concentration of just over 418 parts per million.) The team also expected that at its seasonal low in September, it would be around 410 parts per million. So the final prediction, for the average over the course of the year: 414 parts per million. That's barely different than what the team expected without the coronavirus-related impacts.

"The message of all that is that there's a limit of what you can do with individual actions," says Betts—actions such as driving or flying less. "We've probably done as much as we can, personally, to reduce our own emissions during this devastating time."

So, he says, "it's not about going back to the way things were, but to a better way."

We're still emitting way too much CO_2

What Betts showed was the dark side of the emissions problem. Even with all this economic upheaval and the emotional toll of isolating, our emissions have dropped only 17 percent in the short term and will likely drop by less than ten percent for the year. The effects of those declines on the overall greenhouse gas problem are infinitesimal.

Framed another way: We're still spitting out more than 80 percent as much CO_2 as normal, even when life feels devastatingly different. Staying home, it is abundantly clear now, is far from enough to solve the climate crisis.

"From humanity's perspective, the COVID–19 pandemic is the largest event many of us have ever experienced. It affects literally everyone on the planet," says *Anna Michalak,*[15] a scientist at Stanford's Carnegie Institution for Science.

"In a way, it's hard to mentally reconcile that with just a small difference in emissions; it seems almost dismissive. But what's important to remember is that this shows how the use of carbon as a fuel source is so deeply embedded in every aspect of how humanity runs itself, so the emissions keep happening," she says.

The IPCC has warned that global temperature rises should be limited to *2.7 °F (1.5 °C)*[16] beyond pre-industrial levels in order to keep *the worst,*[17] *most devastating*[18] effects of climate change from battering human societies. To hit that goal, overall human-caused greenhouse gas emissions need to *start dropping by about 7.6 percent each year*[19] from now until 2030 (and beyond). Eventually, of course, they need to get to zero.

This year's emissions drop is right around eight percent. Samaras says that in no way represents what a concerted global effort to actually hit that goal would do. But it also shouldn't be taken as an indication that efforts would be futile.

"The message shouldn't be: It's too hard," he says. "The message should be: We have to work hard to find a way to do this well."

Where is all the CO_2 still coming from?

The Nature Climate Change team split the CO_2 sources into six categories and looked at how much each changed between January and April, while countries rolled in and out of confinement.

The biggest change in activity was in aviation; it dropped by an average of 75 percent by early April. But planes only make up about three percent of the CO_2 emissions problem, so even that giant decrease has had only a small effect on the gushing of the CO_2 "tap."

The other huge change was in surface transport such as cars and trucks, where daily activity sank an average of 50 percent. That change translated into a big effect on emissions, because driving makes up a bigger piece of the normal CO_2-waste pie.

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[14] *https://royalsocietypublishing.org/doi/10.1098/rstb.2017.0301.*

[15] *https://dge.carnegiescience.edu/people/michalak.*

[16] *https://www.nationalgeographic.com/environment/article/ipcc-report-climate-change-impacts-forests-emissions.*

[17] *https://www.nationalgeographic.com/environment/article/climate-change-model-warns-of-difficult-future.*

[18] *https://www.nationalgeographic.com/environment/article/ipcc-un-food-security.*

[19] *https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf?sequence=1&isAllowed=y.*

In the 4 months that people drove less, about 6 megatons of CO_2 didn't go into the atmosphere each day, equal to about 1.2 million American cars' yearly mileage.

About 45 percent of the world's CO_2 waste generally comes from making heat and power. During the crisis, people needed those almost as much as ever. Emissions from power use dropped by about 15 percent—which translated into about 3.3 megatons of CO_2 not added to the atmosphere each day.

All in all, the reduction in daily emissions got us, as a planet, back down to the levels we were at in 2006. The IPCC's 2.7 °F goals suggest that we need to get back to 1990s emissions levels within about a decade.

"This pandemic—it's tragic," says Michalak. "It's not anyone's preferred way to get [CO_2 reductions]. But what this experience does show is when humanity is united around a goal, big changes can happen on short time scales."

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