S. HRG. 114–53

THE IMPACTS OF EPA'S PROPOSED CARBON REGULATIONS ON ENERGY COSTS FOR AMERICAN BUSINESSES, RURAL COMMUNITIES AND FAMILIES, AND A LEGISLATIVE HEARING ON S. 1324

HEARING

BEFORE THE

SUBCOMMITTEE ON CLEAN AIR
AND NUCLEAR SAFETY

OF THE

COMMITTEE ON
ENVIRONMENT AND PUBLIC WORKS
UNITED STATES SENATE

ONE HUNDRED FOURTEENTH CONGRESS

FIRST SESSION

JUNE 23, 2015

Printed for the use of the Committee on Environment and Public Works

Available via the World Wide Web: http://www.gpo.gov/fdsys

U.S. GOVERNMENT PUBLISHING OFFICE
95–744 PDF WASHINGTON : 2015

For sale by the Superintendent of Documents, U.S. Government Publishing Office
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C O N T E N T S

THE IMPACTS OF EPA'S PROPOSED CARBON REGULATIONS ON ENERGY COSTS FOR AMERICAN BUSINESSES, RURAL COMMUNITIES AND FAMILIES, AND A LEGISLATIVE HEARING ON S. 1324

TUESDAY, JUNE 23, 2015

U.S. SENATE,
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS,
SUBCOMMITTEE ON CLEAN AIR AND NUCLEAR SAFETY,
Washington, DC.

The subcommittee met, pursuant to notice, at 2:05 p.m. in room 406, Dirksen Senate Building, Hon. Shelley M. Capito (chairman of the subcommittee) presiding.

Present: Senators Capito, Carper, Barrasso, Crapo, Sessions, Fischer, Merkley, Markey, and Inhofe.

OPENING STATEMENT OF HON. SHELLEY MOORE CAPITO, U.S. SENATOR FROM THE STATE OF WEST VIRGINIA

Senator CAPITO. I am going to go ahead and begin.

I know Senator Carper is planning to be here. When he gets here, we will make time for him to make his opening statement. In the interest of the panelists and other Senator, I think it would be best to go ahead and move on.

I want to welcome everyone to the hearing of the Clean Air and Nuclear Safety Subcommittee. The hearing is entitled The Impacts of EPA's Proposed Carbon Regulations on Energy Costs for American Businesses, Rural Communities and Families, and a Legislative Hearing on my bill, S. 1324, better known as the ARENA Act, Affordable Reliable Electricity Now Act.

I introduced ARENA in May and am proud to have more than 30 co-sponsors, including Leader McConnell, Chairman Inhofe, and all my fellow Environment and Public Works Committee Republicans. I introduced ARENA and am holding this hearing today because of the devastating impact that EPA's proposed regulations will have on the families and businesses in my home State of West Virginia and across the Nation.

I am not exaggerating when I say almost every day back home in West Virginia, there are new stories detailing closed plants, lost jobs, and price increases. I have a letter here sent to me by Ammar's Inc., a family owned company that operates 19 Magic Mart stores in West Virginia, Virginia and eastern Kentucky. The letter is accompanied by a petition signed by 26,000 Magic Mart customers, calling on EPA to end its war on coal and catastrophic impact on local economies.

Ammar's Inc. has been active in the region for 95 years, and according to this letter, the present economic crunch is the most difficult challenge the company has faced. Let me quote directly: "There was a time when your greatest obstacle was your competitor, but if you worked hard, took care of your customers and offered quality merchandise at a fair price, you could compete successfully. Unfortunately, that is now not the case. The largest impediment we have to operating our business successfully is our own government, particularly the EPA. The rulings issued by the EPA have devastated our regional economy."

Coal provided 96 percent of West Virginia's electricity last year. West Virginia had among the lowest electricity prices in the Nation. The average price was 27 percent below the national average, but that advantage will not survive this Administration's policies. Studies project our electricity prices will between 12 and 16 percent.

Earlier this month, 450,000 West Virginians learned of a 16 percent increase in the cost of electricity. While there were multiple factors that contributed to this rate increase, compliance with previous EPA regulations played a significant part. If we allow EPA's plan to move forward, last week's rate increase will only be the tip of the iceberg.

Affordable energy matters. The 430,000 low and middle income families in West Virginia, nearly 60 percent of our State's households, take home an average of less than $1,900 a month and spend 17 percent of their after-tax income on energy. These families are especially vulnerable to the price increases that will result from the Clean Power Plan.

This is not just about the impacts on coal producing States like West Virginia. This is about the impacts across the United States.

It is important to note that all electricity has to come from somewhere. In many States, odds are that it is being imported from a State that relies on coal, but no one talks about that.

We will learn from some of the testimony about the Regional Greenhouse Gas Initiative, RGGI. One of the witnesses we will hear from today, Mr. Martens, thank you for coming, is affiliated with RGGI, a program of nine northeastern States that uses market principles to reduce greenhouse gas emissions from the power sector.

Mr. Martens may not mention that RGGI's nine States consume five times more energy than they produce. My little State of West Virginia produces twice as much energy as all nine of the RGGI States combined.

There are energy-producing States and there are energy-consuming States. Only 13 States produce more energy than they consume. West Virginia ranks second and Wyoming ranks first. For 10 of the 13 States that export energy, coal is critical to maintaining that net positive result.

Put simply, there is no way that this massive, largely EPA-driven reduction in coal-fired electricity generation is going to impact only coal States. It is going to impact the majority of States, the families and businesses within them. Often, the poorest and most vulnerable populations will bear the brunt of this increase.

I look forward to hearing in greater detail from our witnesses about the impact of these proposed regulations and the need for clean air policies that do not overburden our States and cripple our economy.

With that, we will begin testimony of our panelists. Our first panelist is Mr. Eugene M. Trisko. Welcome and thank you for coming.

[The prepared statement of Senator Capito follows:]

STATEMENT OF HON. SHELLEY MOORE CAPITO, U.S. SENATOR FROM THE STATE OF WEST VIRGINIA

Welcome to this hearing of the Clean Air and Nuclear Safety Subcommittee entitled "The Impacts of EPA's proposed Carbon Regulations on Energy Costs for American Businesses, Rural Communities and Families, and a legislative hearing on S. 1324". S. 1324 is better known as the Affordable Reliable Electricity Now Act, or ARENA. I introduced ARENA in May and am proud to have more than 30 cosponsors, including Leader McConnell, Chairman Inhofe, and all my fellow EPW Republicans.

I introduced ARENA and am holding this hearing today because of the devastating impact that EPA's proposed regulations will have on the families and businesses in my home State and across the Nation. I am not exaggerating when I say almost every day back home in West Virginia, there are new stories detailing plants closed, jobs lost, and price increases.

I have a letter here sent to me yesterday from Ammar's Inc., a family owned company that operates 19 Magic Mart stores in West Virginia, Virginia and Kentucky. The letter is accompanied by a petition signed by 26,000 Magic Mart customers, calling on EPA to end its war on coal and catastrophic impact on local economies.

Ammar's Inc. has been active in the region for 95 years, and according to this letter, the present economic crunch is the most difficult challenge the company has faced. Let me quote directly:

"There was a time when your greatest obstacle was your competitor, but if you worked hard, took care of your customers and offered quality merchandise at a fair price, you could compete successfully. Unfortunately, that is now not the case. The largest impediment we have to operating our business successfully is our own government, particularly the EPA. The rulings issued by the EPA have devastated our regional economy."

Coal provided 96 percent of West Virginia's electricity last year. West Virginia has among the lowest electricity prices in the Nation: last year, the average price was 27 percent below the national average. But that advantage will not survive this Administration's policies. Studies have projected the Clean Power Plan will raise electricity prices in West Virginia by between 12 and 16 percent.

Earlier this month, 450,000 West Virginians learned of a 16 percent increase in the cost of electricity. While there were multiple factors that contributed to this rate increase, compliance with previous EPA regulations played a significant part. If we allow EPA's plan to move forward, last week's rate increase will only be the tip of the iceberg.

Affordable energy matters. The 430,000 low and middle income families in West Virginia—nearly 60 percent of our State's households—take home an average of less than $1900 a month and spend 17 percent of their after tax income on energy. These families are especially vulnerable to the price increases that will result from the Clean Power Plan.

But this isn't just about the impacts on coal producing States like West Virginia. This is about the impacts across the United States.

It is important to note that all electricity has to come from somewhere. In many States, odds are that it is being imported from a State that relies on coal. But no one is talking about that.

Turning to the Regional Greenhouse Gas Initiative (RGGI) States. One of the witnesses we will hear from today, Mr. Martens, is affiliated with RGGI, a program of nine northeastern States that uses market principles to reduce greenhouse gas emissions from the power sector. Mr. Martens probably won't mention that RGGI's nine States consume five times more energy than they produce. Or that my little State of West Virginia produces twice as much energy as all nine of the RGGI States combined.

There are energy producing States, and there are energy consuming States. Only 13 States produce more energy than they consume. West Virginia ranks second, behind only Wyoming. And for 10 of the 13 States that export energy, coal is critical to maintaining that net positive result.

Put simply, there is no way that this massive, largely EPA-driven reduction in coal fired electricity generation is going to impact only coal States. It's going to impact the majority of States, and the families and businesses within them. Often, the poorest and most vulnerable populations will bear the brunt of this increase.

I look forward to hearing in greater detail from our witnesses about the impact of these proposed regulations and the need for clean air policies that don't over burden our States and cripple our economy.

STATEMENT OF HON. EUGENE M. TRISKO, ATTORNEY AT LAW, ON BEHALF OF THE UNITED MINE WORKERS OF AMERICA

Mr. TRISKO. Thank you very much, Chairman Capito, Chairman Inhofe and distinguished members.

I am Eugene Trisko, an energy economist and attorney in private practice. I am here today to summarize the findings of a study of the impacts of energy costs on American families.

I have conducted household energy cost studies periodically since 2000 for the American Coalition for Clean Coal Electricity and its predecessor organizations. The study I will summarize today, Energy Cost Impacts on American Families, estimates consumer energy costs for households in 2016.

The principal findings of this study are as follows. One, some 48 percent of American families have pre-tax annual incomes of $50,000 or less, with an average after-tax income among these households of $22,732 or a take-home income of less than $1,900 per month.

Second, 48 percent of households earning less than $50,000 devote an estimated average of 17 percent of their after tax incomes to residential and transportation energy. Energy costs for the 29 percent of households earning less than $30,000 before taxes represent 23 percent of their after-tax family incomes, before accounting for any energy assistance programs. This 23 percent of income is more than three times higher than the 7 percent of gross income paid for energy by households earning more than $50,000 per year.

Third, American consumers have benefited recently from lower gasoline prices, but higher oil prices are now reducing consumer savings at the gas pump. Meanwhile, residential electricity prices are continuing to rise. Residential electricity represents 69 percent of total household utility bills.

A 2011 survey of low-income households for the National Energy Assistance Directors Association reveals some of the adverse health and welfare impacts of high energy costs. Low-income households reported these responses to high energy bills.

Twenty-four percent went without food for at least 1 day. Thirty-seven percent went without medical or dental care. Thirty-four percent did not fill a prescription or took less than the full dose. Nineteen percent had someone become sick because their home was too cold. The relatively low median incomes of minority and senior households detailed in the study attached to my statement indicate that these groups are among those most vulnerable to energy price increases.

Recent and prospective increases in residential energy costs should be assessed in the context of the long-term declining trend of real income among American families. The U.S. Census Bureau reports that the real pre-tax incomes of American households have declined across all five income quintiles since 2001, measured in constant 2013 prices. The largest percentage losses of income are in the two lowest income quintiles. In 2014, the average price of residential electricity in the U.S. was 32 percent above its level in 2005, compared with the 22 percent increase in the Consumer Price Index.

DOE projects continued escalation of residential electricity prices due to the cost of compliance with environmental regulations and other factors. Moreover, DOE, EPA, NERA and others project that electricity prices will increase even more because of EPA's proposed Clean Power Plan.

Lower income families are more vulnerable to energy cost increases than higher income families because energy represents a larger portion of their household budgets. Energy costs reduce the amount of income that can be spent on food, housing, health care and other basic necessities.

Fixed income seniors are among the most vulnerable to energy cost increases due to their relatively low average incomes and high per capital energy use. Senior citizens and other low income groups will bear the burden of higher energy costs imposed by EPA's Clean Power Plan but will be among the least likely to invest in or to benefit from the energy efficiency programs the proposed rule envisions.

Thank you for the opportunity.

[The prepared statement of Mr. Trisko follows:]

Statement of Eugene M. Trisko
Before the Committee on Environment & Public Works
Subcommittee on Clean Air and Nuclear Safety
U.S. Senate
June 23, 2015

Good afternoon, Chair Capito, Ranking Member Carper, and distinguished members of the Subcommittee. I am Eugene Trisko, an energy economist and attorney in private practice. A brief bio is attached to my statement.

I am here today to summarize the findings of a study of the impacts of energy costs on American families. I have conducted household energy cost studies periodically since 2000 for the American Coalition for Clean Coal Electricity and its predecessor organizations. The study I will summarize today, Energy Cost Impacts on American Families, estimates consumer energy costs for households in 2016. It is based on U.S. Census Bureau household income data, Congressional Budget Office data on federal income taxes and social security payments, and U.S. DOE/EIA energy price projections and energy consumption data for residential utilities and gasoline. A copy of the study is attached to my statement.

The principal findings of this study are:

1) Some 48% of American families have pre-tax annual incomes of $50,000 or less, with an average after-tax income among these households of $22,732, less than $1,900 per month. In other words, nearly half of U.S. families - some 59 million households - have average take-home incomes of less than $1,900 per month.

2) Energy costs are consuming the after-tax household incomes of America's lower- and middle-income families at levels comparable to other necessities such as housing, food, and health care. The 48% of households earning less than $50,000 devote an estimated average of 17% of their after-tax incomes to residential and transportation energy. Energy costs for the 29% of households earning less than $30,000 before taxes represent 23% of their after-tax family incomes, before accounting for any energy assistance programs.

3) American consumers have benefitted recently from lower gasoline prices, but higher oil prices are now reducing consumer savings at the gas pump. Meanwhile, residential electricity prices are rising due to the costs of compliance with U.S. EPA and other regulations, and other factors such as fuel and capital costs. Residential electricity represents 69% of total household utility bills.

4) A 2011 survey of low-income households for the National Energy Assistance Directors Association reveals some of the adverse health and welfare impacts of high energy costs. Low-income households reported these responses to high energy bills:

· 24% went without food for at least one day.
· 37% went without medical or dental care.
· 34% did not fill a prescription or took less than the full dose.
· 19% had someone become sick because their home was too cold.

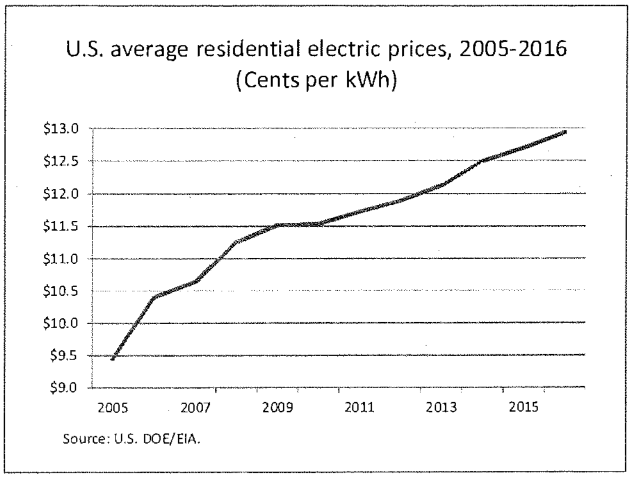
5) The relatively low median incomes of minority and senior households indicate that these groups are among those most vulnerable to energy price increases. The median pre-tax income of Black households, representing 13% of U.S. households, is 33% below the U.S. median income of $51,939. The median income of Hispanic households, 13% of all households, is 21% below the national median income. American households aged 65 or more, 23% of all households, have a median income 31% below the U.S. median.

Recent and prospective increases in residential energy costs should be assessed in the context of the long-term declining trend of real income among American families. The U.S. Census Bureau reports that the real pre-tax incomes of American households have declined across all five income quintiles since 2001, measured in constant 2013 prices. As shown in the table below, the largest percentage losses of income are in the two lowest income quintiles. Households in the lowest quintile lost 13% of their real income between 2001 and 2013.

Real U.S. pre-tax household incomes by income quintile,
2001-2013
(In constant 2013 $)

	1Q	2Q	3Q	4Q	5Q
2001	$13,336	$33,510	$56,090	$87,944	$192,063
2013	$11,651	$30,509	$52,322	$83,519	$185,206
% Chg	-13%	-9%	-7%	-5%	-4%
$ Chg	($1,685)	($3,001)	($3,768)	($4,425)	($6,857)

In 2014, the average price of residential electricity in the U.S. was 32% above its level in 2005, compared with a 22% increase in the Consumer Price Index during this period. DOE/EIA projects continued escalation of residential electricity prices due to the costs of compliance with environmental regulations and other factors, including fuel, capital, and operating and maintenance costs. Moreover, EIA, EPA, National Economic Research Associates, and others project that electricity prices will increase even more because of EPA's proposed Clean Power Plan.



The share of household income spent for energy falls disproportionately on lower- and middle-income families earning less than $50,000 before taxes. While many lower-income consumers qualify for energy assistance, Congress has pared back budgetary support for these programs in recent years. The $3.0 billion that Congress has appropriated for the LIHEAP energy assistance program compares with estimated total residential energy expenditures of some $62 billion for the 36 million households with gross pre-tax incomes less than $30,000.

Lower-income families are more vulnerable to energy costs than higher-income families because energy represents a larger portion of their household budgets. Energy costs reduce the amount of income that can be spent on food, housing, health care, and other basic necessities.

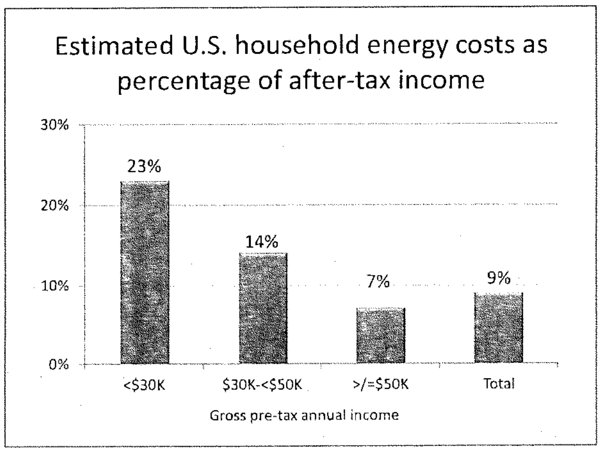
Fixed-income seniors are a growing proportion of the U.S. population, and are among the most vulnerable to energy cost increases due to their relatively low average incomes and high per capita energy use. In 2013, the median pre-tax income of 29 million households with a principal householder aged 65 or older was $35,611, 31% below the national median household income of $51,939. Senior citizens and other lower-income groups will bear the burden of higher energy costs imposed by EPA's Clean Power Plan, but will be among the least likely to invest in – or benefit from - the energy efficiency programs that the proposed rule envisions.

Thank you for the opportunity to appear before you today. I am happy to answer any questions that the Subcommittee may have.

ACCCE
AMERICAN COALITION FOR CLEAN COAL ELECTRICITY

Energy Cost Impacts on American Families

Rising electricity prices and declining family incomes are straining the budgets of America's lower- and middle-income families. U.S. households with pre-tax annual incomes below $50,000, representing 48% of the nation's households, spend an estimated average of 17% of their after-tax income on residential and transportation energy. Energy costs for the 29% of households earning less than $30,000 before taxes represent 23% of their after-tax family incomes, before accounting for any energy assistance programs. Minorities and senior citizens are among the most vulnerable to energy price increases due to their relatively low household incomes.



June 2015
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Energy Cost Impacts on American Families

This paper assesses the impact of energy costs on U.S. households using energy consumption survey data and energy price data and projections from the U.S. Department of Energy's Energy Information Administration (DOE/EIA).[1] Energy costs are summarized by household income group using data from the Bureau of the Census, tax data from the Congressional Budget Office, and state income tax rates.[2] Due to recent volatility in energy markets, energy expenditure estimates are based on DOE/EIA energy price projections for 2016.

Key findings include:

- Some 48% of American families have pre-tax annual incomes of $50,000 or less, with an average after-tax income among these households of $22,732, less than $1,900 per month. In other words, nearly half of U.S. families - some 59 million households - have average take-home income of less than $1,900 per month.

- Energy costs are consuming the after-tax household incomes of America's lower- and middle-income families at levels comparable to other necessities such as housing, food, and health care. The 48% of households earning less than $50,000 devote an estimated average of 17% of their after-tax incomes to residential and transportation energy.

- American consumers have benefitted in recent months from lower gasoline prices, but rising oil prices are now reducing consumer savings at the gas pump. Meanwhile, residential electricity prices are rising due to the costs of compliance with U.S. EPA and other regulations, and other factors such as fuel and capital costs. Residential electricity represents 69% of total household utility bills.

- A 2011 survey of low-income households for the National Energy Assistance Directors Association reveals some of the adverse health and welfare impacts of high energy costs. Low-income households reported these responses to high energy bills:

  - 24% went without food for at least one day.
  - 37% went without medical or dental care.
  - 34% did not fill a prescription or took less than the full dose.
  - 19% had someone become sick because their home was too cold.

- The relatively low median incomes of minority and senior households indicate that these groups are among those most vulnerable to energy price increases. Median income is the midpoint, where one-half of households have incomes above this amount, and one-half have incomes below it. The median pre-tax income of Black households, representing 13% of U.S. households, is 33% below the U.S. median income of $51,939. The median income of Hispanic households, 13% of all households, is 21% below the national median income. American households aged 65 or more, 23% of all households, have a median income 31% below the U.S. median.

U.S. Household Incomes

U.S. Census Bureau data on household incomes in 2013 (the most recent available) provide the basis for estimating the effects of energy prices on consumer budgets. The table below shows estimated 2013 after-tax incomes for U.S. families in different income brackets. The Congressional Budget Office has calculated effective total federal tax rates, including individual income taxes and payments for Social Security and other social welfare programs. State income taxes are estimated from current state income tax rates.

U.S. households by pre-tax and after-tax income, 2013

Pre-tax annual income:	<$30K	$30-<$50K	<$50K	≥$50K	Total/avg.
Households (Mil.)	35.8	23.1	59.0	64.0	123.0
Pct. of total households	29%	19%	48%	52%	100.0%
Avg. pre-tax income	$15,931	$39,158	$25,043	$116,503	$72,641
Effec. fed tax rate %	4.2%	11.0%	6.9%	19.7%	19.4%
Est. state tax %	0.5%	3.5%	2.4%	6.3%	4.4%
Est. after-tax income	$15,003	$33,480	$22,732	$86,212	$55,344

Some 48% of U.S. families, 59 million households, had estimated pre-tax incomes below $50,000 in 2013. After federal and state taxes, these families had average annual incomes of $22,732, equivalent to an average monthly take-home income of less than $1,900.

The U.S. Census Bureau reports that the real pre-tax incomes of American families have declined across all five income quintiles since 2001, measured in constant 2013 dollars.[3] The loss of real pre-tax incomes is due to a number of factors, including the lack of real wage growth among most American workers,[4] the loss of high-wage jobs in manufacturing and other industry sectors,[5] and the increased share of relatively low-paying jobs in service sectors such as retail trade and food services.[6]

As shown in the table below, the largest losses of income are in the two lowest income quintiles. Households in the lowest quintile lost 13% of their real income between 2001 and 2013. Declining real incomes increase the vulnerability of lower- and middle-income households to energy price increases such as rising utility bills.

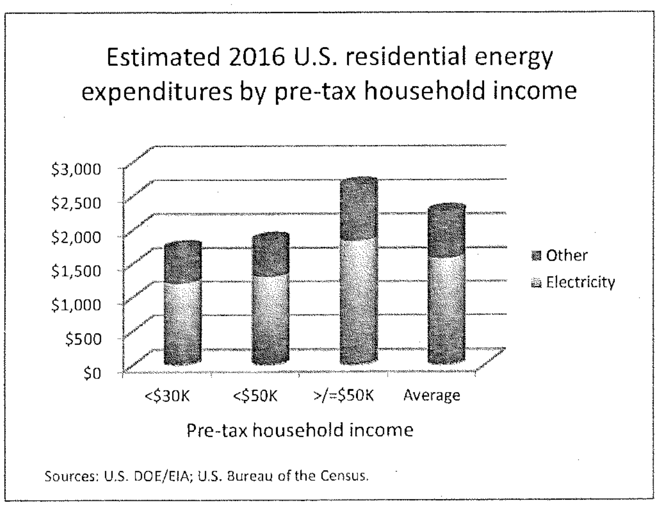
Average real U.S. household incomes by income quintile, 2001-2013
(In 2013 $)

	1Q	2Q	3Q	4Q	5Q
2001	$13,336	$33,510	$56,090	$87,944	$192,063
2013	$11,651	$30,509	$52,322	$83,519	$185,206
Pct Chg	-13%	-9%	-7%	-5%	-4%
$ Chg	($1,685)	($3,001)	($3,768)	($4,425)	($6,857)

Residential and Transportation Energy Expenses

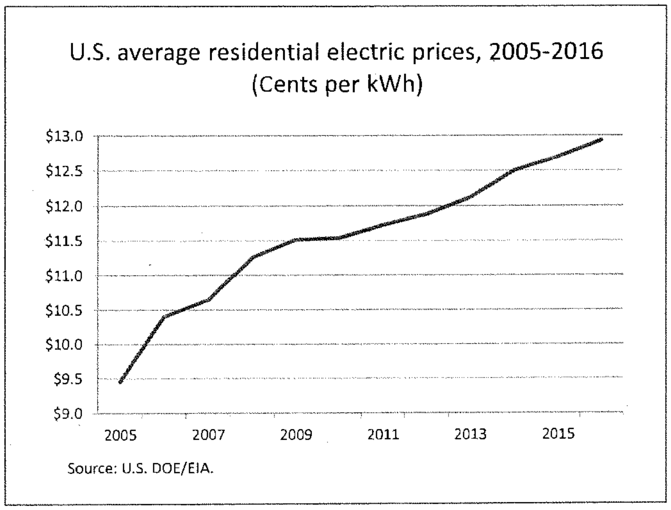
U.S. households are projected to spend an estimated average of $2,256 for residential energy in 2016.[7] As shown in Chart 1 below, electricity is the dominant residential energy source, accounting for 69% of total U.S. residential energy expenditures for home heating, cooling, and appliances. In addition to natural gas, some U.S. homes also use heating oil, propane, and other heating sources such as wood.

Chart 1



In 2014, the average price of residential electricity in the U.S. was 32% above its level in 2005 (see Chart 2), compared with a 22% increase in the Consumer Price Index during this period. DOE/EIA projects continued escalation of residential electricity prices due to the costs of compliance with environmental regulations and other factors, including fuel, capital, and operating and maintenance costs. Moreover, EIA,[8] National Economic Research Associates,[9] and others[10] project that electricity prices will increase even more because of EPA's proposed Clean Power Plan.

Chart 2



Energy Expense Estimates

Estimated household energy expenses for the U.S. are based upon DOE/EIA residential energy price projections for 2016.[11] Total household energy costs are distributed by income category using DOE/EIA residential energy survey data.

Following sharp price declines since late 2014, gasoline prices have begun to increase in response to higher oil prices. EIA's May 2015 Short-Term Energy Outlook projects national average gasoline prices of $2.52/gallon in 2015, rising to $2.71/gallon in 2016. This 2016 projection is based upon EIA's estimate of an average $66/barrel price for West Texas Intermediate crude oil in 2016, with an average imported crude oil price of $62/barrel. These projections may be conservative in view of the ongoing reduction of domestic drilling investments caused by lower oil prices. Baker Hughes reports that domestic oil and gas drill rig counts have declined by 52% since May 2014.[12]

DOE/EIA's 2001 Survey of Household Vehicles Energy Use (2005) provides data on regional gasoline use by household income category. These regional gasoline consumption data are updated using EIA's 2016 national average retail gasoline price projection of $2.71 per gallon. Household gasoline consumption is reduced by 15% from 2001 levels, reflecting trends in per capita retail gasoline sales.[13]

The table below summarizes estimated U.S. household energy expenses in 2016 by income group, with the percentage of after-tax income represented by energy costs:

Estimated U.S. household energy costs by pre-tax income category

Pre-Tax Annual Income:	<$30K	$30-<$50K	<$50K	≥$50K	Average
Residential energy $	$1,712	$1,990	$1,834	$2,644	$2,256
Electric $	$1,187	$1,406	$1,282	$1,818	$1,561
Other* $	$526	$584	$553	$826	$695
Gasoline $	$1,729	$2,569	$2,059	$3,447	$2,781
Total energy $	$3,441	$4,559	$3,893	$6,091	$5,037
Energy % of after-tax income	23%	14%	17%	7%	9%

*Other includes natural gas, heating oil, LPG, and wood.

The share of household income spent for energy falls disproportionately on lower- and middle-income families earning less than $50,000 per year before taxes. The 59 million U.S. households earning less than $50,000 before taxes spend an estimated 17% of their after-tax income on energy.

While many lower-income consumers qualify for energy assistance, budgetary support for these government programs has been pared back in recent years.[14] Most of the $3.0 billion of funds available to states under the federal LIHEAP program are concentrated on relief for low-income home heating customers in the Northeast. In comparison to the $3.0 billion available under LIHEAP, total residential energy costs for the 36 million households with pre-tax incomes less than $30,000 are estimated at $62 billion in 2016, including $43 billion in electricity costs.

The average U.S. family will spend an estimated $5,037 on residential and transportation energy in 2016, or 9% of the after-tax family budget. The 36 million U.S. households earning less than $30,000 before taxes, representing 29% of households, will allocate, on average, an estimated 23% of their after-tax incomes to energy.

These findings are consistent with the most recent consumer expenditure survey by the Bureau of Labor Statistics.[15] BLS reports that total expenditures for residential utilities and gasoline are 9% of the average American after-tax household budget. BLS's survey also indicates that energy costs for residential utilities and gasoline rank among those for other basic necessities such as rent, education, clothing, and health care:

BLS 2013 annual consumer expenditure survey
findings for selected expenditure categories,
all U.S. households

Expenditure	Annual $2013	Pct. of Average After-Tax Household Income
Food	$6,602	12%
Rent	$3,324	6%
Health care	$3,631	6%
Mortgage interest	$3,078	5%
Gasoline	$2,611	5%
Residential utilities & fuels*	$1,957	4%
Clothing	$1,604	3%
Education	$1,138	2%

*Excluding water, telephone, and cell phone service.

The large share of after-tax income devoted to energy by lower-income households poses difficult budget choices among food, health care and other basic necessities. A 2011 survey of low-income households for the National Energy Assistance Directors Association (NEADA) reveals many of the adverse health and welfare implications of high energy costs. Ninety-two percent of the NEADA survey participants reported pre-tax household incomes of $30,000 or less. Principal findings of the survey include:

Households reported that they took several actions to make ends meet:
- 39% closed off part of their home.
- 23% kept their home at a temperature that was unsafe or unhealthy.
- 21% left their home for part of the day.
- 33% used their kitchen stove or oven to provide heat.

Many survey respondents had problems paying for housing in the past five years, due at least partly to their energy bills:
- 31% did not make their full mortgage or rent payment.
- 6% were evicted from their home or apartment.
- 4% had a foreclosure on their mortgage.
- 14% moved in with friends or family.
- 4% moved into a shelter or were homeless.
- 13% got a payday loan in the past five years.

Many of the respondents faced significant medical and health problems in the past five years, partly as a result of high energy costs:
- 24% went without food for at least one day.
- 37% went without medical or dental care.
- 34% did not fill a prescription or took less than the full dose.
- 19% had someone become sick because their home was too cold.[16]

Disproportionate Impacts on Minorities and Senior Citizens

The impacts of high energy costs are falling disproportionately on minorities and senior citizens. Black and Hispanic households together represent 26% of U.S. households. Elderly households represent 23% of American households. Unlike young working families with the potential to increase incomes by taking on part-time work or increasing overtime, many fixed income seniors are limited to cost-of-living increases that may not keep pace with energy prices.

The table below summarizes 2013 median pre-tax incomes for elderly and minority households, and compares these with the U.S. median household income of $51,939.

U.S. median pre-tax household incomes, 2013

	Median Household Income	Pct. Diff. Vs. U.S. Median	Pct. of Households
U.S.	$51,939		100%
Black	$34,598	-33%	13%
Hispanic	$40,963	-21%	13%
Age 65+	$35,611	-31%	23%

Source: U.S. Bureau of the Census, Current Population Reports Supplement (2014).

These relatively low median incomes - ranging from 21% to 33% below the national median - indicate that minority and senior households are among those most vulnerable to energy price increases such as rising household utility bills.

Conclusion

High consumer energy prices - together with negative real income growth among lower- and middle-income households - underscore the need to maintain affordable energy prices, especially for lower- and middle-income U.S. families. Maintaining the relative affordability of electricity and other energy sources is essential to the wellbeing of America's lower- and middle-income families.

Acknowledgment: This paper was prepared for ACCCE by Eugene M. Trisko, an energy economist and attorney in private practice. Mr. Trisko has served as an attorney in the Bureau of Consumer Protection at the Federal Trade Commission and as an expert economic witness before state public utility commissions. He represents labor and industry clients in environmental and energy matters. Mr. Trisko can be contacted at emtrisko@earthlink.net.

End Notes

[1] Data on residential energy consumption patterns by income category are derived from U.S. Department of Energy, Energy Information Administration, 2009 Survey of Residential Energy Consumption (2012). 2016 gasoline price projections are from DOE/EIA Short Term Energy Outlook (May 2015).

[2] Household incomes by income category are calculated from the distribution of household income in U.S. Census Bureau, Current Population Reports, Supplement (2014). Federal income tax rates are from Congressional Budget Office, "The Distribution of Household Income and Federal Taxes, 2010 with Estimates for 2013," (December 2013). Effective federal tax rates for the income categories employed in this report were interpolated from CBO's 2013 tax rates by income quintile. State tax data are estimated from state tax rates compiled by the Tax Foundation (2014).

[3] *See*, https://www.census.gov/hhes/www/income/data/historical/household/.

[4] *See*, H. Shierholz and L. Mishel, A Decade of Flat Wages - The Key Barrier to Shared Prosperity and a Rising Middle Class (Economic Policy Institute, August 21, 2013), available at: http://www.epi.org/publication/a-decade-of-flat-wages-the-key-barrier-to-shared-prosperity-and-a-rising-middle-class/.

[5] The U.S. lost 5.7 million manufacturing jobs in the decade of the 2000s, the largest decline of manufacturing jobs since the 1980s, while total manufacturing output declined by 11%. The sectors with large output losses included motor vehicles (-45%), textiles (47%) and apparel (-40%). Increased foreign competition is cited as one factor underlying these trends. *See, e.g.*, http://www.industryweek.com/global-economy/why-2000s-were-lost-decade-american-manufacturing.

[6] The share of U.S. employment in service sectors increased from 76% in 1990 to 84% in 2010, while the share of employment in goods-producing sectors declined from 20% to 13%. *See*, C. Haksaver and B. Render, The Important Role Services Play in an Economy (2013), excerpted at http://www.ftpress.com/articles/article.aspx?p=2095734&seqNum=3.

[7] Residential energy expenditures are estimated from DOE/EIA 2009 Residential Energy Consumption Survey (2012) updated for 2013 household demographics and DOE/EIA's 2016 projections of residential energy costs for electricity, natural gas, LPG, and home heating oil in EIA's Short-Term Energy Outlook (May 2015).

[8] DOE/EIA, Analysis of the Impacts of the Clean Power Plan (May 2015).

[9] National Economic Research Associates, Potential Energy Impacts of the Proposed Clean Power Plan (prepared for ACCCE, October 2014).

[10] *See, e.g.*, Energy Ventures Analysis, Inc., EPA Clean Power Plan: Costs and Impacts on U.S. Energy Markets (prepared for National Mining Association, October 2014).

[11] U.S. DOE/EIA, Short-Term Energy Outlook (May 2015).

[12] Drilling rig data as of May 8, 2014 and May 8, 2015. *See*, http://phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-rigcountsoverview

[13] DOE/EIA and Census Bureau data indicate that per capita retail gasoline consumption declined by 15% from 2001 to 2014. *See*, D. Short, Gasoline Sales and Our Changing Culture (April 22, 2015), available at http://www.advisorperspectives.com/dshort/updates/Gasoline-Sales.php

[14] Federal funding for the Low Income Home Energy Assistance Program (LIHEAP) has declined from $4.5 billion in FY2011 to $3.0 billion in FY2015. *See*, http://www.liheapch.acf.hhs.gov/Funding/funding.htm.

[15] Bureau of Labor Statistics, 2013 Consumer Expenditure Survey, Table 1202, Annual expenditure means, shares, standard errors and coefficient of variation (2014).

[16] NEADA, National Energy Assistance Survey Report (November 2011) at ii.

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Honorable James M. Inhofe, Chairman
Honorable Barbara Boxer, Ranking Member
Committee on Environment & Public Works
United States Senate
Washington, D.C. 20510-6175

July 31, 2015

Re: Response to Question from Chair Capito re June 23, 2015 Hearing before the Subcommittee on Clean Air and Nuclear Safety

Dear Chairman Inhofe and Ranking Member Boxer:

Thank you for transmitting the question posed by Chair Capito following the Subcommittee's June 23rd hearing entitled, "The Impacts of EPA's Proposed Carbon Regulations on Energy Costs for American Businesses, Rural Communities and Families, and a Legislative Hearing on S. 1324."

The question asked by Chair Capito is:

> Proponents of the New Source standard often make the statement that new coal plants are not being built, because of competition from low cost natural gas. But doesn't the NSPS proposal ensure that coal plants won't be built even if the market changes? Does the ARENA help to keep coal as an option for the future?

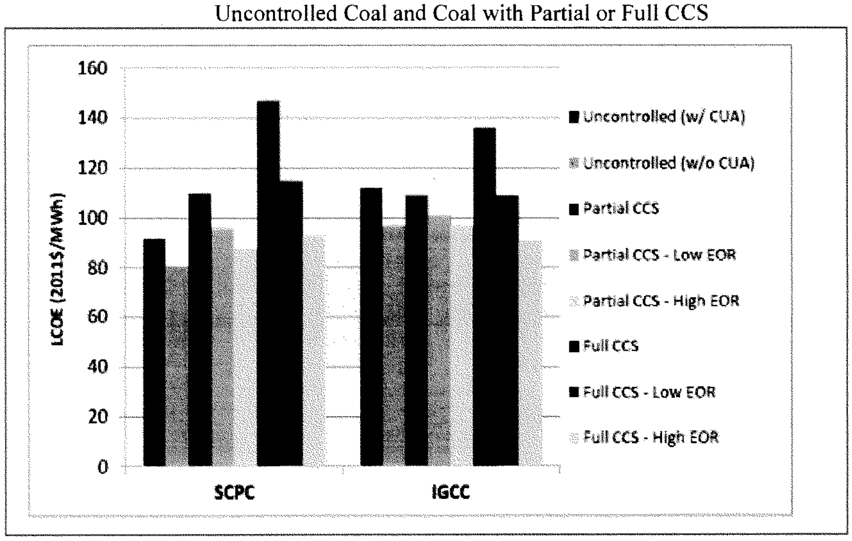
Response

Several factors are responsible for the low level of current and projected new coal generation plant construction. These include relatively low natural gas prices and regulatory uncertainties and barriers created by U.S. EPA's proposed carbon dioxide emission limits for new and existing coal-based facilities.

The proposed NSPS for CO2 emissions tilts the economic playing field against coal by requiring partial carbon capture and storage (CCS) for new coal generation plants, but not for natural gas facilities. This requirement significantly increases generation costs for any new coal plant. EPA's stringent NSPS for mercury and other hazardous air pollutants also increase the costs of generation from new coal-based facilities.

As illustrated in the chart below, EPA's Regulatory Impact Analysis for the proposed GHG NSPS rule estimated that CCS would increase the cost of electricity from a new supercritical unit by approximately 36% to 81%, depending on whether the unit uses partial or full CCS.[1] Costs for plants that have access to enhanced oil recovery markets for CO2 sales were estimated to be 17% to 42% higher than EPA's base case. Given the relatively lower cost of generation that EPA projects for natural gas combined-cycle units, these additional cost penalties for new coal-based units would pose virtually insurmountable barriers for obtaining state regulatory approvals in states with traditional utility regulation.

EPA Estimates of the Levelized Cost of Electricity from Uncontrolled Coal and Coal with Partial or Full CCS



Source: EPA, Regulatory Impact Analysis, Fig. 5-7 (2013). Where indicated, data include a "climate uncertainty adder" (CUA) that increases the weighted average cost of capital by 3%. The "low" EOR estimates in the above chart assume CO2 sales at $20/ton, and the "high" EOR estimates assume CO2 sales at $40/ton.

Previous EPA NSPS rules requiring the application of relatively new or unproven emission control technologies, such as flue gas desulfurization (FGD) for SO2 control, were promulgated only after FGD technologies had been extensively tested and successfully applied at commercial-scale electric generating units. For example,

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[1] EPA, Regulatory Impact Analysis for the Proposed Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units (2013) at Fig. 5-7.

the initial 1971 NSPS required coal-based units to meet an emission rate limit of 1.2 lbs. SO2/MMBTU, which could be achieved by FGD or by low-sulfur coals without add-on controls.[2] After the 1971 NSPS rule was promulgated, many utilities chose to adopt FGD technology despite its optional status.[3] The experience gained through these deployments provided the basis for EPA's 1979 revision of the SO2 NSPS to require the use of FGD technology.[4]

S. 1324, The Affordable and Reliable Electricity Now Act (ARENA), would help to level the playing field between new coal- and natural gas-based generation sources by providing a rational, fact-driven set of procedures for EPA's determination of applicable emission limits for new sources. EPA's current proposed GHG NSPS relies on data from a handful of CCS-based projects, mainly in the industrial sector, several receiving federal support from U.S. DOE, and none representing a commercial-scale operating electric utility generation facility.

ARENA would require that future NSPS be established based on actual operating experience at several plants. Specifically, Section 3(b) requires:

> (b) REQUIREMENTS.—In issuing any rule pursuant to section 111 of the Clean Air Act (42 U.S.C. 7411) establishing standards of performance for emissions of any greenhouse gas from new sources, modified sources, or reconstructed sources that are fossil fuel-fired electric utility generating units, the Administrator, for purposes of establishing those standards—
> (1) shall separate sources fueled with coal and natural gas into separate categories; and
> (2) shall not establish a standard based on the best system of emission reduction for new sources within a fossil-fuel category unless—
> (A) the standard has been achieved, on average, for at least 1 continuous 12-month period (excluding planned outages) by each of at least 6 units within that category—
> (i) each of which is located at a different electric generating station in the United States;
> (ii) that, collectively, are representative of the operating characteristics of electric generation at different locations in the United States; and
> (iii) each of which is operated for the entire 12-month period on a full commercial basis; and
> (B) no results obtained from any demonstration project are used in setting the standard.

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[2] 36 FR 24876 (December 23, 1971).

[3] *See*, National Research Council, Committee on Evaluation of Sulfur Oxides Control Technology, *Flue Gas Desulfurization* (1980) at Table 4.3.

[4] 44 FR 33580 (June 11, 1979).

Requiring the use of empirical data from operating commercial-scale power plants would improve the evidentiary basis for any future NSPS, while avoiding reliance on speculative estimates of the performance capabilities of technologies that have not yet been deployed at commercial scale. In sum, ARENA would provide new coal-based electric generating units with a more level playing field relative to natural gas units independent of the future prices of these competing fuels.

Thank you for the opportunity to respond to Chair Capito's followup question.

Sincerely,

Eugene M. Trisko

Senator CAPITO. Thank you very much.

Our next witness is Paul Cicio, President of the Industrial Energy Consumers of America. Welcome.

STATEMENT OF PAUL CICIO, PRESIDENT, INDUSTRIAL ENERGY CONSUMERS OF AMERICA

Mr. CICIO. Thank you, Chairman Capito, Ranking Member Carper and members of the subcommittee. Thank you for this opportunity.

The Industrial Energy Consumers of America is a trade association whose members are exclusively large companies who are energy intensive trade exposed. These industries, often referred to as EITE industries, consume 73 percent of the manufacturing sector's use of electricity and 75 percent of the natural gas. As a result, small changes in energy prices can have relatively large impacts to our global competitiveness.

As a manufacturing sector, we use 40 quads of energy and this has basically not changed in 40 years. Meanwhile, manufacturing output has increased 761 percent. This is a true success story.

The industrial sector is the only sector of the economy whose greenhouse gas emissions are 22 percent below 1973 levels. These industries are very energy efficient. IECA supports action to reduce greenhouse gas emissions so long as it does not impact our competitiveness. We must have a level playing field with our global competitors.

Several countries we compete with control electric and natural gas prices to their industrials. Two of them are China and Germany. They provide subsidies and practices to give them competitive advantages.

If we were military, one would say we are engaged in hand to hand combat in competitiveness. All costs of unilateral action by the United States through the Clean Power Plan will be passed on to us, the consumer.

As proposed, the Clean Power Plan will dramatically increase the costs of power and natural gas, accomplish little to reduce the threat of global climate change and provide offshore competitors an economic advantage, potentially creating an industrial greenhouse gas emission leakage with harmful effect to the middle class, the economy and the environment.

The EPA cannot look at the Clean Power Plan in isolation from the significant cumulative cost that it will impose on the industrial sector either directly or indirectly through a number of recent rulemakings.

Since 2000, the manufacturing sector is still down 4.9 million jobs. Since 2010, manufacturing employment has increased 525,000 jobs. We are still in the early stages of recovery. We do fear that the Clean Power Plan and also the ozone rule are going to threaten this recovery.

In contrast, for example, China, our primary competitor, has increased employment by 31 percent since 2000. The U.S. manufacturing trade deficit since 2002 has grown $524 billion, 70 percent with one country, China.

China's industrial greenhouse gas emissions have risen over 17 percent since 2008 alone. China produces 29 percent more manufactured goods than we in the United States and emits 317 percent more CO_2. That is over three times the amount of CO_2 than the U.S. industrial sector.

Despite our low greenhouse gas emission levels, the EPA will increase our costs and will make it easier for China's carbon intensive products to be imported, which means the Clean Power Plan will be directly responsible for increasing global emissions.

There are consequences to increasing energy costs on the industrial sector and it is called greenhouse gas leakage. The EPA has failed to address this issue and thus, the costs are under-estimated. For example, when a State's electricity costs rise due to the Clean Power Plan, companies with multiple manufacturing locations will shift their production to States with lower costs, along with the greenhouse gas emissions creating State winners and losers. When they do, it will increase the price of electricity to the remaining State ratepayers, including the households.

If these companies cannot be competitive, they move offshore, moving jobs and greenhouse gas emissions, accomplishing nothing environmentally. One only needs to look at California.

Since AB32, to our knowledge, there is not a single energy-intensive trade-exposed company that has built a new facility in California. The same goes for the EU under the ETUS. California is importing their energy intensive products and they are losing or forfeiting jobs.

It is for this reason we would urge policymakers to hold offshore manufacturing competitors to at least the same carbon content standard as we in the United States.

Thank you.

[The prepared statement of Mr. Cicio follows:]

Senate Subcommittee on Clean Air and Nuclear Safety

Hearing on "The Impacts of EPA's Proposed Carbon Regulations on Electricity Costs for American Businesses, Rural Communities and Families, and a Legislative Hearing on S. 1324"

June 23, 2015

Testimony of
Paul N. Cicio
President
Industrial Energy Consumers of America

Summary of Key Points on the EPA's Clean Power Plan (CPP)
Paul Cicio
Industrial Energy Consumers of America

1. It is not prudent and is irresponsible to the state ratepayer, for states to make significant and costly decisions, for example, to shut down coal-fired power plants incurring stranded costs to meet a CPP compliance target until after judicial review. It is prudent for states to only take those actions that will reduce GHG emissions at little costs, like residential energy efficiency programs, to accelerate cogeneration/waste heat to power initiatives, and to modify NSR in order to remove a barrier to industrial and power generation energy efficiency investments.

2. Significant costs with insignificant benefits. The CPP accomplishes little globally to reduce the threat of climate change.

3. The CPP will dramatically increase the cost of power and natural gas, while providing our offshore competitors an economic advantage, potentially creating GHG emission leakage, with a harmful effect on middle class jobs, the economy, and the environment.

4. Unilateral U.S. action will require additional action to hold offshore manufacturing competitors to at least the same carbon content standard as domestic manufacturers, which should be calculated as a $/ton of carbon content on imported products.

5. Industrial companies are concerned that the CPP and its approach of regulating from outside-the-fence line, and setting GHG reduction targets that cannot be achieved from inside-the-fence line, will set a precedent for them.

6. As state electric prices rise, industrials will shift their production to low-cost electricity states creating state winners and losers, resulting in higher electricity bills for residential ratepayers. Industrial GHG leakage shifts emissions to other states, which accomplishes nothing environmentally.

7. It is not the regulated entity that pays for the CPP. Despite the manufacturing GHG reduction success story, the manufacturing sector is going to pay up to one-third of the cost of the CPP. The consumer (ratepayer) is the primary stakeholder.

8. The CPP targets coal and greatly weakens our greatest strength – fuel diversity in power generation that has kept electric prices low and reliability high.

9. Overdependence on one fuel, natural gas, will increase electricity costs long-term, potentially jeopardizing reliability and increasing natural gas prices. The industrial sector is dependent upon natural gas as a fuel and feedstock, and there are no substitutes.

10. The CPP could cause power generation reliability problems costing an industrial facility tens of millions of dollars per day.

11. EPA did not address industrial GHG leakage or account for increased GHG emissions through greater imports of high GHG content manufactured goods.

12. The Social Cost of Carbon (SCC) adds “global” carbon costs onto “domestic” industrial companies – creating another advantage for our global competitors.

13. Energy efficiency efforts are best directed at the residential sector. Industrials operate at high levels of energy efficiency.

14. Escalating cumulative costs of federal regulations, including the CPP, are a significant business concern and a barrier to middle class manufacturing job creation.

I. IDENTITY OF THE INDUSTRIAL ENERGY CONSUMERS OF AMERICA (IECA)

This testimony is submitted on behalf of the Industrial Energy Consumers of America (IECA), a nonpartisan association of leading manufacturing companies with $1.0 trillion in annual sales, over 2,900 facilities nationwide, and with more than 1.4 million employees. It is an organization created to promote the interests of manufacturing companies for which the availability, use and cost of energy, power or feedstock, play a significant role in their ability to compete in domestic and world markets.

IECA companies are energy-intensive trade-exposed (EITE) industries, which means that relatively small changes to the price of energy can have significant negative impacts to competitiveness. EITE companies are major stakeholders in this debate. EITE industries consume 73 percent of the entire manufacturing sector's use of electricity (26% of U.S.), 75 percent of the natural gas (29% of U.S.), and 82 percent of all energy from the manufacturing sector.

IECA membership represents a diverse set of industries including: chemical, plastics, steel, iron ore, aluminum, paper, food processing, fertilizer, insulation, glass, industrial gases, building products, brewing, independent oil refining, and cement.

II. IECA SUPPORTS S. 1324, THE "AFFORDABLE RELIABLE ELECTRICITY NOW ACT OF 2015"

IECA supports the requirements set forth in S. 1324 that the EPA must fulfill before regulating standards of performance for new, modified, and reconstructed fossil fuel-fired electric utility generating units. The ratepayer protections are also critically important. This provision provides flexibility, such that in the event that compliance would have a negative impact on economic growth, competitiveness, reliability, or on electric ratepayers, the governor would be able to opt-out from compliance. Higher electric rates can result in industrial demand destruction and middle class job losses. Some states would be significantly impacted by the EPA's target GHG reductions.

III. POSITION ON CLIMATE ACTION

IECA supports action to reduce GHG emissions in a manner that will not impair manufacturing competitiveness. The manufacturing sector must have a level playing field with global competitors. Climate change is global in scope and requires meaningful global action. Offshore competitors, who import product into the U.S., must be held to the same environmental standards as domestic manufacturers, or GHG leakage of jobs and emissions will occur, which accomplishes nothing environmentally.

For decades, IECA companies have had energy efficiency programs that reduce GHG emissions driven by intense global competition and sustainability goals. This means that these companies have achieved high levels of energy efficiency. They include chemicals, iron and steel, petroleum refineries, aluminum, paper, glass, and cement. IECA companies are active participants in both DOE and EPA energy efficiency programs, including EPA's ENERGY STAR. Numerous IECA companies have received awards and special recognition by federal and state government agencies for excellence in energy efficiency performance. Plus, EITE companies provide the majority of all industrial combined heat and power generation in the U.S.

IV. SUMMARY OF IECA POSITION ON EPA'S CLEAN POWER PLAN

It is the consumer, the ratepayer who is the true stakeholder, since they will bear the burden of any costs from the CPP. We urge the EPA and states to work closely with these stakeholders as they address the CPP.

IECA does not believe that the EPA has the legal authority to regulate GHG emissions outside-the-fence line as proposed. We find that the CPP is incompatible with numerous practical and technical aspects of America's electricity system, and would represent a vast expansion of the agency's regulatory reach into the authority held by states and other federal regulatory agencies. In effect, the CPP dictates environmental, and energy and economic policy, something the authors of the Clean Air Act never intended.

IECA has serious concerns about the impacts of the CPP on the cost and potential reliability of electricity and natural gas regionally, and therefore the competitiveness of U.S. manufacturers, but especially EITE industries. It is clear that the CPP as proposed will dramatically increase the cost of power and natural gas, while providing our offshore competitors an economic advantage, potentially creating GHG emission leakage, with a harmful effect on jobs, the economy, and the environment. The U.S. manufacturing sector is currently experiencing growth accelerated by the increase in domestic shale gas production. The U.S. chemical industry alone has announced the construction of over 200 projects representing a potential cumulative investment of $135 billion. These projects will only go forward if the U.S. maintains its relatively new competitive advantage in energy affordability and reliability. The proposed rule will increase demand for natural gas in a relatively short period of time, threatening the shale gas portion of the promise of a U.S. manufacturing renaissance. The proposed rule poses a significant risk to the continued shale gas stimulus of the U.S. manufacturing sector.

On flexibility, while the CPP has options touted as "flexibility" by the four blocks, examining the comments by many states, the options cannot be used for several reasons that result in often significant limits to utilization of these options. Less flexibility means higher costs to the consumer. We believe this lack of flexibility drives even higher natural gas demand than EPA anticipates and results in even higher costs of electricity and natural gas, thereby directly impacting industrial competitiveness.

The EPA and states have underestimated the cost of the CPP, because they have not taken industrial GHG leakage into consideration. It is important to note that the industrial load often operates 24/7, and this has the effect of keeping rates lower for the residential ratepayer than they would be otherwise. When a state's electricity price increases due to the CPP, manufacturing facilities with multiple locations will shift their production to other states with lower electricity costs. Some will be able to switch quickly, others would take more time. The reduction of industrial load will increase costs to all other remaining ratepayers and it will shift GHG emissions to other states as well, accomplishing nothing environmentally.

On energy efficiency, the residential sector significantly lags in energy efficiency and stands in contrast to the high level of industrial energy efficiency performance. If states were to act under the CPP's Block 4, their efforts are best directed at the residential sector.[1]

Lastly, the CPP and its resulting GHG emission reductions, that are insignificant when compared to the increases in GHG emissions that will occur in countries with which we compete. The bottom line is that the CPP has high costs with little benefit.

V. IECA PERSPECTIVES ON THE EPA'S CLEAN POWER PLAN

1. Significant costs with insignificant benefits: Accomplishes little globally to reduce the threat of climate change.

[1] IECA Comments on EPA's Clean Power Plan Proposed Rule, December 1, 2014; page 12.

By the EPA's own admission, the proposed rule will decrease GHG emissions by 730 million tonnes by 2030. EPA's rule would decrease global emissions by 1.6% of today's level. China CO2 emissions increased by 705 million in one year!

The CPP will cost consumers tens of billions of dollars per year and reduce the global temperature by no more than 0.006 of a degree in 90 years, an insignificant and costly improvement. In rulemaking documents from April 2010, EPA writes, "Based on the re-analysis the results for projected atmospheric CO2 concentrations are estimated to be reduced by an average of 2.9 ppm [parts per million] (previously 3.0 ppm), global mean temperature is estimated to be reduced by 0.006 to 0.0015 °C by 2100"[2] (See figure 1).

FIGURE 1

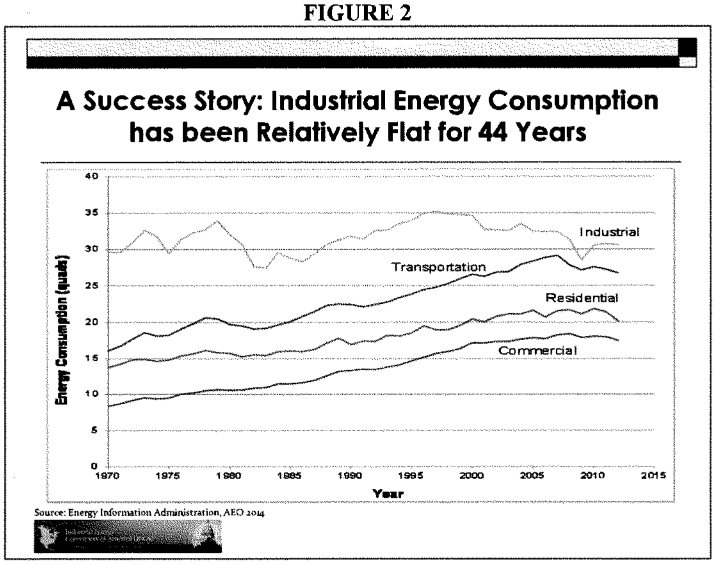
16 to 1 GHG increase	The Partnership for a Better Energy Future reports: "for every ton of CO2 reduced in 2030 as a result of EPA's rule, the rest of the world will have increased emissions by more than 16 tons."
13.5 days China emissions	U.S. reduction by 2030 would offset the equivalent of just 13.5 days of CO2 emissions from China alone.
1% global reduction	The GHG reduction from the rule equates to a global GHG emission reduction of approximately 1.3%.
2/100	Using the accepted climate change model (Cato Institute Model for Assessment of Greenhouse-gas Induced Climate Change), projected global warming temperature increase is reduced by about 18/1000 degree.

2. It is not the regulated entity that pays for the CPP. Despite the manufacturing GHG reduction success story, the manufacturing sector is going to pay up to one-third of the cost of the CPP.

[2] http://www.cnsnews.com/news/article/epa-estimates-its-greenhouse-gas-restrictions-would-reduce-global-temperature-no-more.

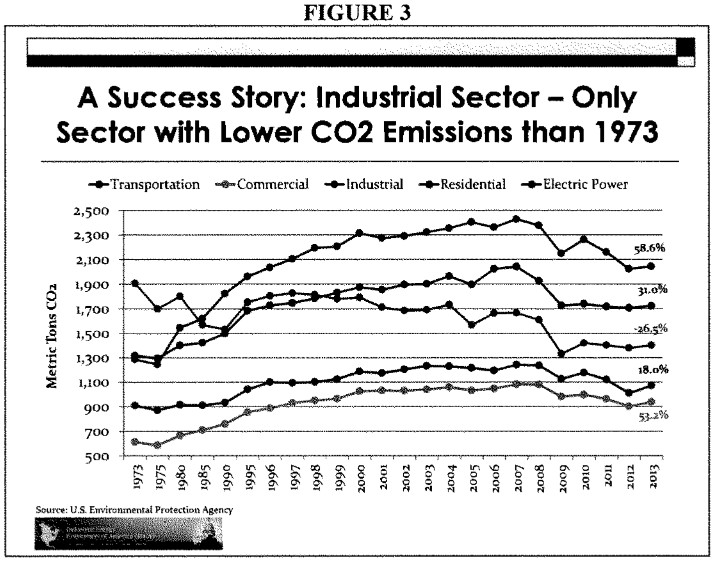
U.S. manufacturing consumption of energy has basically not increased in over 40 years, using about 40 quads of energy per year (See figure 2), while all other sectors of the economy have substantially increased energy consumption. According to the U.S. Bureau of Labor Statistics (BLS), over that same time period manufacturing value-added output has increased by 761 percent, from $235 billion in 1970 to over 2 trillion in 2013, a tremendous success story.

FIGURE 2



Because of investment in productivity, including consistent improvement in energy efficiency and greater use of natural gas, GHG leakage, GHG emissions are 22 percent below 1973 levels, while all other sectors of the economy have significantly higher emissions (See figure 3). The point is obvious, and it is that the industrial sector is not the problem, yet in the CPP the manufacturing sector is going to pay substantially higher electricity and natural gas costs, and with potential costs due to reliability outages.

FIGURE 3

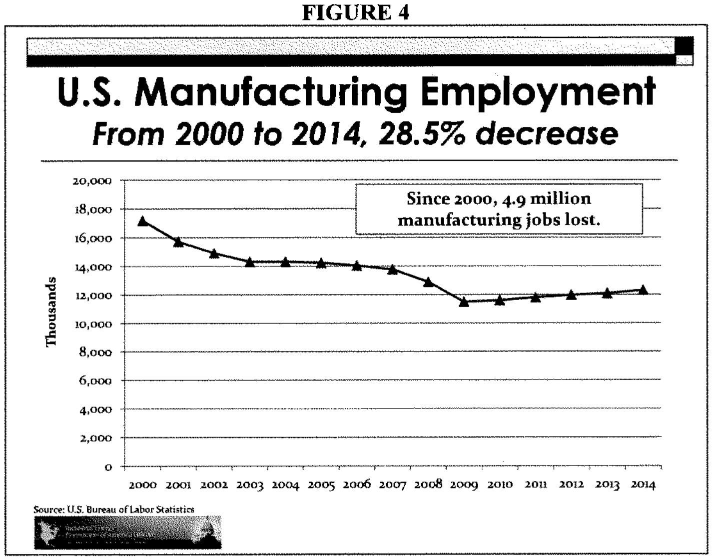


3. Escalating cumulative costs of federal regulations, including the CPP, are a significant business concern and a barrier to middle class manufacturing job creation.

It is inconsistent for the Administration to say they support middle class job creation, while continuing to increase costs and barriers to producing manufactured products in the U.S. From 2000 to 2013, according to the analysis of the American Community Survey, U.S. Census, IPUMS-USA, University of Minnesota, and Pew, every state has experienced a decline in the share of households that are middle class, and all but four have experienced a decline in medium income (see Appendix 1 and 2).

We urge policymakers to be mindful of the economic realities that have and will cause manufacturers to move their facilities to offshore locations to survive. Unfortunately, this already has resulted in significant changes to employment (See figure 4).

FIGURE 4



Despite a recent recovery in job creation, manufacturing employment is still down 4.9 million since 2000, according to the BLS. Global competition is cutthroat and we often must compete with companies that are government-owned, or subsidized in many different ways. Many countries actually priortize and support their manufacturing sector. That cannot be said of U.S. federal policy, especially EPA policy. Figure 5 illustrates for example, that China's manufacturing sector continues to increase employment, while the U.S. and the EU-28 have experienced subtantial job declines since 2000. And, while the U.S. and E.U. industrial sector GHG emissions have declined, China's industrial GHG emissions have substantailly inceased (See figure 6). While no U.S. corporation would want to substitute the quality of air in the U.S. for that of China, these numbers are a clear reminder that there are clear winners and losers, and consequences for higher cumulative costs heaped upon the U.S. manufacturing sector.

FIGURE 5

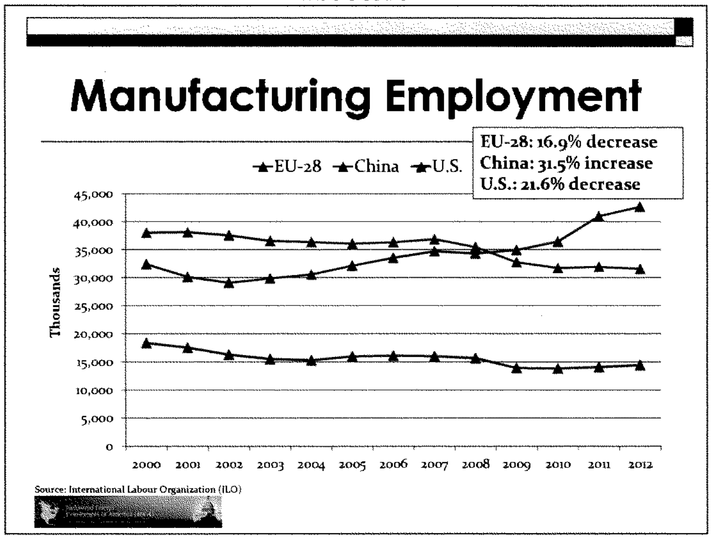
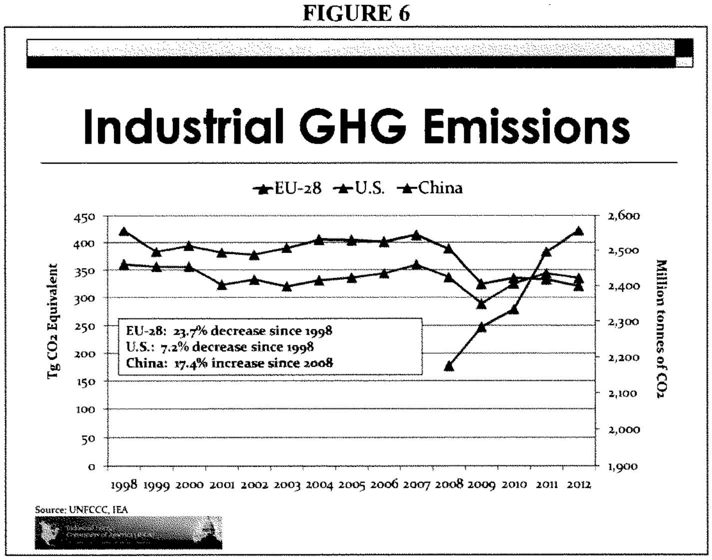


FIGURE 6



While the manufacturing sector, especially the EITE industries, have benefited from the low cost of natural gas, the cost of regulation continues to weigh heavily on investment, job creation, and global competitiveness. According to the National

Association of Manufacturers (NAM) 2014 study "The Cost of Federal Regulations to the U.S. Economy, Manufacturing and Small Business," the total cost of federal regulations in 2012 was $2.028 trillion (in 2014 dollars). Of course, not all regulation is bad regulation. Nonetheless, a significant amount of these regulatory costs are costs that our offshore competitors do not have.

The U.S. trade deficit is a key measurement of competitiveness. The manufactuing trade deficit has grow 45 percent since 2002, and in 2014, 70 percent is with one country, which is China. If fact, China's share of the deficit increased 145 percent since 2002.

FIGURE 7
U.S. MANUFACTURING TRADE DEFICIT

	2002	2005	2010	2014	% Change ('02 to '14)
$ Billions	-361.5	-541.4	-411.7	-524.2	+45.0%
China Trade Deficit (%)	28.5%	38.0%	71.1%	70.0%	+145.6%

Source: International Trade Administration

4. The significant cumulative direct and indirect cost of EPA regulations impact manufacturing competitiveness, investment, and jobs. All electric generating units (EGUs) costs are eventually passed onto the consumer.

Even though the EPA GHG rule is directed at the EGUs, it is the consumer of electricity that will bear the cost of the rule. Depending upon what state a manufacturer is located, they could pay up to one-third of the costs. Higher electricity and natural gas costs reduce profitability and directly reduce capital investment and middle class jobs. According to the EPA, the CPP will cost the manufacturing sector $3.7 billion per year or $37 billion over the next 10 years in increased electricity and natural gas costs.

Non-EPA economic studies suggest that the EPA's cost estimate is significantly understated. The May 2015 Energy Information Administration (EIA) report, "Analysis of the Impacts of the Clean Power Plan"[3] indicates there will be much higher prices. Page 41 states, "The increased investment in new electricity generation capacity as well as the increased use of natural gas for electricity generation leads to electricity prices in 2020 that are 2% to 5% higher in the compliance cases than the respective base prices." Economic activity is also reduced. The EIA report on page 22 says, "Economic activity indicators, including real gross domestic product (GDP), industrial shipments, and consumption, are reduced relative to baseline under the Clean Power Plan. Across cases that start from the AEO2015 Reference case, the reduction in cumulative GDP over 2015-40 ranges from 0.17%-0.25%, with the high end reflecting a tighter policy beyond 2030."

In November 2014, Energy Ventures produced an analysis which states that annual power and gas costs for residential, commercial, and industrial customers in America would be $284 billion higher ($173 billion in real terms) in 2020 compared to 2012—a 60% (37%) increase. See Appendix 3 for more non-EPA economic study examples that show substantially higher costs for the CPP than the EPA estimate.

The proposed ozone rule could add even higher costs to electricity and natural gas. According to the EPA, the proposed ozone rule would increase electricity costs another $2.7 billion and $3.8 billion for natural gas. Combined, industrial electricity and natural gas costs could increase to $6.5 billion per year or $65 billion over the next ten years.

When the proposed CPP and ozone regulations are added to the EIA AEO 2014 forecast, industrials could expect a 41.2 percent increase in electricity prices and a 107.3 percent increase in natural gas prices by 2025 (see figures 8, 9, and 10).

[3] http://www.eia.gov/analysis/requests/powerplants/cleanplan/pdf/powerplant.pdf

FIGURE 8

Annual Costs Due To EPA Regulations In 2025

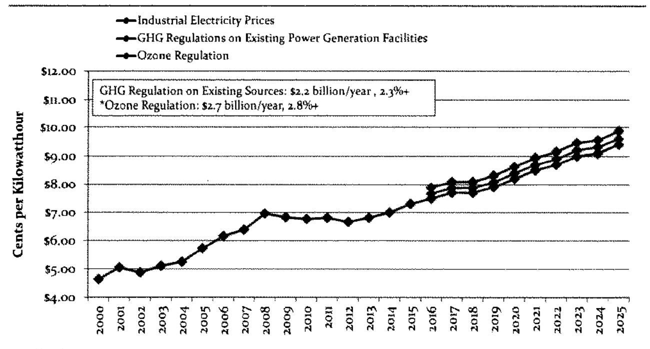
Regulation	Industrial Electricity Costs	Industrial Natural Gas Costs	Total Costs/Year
GHG Regulations on Existing Power Generation Facilities	$2.2 billion, 2.3%+	$1.5 billion, [illegible]	$3.7 billion
Ozone*	$2.7 billion, 2.8%+	$3.8 billion, 6.3%+	$6.5 billion
TOTAL	$4.9 billion, 5.1%+	$5.3 billion, [illegible]	$10.2 billion

*Note: This analysis includes rules MATS, CAIR, most NSPS, and Tier 3 vehicle standards, amongst others.

Source: EPA, NAM, NERA

FIGURE 9

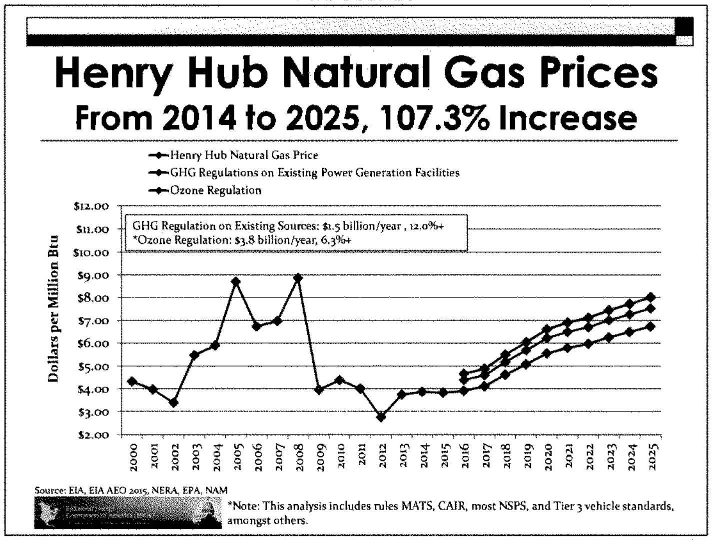
Industrial Electricity Prices
From 2014 to 2025, 41.2% Increase



Source: EIA, EIA AEO 2015, NERA, EPA, NAM

*Note: This analysis includes rules MATS, CAIR, most NSPS, and Tier 3 vehicle standards, amongst others.

FIGURE 10



For total costs, EPA's own estimates project that the rule will cause nationwide electricity price increases averaging between 6 and 7 percent in 2020, and up to 12 percent in some locations.[4] EPA estimates annual compliance costs between $5.4 and $7.4 billion in 2020, rising up to $8.8 billion in 2030. These are power sector compliance costs only, and do not capture the subsequent spillover impacts of higher electricity rates on overall economic activity.

The United Mine Workers of America have estimated that the rule will result in 187,000 direct and indirect job losses in the utility, rail, and coal industries in 2020, and cumulative wage and benefit losses from these sectors of $208 billion between 2015 and 2035.[5]

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[4] EPA, Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for Modified and Reconstructed Power Plants, June 2014, available at http://www2.epa.gov/sites/production/files/2014-06/documents/20140602ria-clean-power-plan.pdf.

[5] http://environmental.pasenategop.com/files/2014/06/Trisko-Testimony.pdf.

Higher energy prices disproportionately harm low-income and middle-income families. Since 2001, energy costs for middle-income and lower-income families have increased by 27 percent, while their incomes have declined by 22 percent.[6] EPA's rule will only exacerbate this trend.

In late July 2014, the Center for Strategic and International Studies (CSIS) released a preliminary analysis of the EPA proposal.[7] This analysis found that the EPA proposal could result in:

- Nationwide costs of up to $32 billion per year; and
- Average electricity rate increases of up to 9.9 percent per year.

The Wall Street Journal called EPA's rule a "huge indirect tax and wealth redistribution scheme that the EPA is imposing by fiat [that] will profoundly touch every American."[8] The paper further noted that "it is impossible to raise the price of carbon energy without also raising costs across the economy. The costs will ultimately flow to consumers and businesses."

5. As state electric prices rise, industrials will shift their production to low-cost electricity states creating state winners and losers, and higher electric bills for residential ratepayers.

Under the CPP, if a state's electricity prices rise, states can expect manufacturers who have multiple U.S. production sites to shift production to other states with lower electricity costs. This results in higher electricity rates for all remaining retail consumers because the fixed costs to generate electricity are spread over fewer electrons. Secondly, it shifts GHG emissions and jobs to other states, accomplishing nothing environmentally.

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[6] http://americaspower.org/sites/default/files/Trisko_2014_1.pdf.
[7] Rhodium Group and Center for Strategic and International Studies, Remaking American Power: Preliminary Results, July 24, 2014.
[8] http://online.wsj.com/articles/carbon-income-inequality-1401752504.

If industrials cannot shift production to other U.S. manufacturing sites, GHG leakage to other countries will occur.

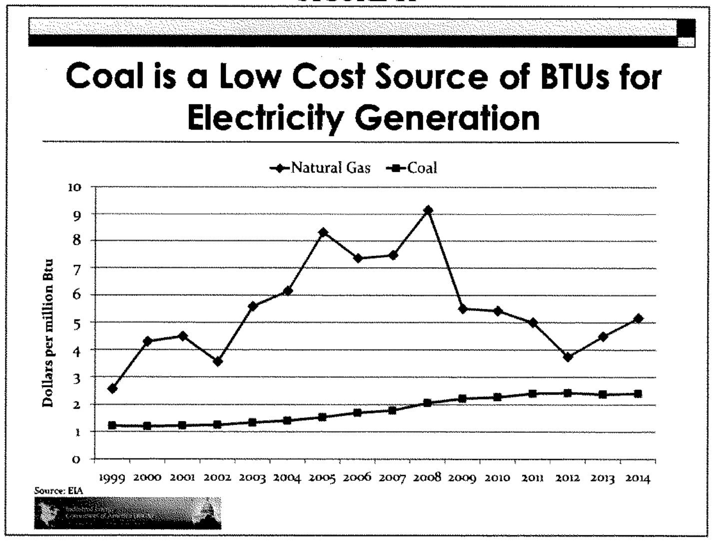
6. The CPP targets coal and greatly weakens our greatest strength, fuel diversity in power generation that has kept electric prices low and reliability high.

The CPP dramatically reduces the use of coal, an abundant resource of low-cost energy that has helped to keep electricity and natural gas costs low. Coal is needed in the mix of generation energy alternatives to provide diversified, stable, and reliable base load energy, to provide voltage support, to provide one of the few sources of onsite "stored" energy in the supply mix, and to compete economically with natural gas.

Here again, the EPA underestimates the number of coal-fired power plant retirements and the risks of higher reliance on natural gas. The EIA report, (Page 16) "Analysis of the Impacts of the Clean Power Plan" says, "Projected coal plant retirements over the 2014-40 period, which are 40 GW in the AEO2015 Reference case (most before 2017), increase to 90 GW (nearly all by 2020) in the Base Policy case (CPP).

With a significant reduction of coal in the mix, as natural gas prices rise, it will substantially drive up electricity prices. Figure 11 illustrates the significant cost benefits provided by coal that have helped to keep U.S. electricity prices low.

FIGURE 11



According to the International Energy Agency (IEA), while the EPA has consistently pursued regulations to stop coal use in the U.S., the rest of the world is forecasted to increase coal use by 2019 (See figure 12). Even Japan has made new commitments to coal-fired power generation, having just recently announced they will build 40 coal-fired power plants that will generate 21,200 MWs of electricity.[9]

[9] "Japan's New Coal Plants Threaten Emission Cuts," Bloomberg News, April 9, 2015.

FIGURE 12

Projections from IEA Mid-Term Outlook 2014

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U.S.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
China	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
India	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Africa and Middle East	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Europe/ Eurasia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ASEAN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Latin America	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Other	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

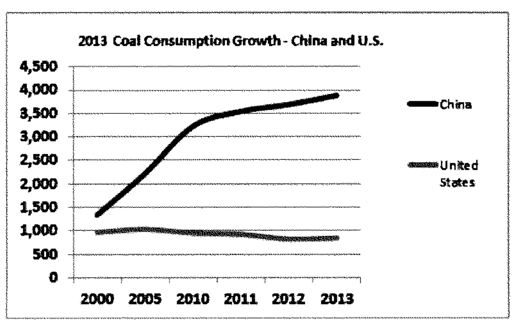
Source: IEA

The most striking difference is between the U.S. and China as illustrated in Figure 13 below. China's GHG emissions growth rates greatly outpace, and more than negate, the potential reductions from the CPP.

FIGURE 13

2013 Coal Consumption Grown – China and U.S.

(Million Tonnes)



Source: IEA Coal Information 2014

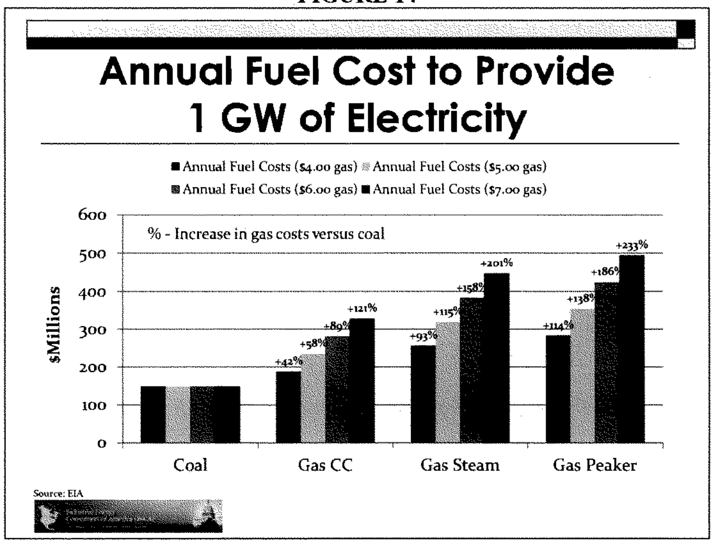
7. Overdependence on one fuel, natural gas, will increase electricity costs, potentially jeopardizing reliability long-term and increasing natural gas prices. The industrial sector is dependent upon natural gas as a fuel and feedstock, and there are no substitutes.

According to the Energy Information Administration (EIA), the U.S has a nearly 300-year supply of coal. Lower 48 natural gas on the other hand, has only a 59-year supply at 2025 demand, according to the AEO 2014. EIA says that proven reserves are only 9.6 years of supply at 2025 demand. It is also troublesome, that EIA forecasts Henry Hub prices to increase by 76 percent by 2025 as compared to 2013, which means that our electricity prices will also rise substantially. These prices do not take into consideration the recent crude oil price decline that has resulted in a significant drop in drilling nationwide with longer term effects to be determined. Shale natural gas has significant decline rates, and without constant drilling, production drops precipitously.

The EIA report, "Analysis of the Clean Power Plan," makes clear that substantial new quantities of natural gas-fired generation will be used. The report says, "Natural gas-fired generation increases substantially in the early 2020s across all cases, as an initial compliance strategy. Natural gas-fired generation increases from 1,118 BkWh in 2013 to 1,382 BkWh in 2020 in the Base Policy case, 24% above the underlying AEO2015 Reference case baseline level (Page 30)."

Figure 14 illustrates the increases in electricity prices that can be anticipated from the three types of gas-fired generation technologies at varying costs of natural gas from $4.00 to $7.00 per MM Btu. The point being is that relatively small increases in the price of natural gas have substantially high impacts to electricity price outputs.

FIGURE 14



8. The CPP could cause power generation shortages. Reliability problems can cost an industrial facility tens of millions of dollars per day.

As recent as April 1, 2015, Gerry Cauley, president and CEO of the North American Electric Reliability Corporation (NERC), said the GHG rules could cause the retirement of 60 GW of generating capacity, mainly coal-fired generation, over the next few years, and could result in power generation shortages. He specifically cites the Great Plains, the Midwest, the Northeast, and Texas as likely reliability problems. NERC plans to release a new report on April 20, 2015.

Furthermore, Mr. Cauley has said that "If there's a reliability issue that comes up, we can't have an environmental rule that trumps reliability. We don't want to put companies in a position where they have to choose between violating an environmental rule or violating a reliability standard." IECA wholeheartedly agrees with his comment.

What does not seem to be said enough is that reliability is simply a question of cost and time. State public policy servants responsible for the reliability of the grid, with time, can simply throw costs (capital) at reliability to ensure there are no problems. But these are costs that would not be incurred without the CPP. And, these are not costs that the EPA has figured into their cost estimates. The bottom line is that here again, it's the consumer who will be forced to absorb these additional costs. Importantly, capital costs, investments to ensure reliability need sufficient time to permit, engineer, construct and put into operation. The 2020 interim target is a significant obstacle to having sufficient time to put these facilities into operation.

From IECA's perspective, there are two reliability threats, one from power outages and the other from regional natural gas curtailments. In both cases, it is manufacturing facilities that are always the first to be curtailed.

For industrial facilities, reducing electric and gas reliability could result in the temporary or permanent shutdown of manufacturing facilities, which could result in costs starting from tens of millions of dollars per day. Damages can occur to the product being produced and the manufacturing equipment.

9. EPA did not address industrial GHG leakage and account for increased GHG emissions through greater imports of high GHG content manufactured goods.

When EPA did its economic analysis of the CPP, it failed to account for industrial GHG leakage. By not including industrial GHG leakage, EPA has overestimated benefits and underestimated costs. IECA urges the EPA to complete a study to understand the impact of the CPP on industrial GHG leakage including increased imported GHG emissions. The imported GHG emissions must be subtracted from domestic GHG reductions.

Examining GHG emissions from imported manufacturing products is overdue. To illustrate, 75 percent of the U.S. trade deficit is with one country, China.[10] According to the IEA and the World Bank,[11] in 2011, China's total manufactured goods value-added were over $2.3 trillion, as compared to $1.8 trillion for the U.S. However, China's total manufacturing industries' CO2 emissions were 2.5 trillion tonnes, while the U.S manufacturing sector was only 598 billion tonnes. This means that China produced 29 percent more manufactured goods, but emitted 317 percent more CO2 than U.S. manufacturing. U.S. manufacturing produces three times the amount of goods for every one tonne of carbon, as compared to China.

Industrial GHG leakage is an accepted climate policy challenge. For example, the Waxman-Markey legislation, the "American Clean Energy and Security Act," included specific provisions to reduce the impact of industrial GHG leakage. In December 2, 2009, several Senators released the report, "The Effects of H.R. 2454 on International Competitiveness and Emission Leakage in Energy-Intensive Trade-Exposed Industries."[12] Both the EU ETS and California's AB32 carbon cap and trade regulation acknowledge GHG leakage as a real problem. Despite this, the CPP does not contain provisions to avoid industrial GHG leakage.

Historically, there is an absolute direct relationship between U.S. energy costs and manufacturing employment, and the manufacturing trade deficit. As energy costs rise, manufacturing jobs and investment decrease, and imports increase. The reverse is also true, as U.S. energy costs decline, manufacturing jobs and investment increase, and exports increase.

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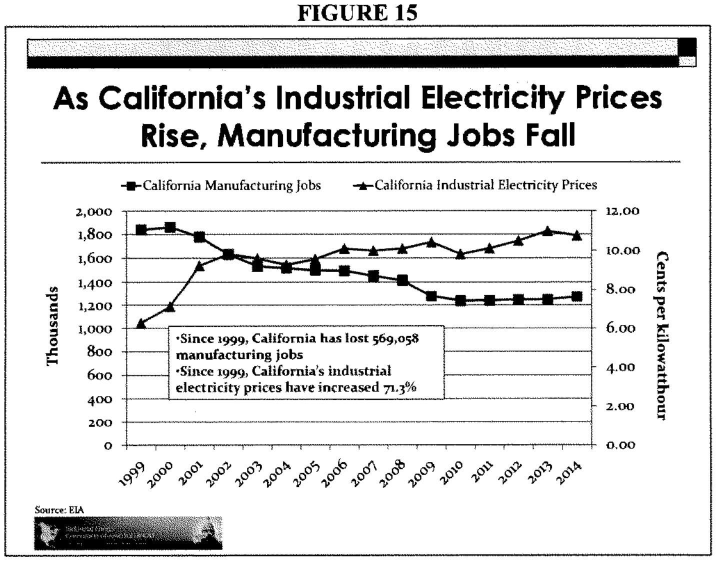
[10] U.S. Bureau of Labor Statistics.
[11] International Energy Agency, The World Bank, http://data.worldbank.org/indicator/NV.IND.MANF.CD.
[12] http://www.epa.gov/climatechange/Downloads/EPAactivities/InteragencyReport_Competitiveness-EmissionLeakage.pdf.

California is a good example. California's electricity prices in 2013 were the fifth highest in the lower 48 states, and the state has also implemented carbon cap and trade. Figure 15 illustrates that California's electricity prices rose over 76 percent since 1999, and they have experienced a corresponding staggering drop in manufacturing employment of 592,361 high paying jobs. It is important to note that while many states have increased manufacturing jobs since 2010, California has not. Manufacturing companies specifically avoid investing in California because of high electricity costs that are only going much higher because of the carbon cap and trade long term. Cap and trade adds significant regulatory and cost uncertainty. The net effect is that imports of industrial GHG intensive manufactured products into California have substantially increased.

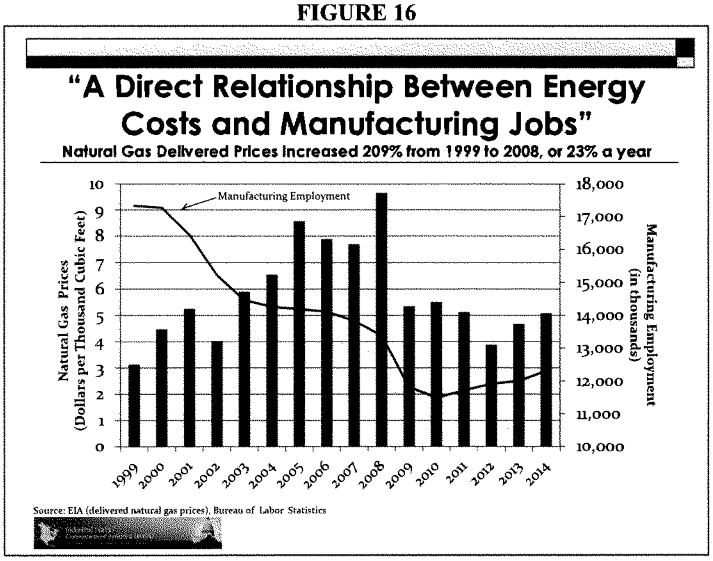
FIGURE 15



Another instructive example is the history of U.S. natural gas prices and their impact on manufacturing jobs. In this case, natural gas is a surrogate for electricity prices.

From 1999 to 2008, when natural gas prices rose 209 percent, it had a significant impact on national manufacturing employment that fell by almost 5.0 million direct jobs, according to BLS, and over 50,000 manufacturing facilities were closed. And now, largely because of lower natural gas costs, the BLS data indicates that manufacturing jobs have increased 466,000 from 2010 to 2013.

FIGURE 16



10. Unilateral U.S. action will require additional action to hold offshore manufacturing competitors to at least the same carbon content standard as domestic manufacturers by imposing carbon standards, calculated as a $/ton of carbon content on imported products.

If the CPP stands unchanged, action will be needed to level the playing field with imported manufactured products. Manufacturing consumes 26 percent of all U.S. electricity and 29 percent of all natural gas, both of which are greatly impacted by the CPP, resulting in higher prices. Imposing costs on domestic manufacturers without imposing at least the same costs on imported manufacturing goods, reduces competitiveness, jobs, and will increase imports, further accelerating the trade deficit and national economic decline.

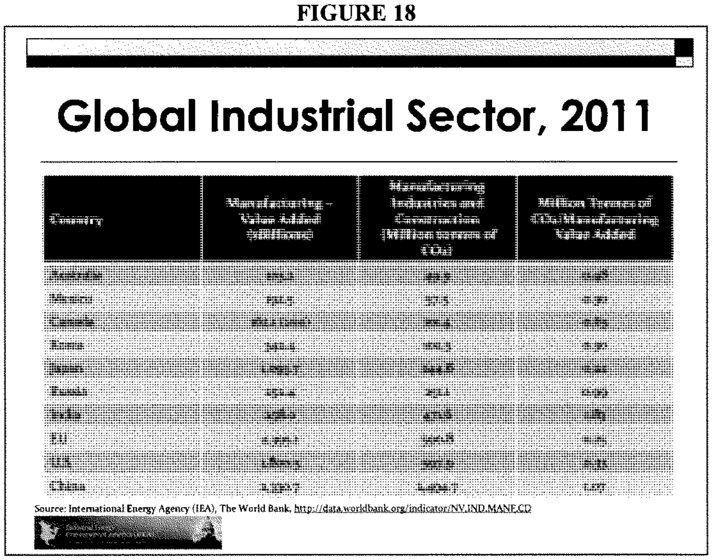
EPA/states must inflict, at least the same economic pain, in dollars per carbon content on imported manufactured products. The EPA must establish an import carbon fee or equivalent based upon the carbon content of the imported product.

Figure 17 illustrates the importance of sound climate policy. If the U.S. can keep energy costs low, reduce GHG emissions cost-effectively and with a level playing field, there is a great opportunity to displace imported products, creating a significant number of domestic manufacturing jobs while reducing global GHGs. To do so, will require the U.S. manufacturing sector to increase the amount of energy it consumes, while reducing GHG intensity long-term. Importantly, this cannot be achieved if the EPA imposes a "cap" on GHG emissions.

Note that 70 percent of the trade deficit is with China, a country very dependent upon coal and whose manufacturing processes, at large, are generally less energy efficient and more carbon intensive than comparable facilities in the U.S. (see number 9 above.)

FIGURE 17

FIGURE 18



11. The Social Cost of Carbon (SCC) adds "global" carbon costs onto "domestic" industrial companies – creating another advantage for our global competitors.

EPA's unilateral domestic application of its arbitrary estimates of the global SCC to justify this proposed rule are contrary to law and federal policy, and the July 2014 U.S. Government Accountability Office (GAO) has confirmed that the EPA did not follow OMB guidelines in the development of the SCC.

The SCC calculates the global cost of carbon to justify domestic costs and benefits. First, to be sure, these are inflated costs because they failed to use the OMB 7 percent discount rate. Second, no other country in the world is imploding "global" carbon costs on their country's economy. One only needs to look at the carbon price of the EU ETS, RGGI or the California AB32 to see that no one is pricing carbon at these elevated levels. And, for U.S. industrials who compete globally, absorbing these therotical higher costs could impact competitiveness and middle class jobs long-term.

Importantly, the EPA did not comply with OMB guidelines as they developed their social cost of carbon. Below is the GAO summary with special emphasis added to highlight critcal errors.[13] For these reasons, the EPA should not proceed to use the exising social cost of carbon.

> "The Environmental Protection Agency (EPA) used the seven Regulatory Impact Analyses (RIA) GAO reviewed to inform decision making, and its adherence to relevant Office of Management and Budget (OMB) guidance varied. According to senior EPA officials, the agency used these RIAs to facilitate communication with management throughout the rulemaking process and communicate information that supported its regulatory decisions to Congress and the public. **However, it generally did not use them as the primary basis for final regulatory decisions.**
>
> "EPA generally adhered to many aspects of OMB's Circular A-4 guidance for analyzing the economic effects of regulations including, for example, considering regulatory alternatives and analyzing uncertainties underlying its RIAs. **However, EPA did not always adhere to other aspects.** Specifically, the information EPA included and presented in the RIAs was not always clear. According to OMB guidance, RIAs should communicate

[13] "EPA Should Improve Adherence to Guidance for Selected Elements of Regulatory Impact Analyses," GAO, July 2014, http://www.gao.gov/products/GAO-14-519.

information supporting regulatory decisions and enable a third party to understand how the agency arrives at its conclusions. **In addition, EPA's review process does not ensure that the information about selected elements that should appear in the analyses—such as descriptions of baselines and alternatives considered—is transparent or clear, within and across its RIAs.** As a result, EPA cannot ensure that its RIAs adhere to OMB's guidance to provide the public with a clear understanding of its decision making.

"In addition to using Circular A-4 (issued in 2003) to analyze the effects of regulations, EPA used more recent guidance developed by an interagency working group co-led by OMB and another White House office in 2010 for valuing carbon dioxide emissions. **Applying this guidance while using Circular A-4 to estimate other benefits and costs yielded inconsistencies in some of EPA's estimates and has raised questions about whether its approach was consistent with Circular A-4. Circular A-4 does not reference the new guidance and the new guidance does not include an overall statement explaining its relationship to Circular A-4.** Without increased clarity about the relationship, questions about the agencies' adherence to OMB guidance will likely persist.

"In assessing EPA's adherence to OMB guidance, GAO identified two other areas in which EPA faced challenges that limited the usefulness of some of its estimates. **First, EPA did not monetize certain benefits and costs related to the primary purposes or key impacts of the rules GAO reviewed, such as reducing hazardous air pollutants and water quality effects.** EPA officials said resource and data limitations constrained the agency's ability to monetize these effects. OMB guidance acknowledges that monetizing effects is not always possible. However, without doing so, the public may face challenges understanding the trade-offs associated with regulatory alternatives. **Second, EPA estimated effects of its regulations on employment, in part, using a study that, according to EPA officials, represented the best reasonably obtainable data when they conducted their analyses. However, the study was based on data that were more than 20 years old and may not have represented the regulated entities addressed in the RIAs.** EPA officials said they are exploring new approaches for analyzing these effects but were uncertain about when such results would be available. Without improvements in its estimates, **EPA's RIAs may be limited in their usefulness** for helping decision makers and the public understand these important effects."

We appreciate the opportunity to provide this testimony on the EPA's Clean Power Plan.

Sincerely,
Paul N. Cicio

APPENDIX 1
SHARE OF HOUSEHOLDS THAT ARE MIDDLE CLASS

State	2000	2013	Difference
Alabama	46.7%	44.1%	-5.6%
Alaska	53.5%	51.8%	-3.2%
Arizona	50.0%	45.9%	-8.2%
Arkansas	48.9%	45.7%	-6.5%
California	46.7%	43.5%	-6.9%
Colorado	51.3%	47.3%	-7.8%
Connecticut	48.9%	44.9%	-8.2%
Delaware	52.2%	47.9%	-8.2%
Florida	48.8%	45.9%	-5.9%
Georgia	49.0%	44.2%	-9.8%
Hawaii	49.9%	48.6%	-2.6%
Idaho	52.7%	51.9%	-1.5%
Illinois	49.8%	45.8%	-8.0%
Indiana	53.0%	48.6%	-8.3%
Iowa	54.1%	51.0%	-5.7%
Kansas	51.8%	48.3%	-6.8%
Kentucky	47.1%	44.5%	-5.5%
Louisiana	45.0%	42.0%	-6.7%
Maine	51.6%	46.9%	-9.1%
Maryland	51.6%	48.2%	-6.6%
Massachusetts	48.6%	44.8%	-7.8%
Michigan	50.6%	46.3%	-8.5%
Minnesota	52.9%	48.9%	-7.6%
Mississippi	46.3%	42.8%	-7.6%
Missouri	50.2%	47.1%	-6.2%
Montana	51.3%	46.6%	-9.2%
Nebraska	52.2%	49.1%	-5.9%
Nevada	53.6%	48.8%	-9.0%
New Hampshire	53.9%	49.7%	-7.8%
New Jersey	48.8%	44.8%	-8.2%
New Mexico	48.0%	43.2%	-10.0%
New York	45.1%	42.3%	-6.2%
North Carolina	50.3%	45.7%	-9.1%
North Dakota	52.6%	47.5%	-9.7%
Ohio	50.9%	45.7%	-10.2%
Oklahoma	48.9%	46.8%	-4.3%
Oregon	51.4%	47.7%	-7.2%
Pennsylvania	49.3%	46.5%	-5.7%
Rhode Island	48.2%	45.1%	-6.4%
South Carolina	50.0%	45.8%	-8.4%
South Dakota	52.6%	49.4%	-6.1%
Tennessee	49.2%	45.8%	-6.9%

State	2000	2013	Difference
Texas	47.8%	45.2%	-5.4%
Utah	55.0%	52.3%	-4.9%
Vermont	52.4%	47.4%	-9.5%
Virginia	49.5%	45.9%	-7.3%
Washington	51.7%	47.4%	-8.3%
West Virginia	46.7%	44.7%	-4.3%
Wisconsin	54.6%	48.9%	-10.4%
Wyoming	51.5%	51.2%	-0.6%

Source: Stateline analysis of American Community Survey, U.S. Census and IPUMS-USA, University of Minnesota, Pew

APPENDIX 2
MEDIAN INCOME

State	2000	2013	Difference
Alabama	$47,038	$42,849	-8.9%
Alaska	$71,065	$72,237	1.6%
Arizona	$55,889	$48,510	-13.2%
Arkansas	$44,347	$40,511	-8.6%
California	$65,445	$60,190	-8.0%
Colorado	$65,046	$58,823	-9.6%
Connecticut	$74,322	$67,098	-9.7%
Delaware	$65,291	$57,846	-11.4%
Florida	$53,493	$46,036	-13.9%
Georgia	$58,473	$47,829	-18.2%
Hawaii	$68,652	$68,020	-0.9%
Idaho	$51,774	$46,783	-9.6%
Illinois	$64,201	$56,210	-12.4%
Indiana	$57,279	$47,529	-17.0%
Iowa	$54,388	$52,229	-4.0%
Kansas	$55,980	$50,972	-8.9%
Kentucky	$46,400	$43,399	-6.5%
Louisiana	$44,876	$44,164	-1.6%
Maine	$51,317	$46,974	-8.5%
Maryland	$72,852	$72,483	-0.5%
Massachusetts	$69,592	$66,768	-4.1%
Michigan	$61,551	$48,273	-21.6%
Minnesota	$64,919	$60,702	-6.5%
Mississippi	$43,173	$37,963	-12.1%
Missouri	$52,273	$46,931	-10.2%
Montana	$45,507	$46,972	3.2%
Nebraska	$54,087	$51,440	-4.9%
Nevada	$61,433	$51,230	-16.6%
New Hampshire	$68,166	$64,230	-5.8%
New Jersey	$75,991	$70,165	-7.7%
New Mexico	$47,035	$43,872	-6.7%

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Industrial Energy Consumers of America

State	2000	2013	Difference
New York	$59,796	$57,369	-4.1%
North Carolina	$53,996	$45,906	-15.0%
North Dakota	$47,684	$55,759	16.9%
Ohio	$56,437	$48,081	-14.8%
Oklahoma	$46,025	$45,690	-0.7%
Oregon	$56,382	$50,251	-10.9%
Pennsylvania	$55,266	$52,007	-5.9%
Rhode Island	$58,000	$55,902	-3.6%
South Carolina	$51,099	$44,163	-13.6%
South Dakota	$48,619	$48,947	0.7%
Tennessee	$50,104	$44,297	-11.6%
Texas	$55,019	$51,704	-6.0%
Utah	$63,010	$59,770	-5.1%
Vermont	$56,300	$52,578	-6.6%
Virginia	$64,321	$62,666	-2.6%
Washington	$63,079	$58,405	-7.4%
West Virginia	$40,921	$41,253	0.8%
Wisconsin	$60,344	$51,467	-14.7%
Wyoming	$52,215	$58,752	12.5%

Source: Stateline analysis of American Community Survey, U.S. Census and IPUMS-USA, University of Minnesota, Pew

APPENDIX 3

NERA, OCTOBER 2014
http://www.americaspower.org/sites/default/files/NERA_CPP%20Report_Final_Oct%202014.pdf

Figure ES-1: Overview of Energy System Impacts of State Unconstrained (BB1-4) and State Constrained (BB1-2) Scenarios (Annual Average, 2017-2031)

	Total Coal Retirements Through 2031	Coal-Fired Generation	Natural Gas-Fired Generation	Henry Hub Natural Gas Price	Delivered Electricity Price	Electricity Sector CO2 Emissions
	GW	TWh	TWh	2013$/MMBtu	2013 ¢/kWh	MM metric tons
Baseline	51	1,672	1,212	$5.25	10.8	2,080
State Unconstrained (BB1-4)	97	1,191	1,269	$5.36	12.0	1,624
Change from Baseline	+45	-481	+57	+$0.11	+1.3	-456
% Change from Baseline	+18%	-29%	+5%	+2%	+12%	-22%
State Constrained (BB1-2)	220	492	2,015	$6.78	12.6	1,255
Change from Baseline	+169	-1,180	+802	+$1.53	+1.9	-825
% Change from Baseline	+69%	-71%	+66%	+29%	+17%	-40%

Note: Coal retirements are cumulative from 2014. Percentage change in coal retirements is relative to total baseline 2031 coal capacity.
Source: NERA calculations as explained in text.

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Industrial Energy Consumers of America

Figure ES-2: Energy System Costs of State Unconstrained (BB1-4) and State Constrained (BB1-2) Scenarios

	State Unconstrained (BB1-4)	State Constrained (BB1-2)
Present Value (Billion 2013$)		
Cost of Electricity, Excluding EE	-$209	$335
Cost of Energy Efficiency	$560	$0
Cost of Non-Electricity Natural Gas	$15	$144
Total Consumer Energy Costs	$366	$479

Notes: Present value is from 2017 through 2031, taken in 2014 using a 5% real discount rate
Source: NERA calculations as explained in text.

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Figure 11: Energy System Cost Impacts of State Compliance Scenarios (billion 2013 dollars)

	2017	2020	2023	2026	2029	PV (2017-2031)
State Unconstrained (BB1-4)						
Cost of Electricity, Excluding EE	-$9	-$13	-$24	-$36	-$42	-$209
Cost of Energy Efficiency	$25	$52	$71	$73	$73	$560
Cost of Non-Electricity Natural Gas	$0	$3	$3	$1	$1	$15
Total Consumer Energy Costs	$16	$42	$49	$39	$33	$366
State Constrained (BB1-2)						
Cost of Electricity, Excluding EE	-$6	$33	$46	$59	$73	$335
Cost of Energy Efficiency	$0	$0	$0	$0	$0	$0
Cost of Non-Electricity Natural Gas	$1	$19	$21	$20	$21	$144
Total Consumer Energy Costs	-$4	$51	$68	$79	$94	$479

Note: Present value is from 2017 through 2031, taken in 2014 using a 5% real discount rate.
Source: NERA calculations as explained in text.

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Figure 16: Ratepayer Class Delivered Electricity Price Impacts of State Scenarios (Annual Average, 2017-2031, 2013 cents per kWh)

	Residential	Commercial	Industrial	All Sectors
Baseline	12.7 ¢	11.0 ¢	7.8 ¢	10.8 ¢
State Unconstrained (BB1-4)	14.3 ¢	12.6 ¢	8.3 ¢	12.0 ¢
Change from Baseline	+1.7 ¢	+1.5 ¢	+0.5 ¢	+1.3 ¢
% Change from Baseline	+13%	+14%	+6%	+12%
State Constrained (BB1-2)	14.6 ¢	12.9 ¢	9.5 ¢	12.6 ¢
Change from Baseline	+2.0 ¢	+1.9 ¢	+1.7 ¢	+1.9 ¢
% Change from Baseline	+15%	+17%	+22%	+17%

Source: NERA calculations as explained in text.

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Figure 19: Consumer Electricity-Related Cost Impacts of State Scenarios (Annual Average, 2017-2031, billion 2013 dollars)

	Residential	Commercial	Industrial	All Sectors
Baseline	$192	$161	$85	$439
State Unconstrained (BB1-4)				
Electricity Bills	$195	$164	$84	$443
Consumer Energy Efficiency Costs	$13	$13	$4	$29
Total Consumer Electricity-Related Costs	$207	$177	$88	$472
Change from Baseline	+$15	+$15	+$3	+$34
% Change from Baseline	+8%	+9%	+3%	+8%
State Constrained (BB1-2)				
Electricity Bills	$210	$179	$98	$487
Consumer Energy Efficiency Costs	$0	$0	$0	$0
Total Consumer Electricity-Related Costs	$210	$179	$98	$487
Change from Baseline	+$18	+$18	+$13	+$48
% Change from Baseline	+9%	+11%	+15%	+11%

Source: NERA calculations as explained in text.

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MISO LETTER TO EPA, PARTICULARLY SECTION ON INTERIM DEADLINES, NOVEMBER 25, 2014, http://greatlakeslegalfoundation.org/wwcms/wp-content/uploads/2014/12/MISO_CPP_Comment_112514.pdf

- Sufficient time is required to engage in rational planning, construction and integration of cost-effective resource and infrastructure solutions that maintain reliable and efficient delivery of electricity (page 2).

- Without sufficient time to plan, cost-effective decisions for the long term will be sacrificed (page 2).

- At best, the truncated timeline created by the interim performance requirements will force state regulators and generation owners to make hasty and perhaps uncoordinated decisions. This will erode the value of MISO's transmission planning process and reduce the overall value of economic dispatch of the system, thereby unnecessarily increasing electric costs to consumers (page 4).

- Flexibility will be crucial to preserving reliability of the electric system and allowing for more cost-effective implementation (page 4).

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ENERGY VENTURES ANALYSIS, PARTICULARLY COST IMPACTS, NOVEMBER 2014 (pages 4-5)
http://greatlakeslegalfoundation.org/wwcms/wp-content/uploads/2014/12/Nov-2014.-EVA-Energy-Market-Impacts-of-Recent-Federal-Regulations-on-the-Electric-Power-Sector.pdf

- Annual power and gas costs for residential, commercial and industrial customers in America would be $284 billion higher ($173 billion in real terms) in 2020 compared to 2012—a 60% (37%) increase.
- Electricity cost increases represent $177 billion ($98 billion) and natural gas increases represent $107 billion ($75 billion) of the $284 billion ($173 billion) cost increase from 2012 to 2020.
- Average annual household gas and power bills would increase by $680 ($293) or 35% (15%) from 2012 to 2020.
  - Annual average electricity bills would increase approximately $340 ($102) or 27% (8%) from 2012 to 2020.
  - Annual average home gas heating bills would increase approximately $340 ($190) or 50% (28%) from 2012 to 2020.
- The cost of electricity and natural gas will be impacted in large part due to an almost 135% increase in the wholesale price of natural gas (100% in real dollars), from $2.82/mmbtu in 2012 to approximately $6.60/mmbtu ($5.63) in 2020. These increases are due to baseline market and policy impacts between 2012 and 2020 as well as significantly increased pressure on gas prices resulting from recent EPA regulations on the power sector and the proposed CPP.
- On a percentage basis, the U.S. industrial sector would be affected most severely, as its total cost of electricity and natural gas would approach $200 billion ($170 billion) in 2020, a 92% (64%) increase from 2012.
  - Increased operational costs in the industrial sector are of particular concern for energy intensive industries in the U.S. such as aluminum, steel and chemicals manufacturing, which require low energy prices to compete.
  - Industrial power consumers would be expected to pass energy cost increases on to their customers, affecting the costs of goods purchased by American consumers over and above increased monthly utility bills.

U.S. Electricity and Natural Gas Cost Increases (Nominal Dollars)	2012	2020 CO_2 Case	Increase ($)	Increase (%)
Avg. Annual Residential Customer's Electricity and Natural Gas Bill ($)	1,963	2,643	680	35%
Industrial Electricity Rate (¢/kWh)	6.7	10.5	3.8	56%
Total Cost of Electricity and Natural Gas for All Sectors ($ Billion)	470	754	284	60%

U.S. Electricity and Natural Gas Cost Increases (Real Dollars)	2012	2020 CO_2 Case	Increase ($)	Increase (%)
Avg. Annual Residential Customer's Electricity and Natural Gas Bill ($)	1,963	2,256	293	15%
Industrial Electricity Rate (¢/kWh)	6.7	8.9	2.2	33%
Total Cost of Electricity and Natural Gas for All Sectors ($ Billion)	470	644	174	37%

**Figures in Constant 2012 Dollars*

NAVIGANT REPORT, MAY 2014 (PAGE 13)
http://appanet.files.cms-plus.com/PDFs/Markets_Matter_--_Hamal_Report.pdf

- Cost Implications of Unnecessary Volatility and Uncertainty – Lastly, while price signals in the RTO-operated markets provide some incentives for resource development, the role such signals can play in ensuring efficient reductions at a reasonable cost depends on predictability. Highly volatile prices that are not predictable introduce uncertainty that will detract from investments, driving up costs and raising customer costs over the long term. The volatile pricing produces an uncertain revenue stream for capacity resources, reducing the ability to finance investment with long-term debt. This is already a problem in capacity auction markets. Today's capacity prices are higher than necessary by 20% or more because of the price volatility inherent to the mandatory auctions. This problem is borne by customers, as they are the ones who pay for the resources over the long term.
- New requirements for CO_2 emission reductions will change the operation of all electricity markets. Costs will be incurred and suppliers compensated under whatever policy choices are made. If policy options create unnecessary volatility in those costs and revenues, it will increase costs that will ultimately be passed on to customers. It could also lead to reliability issues. This is not a problem for programs involving a CO_2 price based on a tax rate which should be predictable. But, programs where the price changes in response to supply and demand can introduce considerable uncertainty. In years of shortage, prices will escalate, potentially dramatically. In a market with merchant generation, a shortage of CO_2 emission credits simply leads to a decision to shut down, with the potential for that outcome much greater if the owner has other sources of supply that will then enjoy even higher prices. Clearly the incentives are not aligned with ensuring reliable system operations. Regulatory provisions such as making additional emission credits available at a fixed price cap can act as a safety valve and ensure reliability is not threatened. But again, the interaction between these factors will be important.

"EPA'S CLIMATE REGULATIONS WILL HARM AMERICAN MANUFACTURING," MARCH 2014
http://www.heritage.org/research/reports/2014/03/epas-climate-regulations-will-harm-american-manufacturing?mb=true#form_anchor

Senator CAPITO. Thank you very much.

Our next witness is Mr. Harry Alford, President and CEO of the National Black Chamber of Commerce. Welcome.

STATEMENT OF HARRY ALFORD, PRESIDENT AND CEO, NATIONAL BLACK CHAMBER OF COMMERCE

Mr. ALFORD. Good afternoon, Chairman Capito, Ranking Member Carper and distinguished members of the subcommittee.

My name is Harry Alford. I am President and CEO of the National Black Chamber of Commerce.

The NBCC represents 2.1 million Black-owned businesses within the United States. I am here today to testify about the Environmental Protection Agency's proposal to regulate greenhouse gas emissions from power plants and the potential impacts of those proposed regulations on energy costs for American businesses, rural communities and families.

In particular, I would like to focus on the potential adverse economic and employment impacts of the Clean Power Plan on low income groups and minorities, including individuals, families and minority businesses.

While increased costs often come with increased regulation, the Clean Power Plan in particular seems poised to escalate energy costs for Blacks and Hispanics in the United States. According to a recent study commissioned by the National Black Chamber of Commerce, the Clean Power Plan would increase Black poverty by 23 percent, Hispanic poverty by 26 percent, result in cumulative job losses of 7 million for blacks, nearly 12 million for Hispanics in 2035, and decrease Black and Hispanic median household income by $455 to $550, respectively, in 2035.

For these minority and low income groups, increased energy costs have an even greater impact on their lives, jobs and businesses because a larger percentage of their incomes and revenues are spent on energy costs.

What may seem like a nominal increase in energy costs to some can have a much more harmful effect on minorities and low income groups. Our members are very concerned about these potentially devastating economic impacts of the Clean Power Plan. We appreciate the opportunity to highlight them for the committee. In light of these concerns, the National Black Chamber of Commerce undertook an effort to examine the potential economic and employment impacts of the Clean Power Plan on minorities and low income groups.

On June 11, 2015, the NBCC released a study on the threat of the EPA regulations to low income groups and minorities. The study finds that the Clean Power Plan will inflict severe, disproportionate economic burdens on poor families, especially minorities. In particular, the rule imposes the most harm on residents of seven States with the highest concentrations of Blacks and Hispanics.

The EPA's proposed regulation for greenhouse gas emissions from existing power plants is a slap in the face to poor and minority families. These communities already suffer from high unemployment and poverty rates compared to the rest of the Country. Yet, the EPA's regressive energy tax threatens to push minorities and low income Americans even further into poverty. I want to highlight some of the key findings of the study.

The EPA rule increases Black poverty by 23 percent and Hispanic poverty by 26 percent. In 2035, job losses will total 7 million for Blacks and 12 million for Hispanics. In 2035, Black and Hispanic median household income will be $455 and $515 less respectively.

Compared to Whites, Blacks and Hispanics spend about 20 and 90 percent more of their income on food, 10 percent and 5 percent more on housing, 40 percent on clothing and 50 percent and 10 percent more on utilities, respectively. The rule will especially harm residents of seven States with the highest concentration of Blacks and Hispanics. Those States are Arizona, California, Florida, Georgia, Illinois, New York and Texas.

The study demonstrates that the EPA Clean Power Plan would harm minorities' health by forcing tradeoffs between housing, food and energy. Inability to pay energy bills is second only to the inability to pay recent as the leading cause of homelessness.

Business groups like the NBCC are not the only entities expressing concerns about the Clean Power Plan. States, which would be responsible for implementing the Clean Power Plan, have criticized the plan for numerous deficiencies.

Officials from 28 States say the EPA should withdraw its proposal citing concerns such as higher energy costs, threats to reliability and lost jobs. Officials from 29 States have said EPA's proposed rule goes well beyond the agency's legal authority under the Clean Air Act and 50 States have already joined in lawsuits.

The NBCC totally supports the ARENA Act, S. 1324. We certainly encourage all members of this committee to put the bill to vote and make it law.

Thank you so much.

[The prepared statement of Mr. Alford follows:]

June 18, 2015

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Harry C. Alford (National Black Chamber of Commerce)
Senate EPW Committee Hearing – Tuesday, June 23, 2015 (2:00 p.m.)
406 Dirksen Senate Office Building

"The Impacts of EPA's Proposed Carbon Regulations on Energy Costs for American Businesses, Rural Communities and Families, and a legislative hearing on S. 1324"

June 18, 2015

<u>Introduction</u>

Good morning, Chairman Capito, Ranking Member Carper, and distinguished Members of the Subcommittee on Clean Air and Nuclear Safety of the Committee on Environment and Public Works. My name is Harry C. Alford and I am the President of the National Black Chamber of Commerce. The National Black Chamber of Commerce represents 2.1 million Black-owned businesses within the United States. I am here today to testify about the Environmental Protection Agency's proposals to regulate greenhouse gas emissions from power plants, and the potential impacts of those proposed regulations on energy costs for American businesses, rural communities and families.

In particular, I would like to focus on the potential adverse economic and employment impacts of the Clean Power Plan on low-income groups and minorities, including individuals, families and minority-owned businesses. While increased costs often come with increased regulation, the Clean Power Plan in particular seems poised to escalate energy costs for Blacks and Hispanics in the United States. According to a recent study commissioned by the National Black Chamber of Commerce, the Clean Power Plan would:

- increase Black poverty by 23% and Hispanic poverty by 26%
- result in cumulative job losses of 7 million for Blacks and nearly 12 million for Hispanics in 2035; and
- decrease Black and Hispanic median household income by $455 and $515, respectively, in 2035.

For these minority and low-income groups, increased energy costs have an even greater impact on their lives, jobs, and businesses because a larger percentage of their incomes and revenues are spent on energy costs. What may seem like a nominal increase in energy costs to some can have a much more harmful effect on minorities and low-income groups. Our members are very concerned about these potentially devastating economic impacts of the Clean Power Plan, and we appreciate the opportunity to highlight them for the Committee.

Background

As you know, in June 2014, EPA proposed the "Clean Power Plan" – a rule under the Clean Air Act that would regulate greenhouse gas emissions from existing power plants.[1] The proposed rule sets a goal of a 30% nationwide reduction of 2005 GHG emission levels by 2030. Using Section 111(d) of the Clean Air Act, the Clean Power Plan creates GHG emissions reduction goals for each state. These goals are based upon the Agency's calculation of the emission reductions that a state can achieve by applying the "best system of emissions reduction."

Portions of those reduction goals would have to be met on an interim basis in 2020, and then the full reductions achieved by 2030. The EPA developed those state-specific goals using four "building blocks": (1) heat rate improvements at coal-fired power plants; (2) replacing coal-fired electricity with increased generation at existing natural gas combined cycle power plants; (3) increasing nuclear and renewable EGU capacity; and (4) demand-side energy efficiency.

[1] *See* Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generation Units, Docket ID No. EPA–HQ–OAR–2013–0602; FRL–9910-86-OAR, 79 Fed. Reg. 34,830 (June 18, 2014).

Much of the business and industrial community have expressed significant concerns with the Clean Power Plan, including whether the EPA is exceeding its legal authority under the Clean Air Act and whether the Plan will adversely impact the reliability and affordability of energy in the United States for industrial and residential consumers.

National Black Chamber of Commerce Economic Study

In light of these concerns, the National Black Chamber of Commerce undertook an effort to examine the potential economic and employment impacts of the Clean Power Plan on minorities and low-income groups. On June 11, 2015, the National Black Chamber of Commerce released a study on the threat of the EPA regulations to low-income groups and minorities.[2] The study finds that the Clean Power Plan will inflict severe and disproportionate economic burdens on poor families, especially minorities. In particular, the rule will impose the most harm on residents of seven states with the highest concentrations of Blacks and Hispanics.

The EPA's proposed regulation for GHG emissions from existing power plants is a slap in the face to poor and minority families. These communities already suffer from higher unemployment and poverty rates compared to the rest of the country, yet the EPA's regressive energy tax threatens to push minorities and low-income Americans even further into poverty.

I want to highlight some of the key findings from the study:

[2] Available at http://nbccnow.org/wp-content/uploads/2015/06/Minority-Impacts-Report-June-2015-Final.pdf. A copy of the study is also attached to this testimony.

- EPA's rule increases Black poverty by 23% and Hispanic poverty by 26%.
- In 2035, job losses total 7 million for Blacks and nearly 12 million for Hispanics.
- In 2035, Black and Hispanic median household income will be $455 and $515 less, respectively.
- Compared to Whites, Blacks and Hispanics spend 20% and 90% more of their income on food, 10% and 5% more on housing, 40% more on clothing, and 50% and 10% more on utilities, respectively.
- The rule will especially harm residents of seven states with the highest concentrations of Blacks and Hispanics: Arizona, California, Florida, Georgia, Illinois, New York, and Texas.

The study demonstrates that the EPA's Clean Power Plan would harm minorities' health by forcing tradeoffs between housing, food, and energy. Inability to pay energy bills is second only to inability to pay rent as the leading cause of homelessness.

The EPA's apparent indifference to the plight of low-income and minority households is inexcusable. We should pursue policies that expand opportunity for the less fortunate, not ones that further disadvantage them. The National Black Chamber of Commerce and its members have always been fully supportive of environmental stewardship – we want clean air for our employees, our customers, and our communities. We also want economic prosperity for our communities, our businesses, and our employees and their families. One does not have to be sacrificed for the other. Unfortunately, the Clean Power Plan, as proposed, does just that – and those who likely will be most disadvantaged by the Plan are minorities and low-income groups. The EPA should withdraw the Clean Power Plan and not move forward with a regulation that could drive up energy costs, eliminate jobs, send more Blacks and Hispanics into poverty, and make the U.S. less competitive for industry and manufacturing.

The ARENA Act (S. 1324)

The economic and employment threats posed by the Clean Power Plan go beyond minorities and low-income group. On a broader level, and as found in a recent NERA Economic Consulting study, the Clean Power Plan would impose between $366 billion and $479 billion in compliance costs.[3] Those costs would be passed along to consumers in the form of a 12 to 17 percent increase in electricity rates.[4] According to the EPA's own numbers, the Clean Power Plan would force the closure of up to 49 gigawatts of coal-fired power plant capacity—equivalent to 15 percent of all nationwide coal capacity.[5]

Business groups like the National Black Chamber of Commerce are not the only entities expressing concerns about the Clean Power Plan. States, which would be responsible for implementing the Clean Power Plan, have criticized the Plan for numerous deficiencies. Officials from 28 states have said that the EPA should withdraw its proposal, citing concerns such as higher energy costs, threats to reliability and lost jobs. Officials from at least 29 states have said that the EPA's proposed rule goes well beyond the agency's legal authority under the Clean Air Act, and 15 states have already joined in a lawsuit against the rule.

[3] Available at http://www.nera.com/content/dam/nera/publications/2014/NERA_ACCCE_CPP_Final_10.17.2014.pdf.
[4] *Id.*
[5] *Id.*

In order to address these concerns in a balanced and bipartisan way, Chairman Capito has introduced S. 1324, The Affordable Reliable Energy Now Act, or ARENA Act. This important legislation would: (1) prevent mandates for unproven technology; (2) extend compliance deadlines, including for state implementation plans, by requiring final judicial review first; (3) require the EPA to issue state-specific model plans showing how states could meet their individual reduction goals; (4) enable states to protect ratepayers by providing that a state does not have to implement the Plan if the governor finds that doing so would negatively impact the reliability and affordability of electricity; and (5) prevent the EPA from withholding highway funds from any states for noncompliance with the Clean Power Plan.

The ARENA Act provides reasonable and thoughtful solutions to addressing the previously identified concerns with the Clean Power Plan, including the potentially adverse economic and employment impacts on minorities and low-income groups. We urge all of the Committee members to vote in support of the ARENA Act.

Conclusion

The National Black Chamber of Commerce and its members value and support clean air, clean water, and environmental quality. We also value and support economic growth, job creation, and prosperity for our individual members and this country as a whole. These are not mutually exclusive goals. For those reasons, we support the ARENA Act and urge the members of this Committee and the Senate to support the legislation. We appreciate the Committee holding this hearing and highlighting this critical issue. Thank you for the opportunity to testify and I look forward to answering any questions you may have.

Senator CAPITO. Thank you very much.

Our next witness is Joseph J. Martens, Commissioner, New York State Department of Environmental Conservation. Welcome, Mr. Commissioner.

STATEMENT OF JOSEPH J. MARTENS, COMMISSIONER, NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION

Mr. MARTENS. Thank you, Chairman Capito, Ranking Member Carper and members of the subcommittee. Thank you for providing the opportunity for me to testify this afternoon.

My name is Joseph Martens and I am the Commissioner of the New York State Department of Environmental Conservation. I am also Vice-Chair of the Board of Directors of RGGI Inc., which administers the Regional Greenhouse Gas Initiative, a program of nine northeastern States that uses market principles to reduce greenhouse gas emissions from the power sector.

I thank the committee for providing me the opportunity to discuss the success we have had in reducing carbon emissions in New York, while creating jobs and keeping energy bills in check.

I have spoken with many of my colleagues from other States across the Country and have heard many of them discuss their concerns about the rule. I recognize that each State faces different circumstances but I think in RGGI, we have a successful model for reducing emissions while creating jobs and reducing energy bills. Other States can use similar approaches to comply with the Clean Power Plan tailored to their own circumstances.

RGGI was started in 2005 by a bipartisan group of Northeastern and Mid-Atlantic Governors. It sets a declining cap on emissions and allows the market to determine efficiently where the emission reductions will occur.

In addition to their participation in RGGI, each of the RGGI States has aggressive energy efficiency and renewable energy programs. The RGGI cap collects the reductions from these efforts under a single emission cap and shares the carbon reductions from these programs are realized and accounted for.

Proceeds from RGGI allowance options helps fund many of these initiatives, creating a virtual cycle of consumer benefits for taxpayers and ratepayers. Our program has been a resounding success.

The State greatly exceeded the original 10 percent reduction target, achieving a 40 percent reduction by 2012. To achieve even greater reduction, the RGGI States acted to further reduce the cap to 50 percent below 2005 levels in 2020.

We achieved this reduction in an economy that grew 8 percent over the period from 2005 to 2013, adjusted for inflation. In New York, we have realized economic benefits from RGGI and associated programs, including creating jobs and reducing energy bills. For example, Governor Cuomo's New York Sun program has made New York fourth in the Nation for solar jobs.

As of the end of 2014, we have committed more than $550 million in proceeds from the auction of RGGI emission allowances to programs that will provide energy bills savings of over $1 billion or other benefits to over 130,000 households and 2,500 businesses.

Beneficiaries of programs funded by RGGI proceeds include low income families and businesses. For example, two energy efficiency programs targeted specifically at income eligible families are providing 100,000 low and moderate income families with more than $80 million in cumulative energy bill savings.

To those who say reducing emissions will cause electric rates for businesses to rise, we have actually reduced industrial electricity rates while reducing carbon emissions from 50 percent over the national average to 13 percent below.

We have enjoyed similar outcomes across the RGGI region. An independent analysis undertaken by the highly respected Analysis Group concludes that the reinvestment of auction proceeds from the first 3 years of the program is reducing total energy bills in the RGGI regions by $1.3 billion, adding $1.6 billion to regional economy and creating an estimated 16,000 jobs.

Reducing emissions also provides substantial public health benefits, including saving lives, reducing illness, health care costs and lost work days. Our experience demonstrates that a group of States can substantially reduce emissions and grow the economy at the same time. Therefore, instead of asking whether we can afford to reduce that pollution, a more pertinent question is whether we can afford not to act now to reduce the emissions that are causing our climate to change.

In New York, we are already experiencing the destructive effects of climate driven extreme weather. Three years ago, Hurricane Sandy decimated many communities and tens of thousands of homes in New York and New Jersey at a cost of $67 billion. Over 70 lives were lost in the area struck by the storm. A year earlier, Hurricanes Irene and Lee caused 66 deaths and $17 billion in damage. These storms disproportionately harmed low income families and small businesses in communities located in low lying areas most vulnerable to flooding.

Our choice as a Nation is straightforward. We can invest in clean energy, creating jobs as a result at little or no net cost and reap the benefits of better health, lower health costs and reduced risk of climate change or we can ignore the science and expect more frequent storm events causing tens of billions of dollars in damages.

To New York, the answer is clear. We have demonstrated it is possible to use energy more efficiently, stimulate economic growth, provide healthier air and reduce the potential damage from climate change.

That concludes my testimony. Thank you.

[The prepared statement of Mr. Martens follows:]

Testimony on "The Impacts of EPA's proposed Carbon Regulations on Energy Costs for American Businesses, Rural Communities and Families, and a Legislative Hearing on S. 1324."

Joseph Martens
Commissioner, New York Department of Environmental Conservation
Vice Chair, Regional Greenhouse Gas Initiative, Inc. Board of Directors

June 23, 2015

Good morning. My name is Joseph Martens and I am the Commissioner of the New York State Department of Environmental Conservation. I am also Vice-Chair of the Board of Directors of RGGI Inc., which administers the Regional Greenhouse Gas Initiative (RGGI), a program of nine northeastern states that uses market principles to reduce greenhouse gas emissions from the power sector. Although I am testifying today on behalf of New York, I will also relate the collective experience of the RGGI states.

I appreciate the opportunity to testify today about the benefits of programs to reduce the greenhouse gas emissions that contribute to climate change, with a particular focus on how families and businesses in New York have benefitted from RGGI and complementary clean energy programs. Simply put, the experience of New York and the other RGGI states over the last seven years clearly establishes that a state can grow its economy while reducing harmful carbon emissions. As I will explain, participation in RGGI is helping to improve energy efficiency and reduce costs for our residents and businesses and create jobs in New York and across the RGGI region. In addition, strategies to reduce harmful power plant emissions provide ample public health benefits that reduce the cost of medical care for our residents. The structure of the proposed federal Clean Power Plan provides flexibility to other states to design their own pathways to reduce carbon pollution and reap similar economic, social and environmental benefits.

The RGGI effort, similar to EPA's Clean Power Plan proposal, recognizes that carbon emissions are not limited to political boundaries or jurisdictions. Individual state and regional efforts like RGGI must be supported by a strong and equitable federal plan that ensures that all states contribute to achieving the reductions needed to address climate change.

My key takeaways include:

- The states participating in RGGI have shown that it is possible to achieve cost-effective pollution reductions while reducing energy costs to our families and businesses and growing our economy.
- Although the participating states set a goal of reducing carbon emissions 10% by 2018, we have reduced emissions 40%, while growing our states' economies.
- Energy efficiency and other projects funded by RGGI auction proceeds to date will provide $2.9 billion in lifetime energy bill savings for 3.7 million households and 17,800 businesses.
- Electricity rates for industrial customers in New York have declined from 50% above the national average before RGGI to 13% below the national average in 2014 after RGGI.
- Overall, 2500 businesses across the state – most of which are small businesses -- have benefitted directly from the investment of RGGI auction proceeds and the program is providing over $60 million in funding for advanced clean energy projects to more than 80 businesses across the state, enabling them to better compete in the global economy.
- New York's energy efficiency programs supported by RGGI proceeds have resulted in over 80 million dollars in energy bill savings to 100,000 low and moderate income families. Overall, 21% of the total electricity savings across the RGGI portfolio are directed to environmental justice areas.
- Recent storms have demonstrated the cost of a changing climate on low-income families that are the least able to bear the resulting costs of recovery.
- A multi-state market-based program can yield the most cost-effective carbon emission reductions.

We should no longer ask whether we can afford to reduce harmful pollution. We, and many other states, have demonstrated that we certainly can, while reducing energy costs and growing our economy. A more pertinent question is whether we can afford not to take action now. To New York's families and businesses, the answer to that is equally clear. Because the potential costs imposed by climate change on our families, businesses and resources greatly exceed the cost of reducing emissions, action to reduce carbon pollution significantly nationwide is needed now.

RGGI Success

RGGI started in 2005, when a bipartisan group of northeastern and mid-Atlantic governors joined in a memorandum of understanding (MOU) to establish the program. In their MOU, those governors recognized the risks posed by the changing climate and emphasized the potential economic benefits to the region of reducing the amount of money our businesses and consumers spend on electricity produced with fossil fuels. The participating states initially set a goal of reducing carbon emissions 10% by 2018, but we have greatly exceeded that goal, already achieving a reduction of more than 40% at the same time as our economy has expanded.

The RGGI states have achieved this success by setting a declining cap on emissions from the electricity sector and auctioning allowances to the businesses covered by the cap. This system allows the market to determine efficiently where the emission reductions will occur. The experience of the RGGI states is that a suite of activities directed at promoting a cleaner energy system provides the best opportunity for emission reductions from the power sector, or the "best system of emission reduction" in the parlance of the Clean Air Act.

In addition to their participation in RGGI, each of the RGGI states have energy efficiency and renewable energy programs that rank among the nation's most progressive. The RGGI cap collects the reductions from these efforts under a single emissions limit and ensures that the carbon reductions from these programs are realized and accounted for. And proceeds from RGGI allowance auctions help fund many of these initiatives – creating a virtuous cycle of consumer benefits for ratepayers.

Our program has been a resounding success. Not content with reducing emissions 40% by 2013, the RGGI states agreed in 2013 to lower the 2020 cap to 50% below 2005 levels – cutting power sector emissions in half in just 15 years. Notably, the RGGI states achieved this reduction in an economy that grew approximately 8% over the period from 2005 to 2013, adjusted for inflation.

The Benefits of Reducing Carbon Emissions Greatly Exceed Any Costs

In New York, we have realized many economic benefits from RGGI and associated programs. We have increased wind power thirty-fold since 2005 and more recently, the NY-Sun program has helped New York become one of the nation's fastest growing markets for solar power, adding more than 300 megawatts (MW) of solar in the first 2 years and we expect to add another 3000 MW of solar by 2023. New York now has the nation's fourth largest solar workforce and at least 10,000 people work in the wind and solar industries in New York. Like the other RGGI states, we have also invested significantly in energy efficiency, saving enough electricity to power nearly a million homes and achieving more than $5.8 billion in cumulative energy bill savings.

By investing RGGI allowance proceeds in job-creating clean energy programs, we are reducing energy bills in New York and across the RGGI region. An independent analysis undertaken by the highly respected Analysis Group concludes that the reinvestment of auction proceeds from the first three years of the program will reduce total energy bills in the RGGI region by $1.3 billion, adding $1.6 billion to the regional economy, and creating an estimated 16,000 jobs in the process. In New York, more than $450 million in proceeds from the auction of RGGI emissions allowances have been committed to programs that will reduce energy costs for over 130,000 households and 2,500 businesses. Region-wide, the investment of auction proceeds through 2013 is expected to produce more than $2.9 billion in lifetime energy bill savings to more than 3.7 million families and 17,800 businesses.

Energy bills are the product of two factors: how much energy is consumed and how much that energy costs. By investing in energy efficiency, we are reducing one half of the equation – the amount of electricity consumed. In addition, the average industrial electricity rate in New York has also declined over the period that RGGI has been in place, while electricity rates have increased nationally over the same period. In 2006, before the RGGI requirements were in place, industrial electricity rates were 50% higher than the national average. In 2014, after RGGI, industrial electricity rates in New York are 13% below the national average.

Businesses in New York are also benefit directly from RGGI investments. The program is providing over $60 million in funding for advanced clean energy projects at over 80 businesses across the state, enabling them to better compete in the global economy. Overall, 2500 businesses across the state – most of which are small businesses -- have benefitted from the investment of RGGI auction proceeds.

Benefits to Low Income Families

In New York, we recognize the importance of enabling all New Yorkers to share in the economic and environmental benefits of our clean energy initiatives. To that end, two energy efficiency programs funded in part by RGGI (the EmPower NY and Assisted Home Performance with Energy Star programs) are targeted specifically at income-eligible families. These two programs are providing 100,000 low and moderate income families with more than 80 million dollars in cumulative energy bill savings through the first quarter of this year. In addition, more than one quarter of the energy efficiency loans provided by the $100 million Green Jobs Green New York efficiency program have gone to low and moderate income New Yorkers. Overall, 15% of RGGI investments have funded projects in designated environmental justice areas across the state, accounting for 21% of the total electricity savings across the RGGI portfolio.

Each state participating in RGGI has the freedom to develop its own approach to using auction proceeds to benefit low income families. For example, in addition to supporting energy efficiency, Maryland uses the proceeds from RGGI auctions for direct energy bill assistance for low income families. The reinvestment of auction proceeds has helped more than 215,000 low-income Maryland families pay their energy bills and supported energy efficiency upgrades for nearly twelve thousand low- and moderate-income families.

Protecting Public Health

RGGI contributes to Governor Cuomo's comprehensive clean energy strategy that is reducing pollution, growing the green economy, and protecting public health in New York. This groundbreaking strategy is called Reforming the Energy Vision, or REV. It will create a cleaner, more resilient, more affordable, integrated energy system that harnesses the local grid with more reliable, green resources. REV will also provide New York's families and businesses with better control over their energy decisions, allowing them to participate in further reducing emissions from New York's energy system.

In addition to economic benefits, New York's clean energy programs are providing substantial public health benefits including reducing illness, health care costs and lost workdays. Over the same period that New York cut power sector carbon pollution by 40%, emissions of sulfur dioxide decreased more than 90%, and nitrogen oxide emissions by around 75%. These reductions are estimated to save hundreds of lives, prevent thousands of asthma attacks and provide public health benefits valued in the billions of dollars. We expect to see similar results nationwide from implementation of the Clean Power Plan, after it is finalized by EPA.

The **High Cost of the Changing Climate**

In my view, the response to the question of whether we can afford as a nation to reduce emissions from the electricity sector is clearly a resounding yes. But an even more important question is whether we can afford not to. Increased carbon emissions are contributing to a warming climate. As a result, high-intensity storm events have become the norm. These events have and will continue to have significant economic impacts on the States. We do not have to rely solely on studies or projections to notice the impact in New York, because we have experienced the destructive effects of climate-driven extreme weather. Three years ago, Hurricane Sandy decimated many communities and tens of thousands of homes in New York and New Jersey at a cost of $67 billion; over 70 lives were lost in the New York and New Jersey area struck by the storm. A year earlier, Hurricanes Irene and Lee caused 66 deaths and $17 billion in damage.

Notably, these storms disproportionately harmed low income families and smaller businesses in communities located in low-lying areas most vulnerable to flooding. In New York, 30% of the homeowners and 65% of the renters directly impacted by Sandy had household incomes below $30,000. In New York City, 800,000 public housing residents lost essential services during

Sandy and thousands of families in the most vulnerable areas did not have power fully restored for several months. As bad as Hurricane Sandy was, we face an even more bleak future if sea levels rise as much as six feet by the end of the century, as could occur if we fail to take substantial action now to reduce carbon emissions worldwide.

Lessons for the Clean Power Plan

RGGI demonstrates that states can achieve carbon emission reductions that exceed the Clean Power Plan's national goal of 30% below 2005 levels using a regional compliance approach, while reducing energy costs, creating jobs, and protecting public health. Our experience informs us that EPA's projection that the Clean Power Plan will lead to lower, not higher, electricity bills, is likely to be true – if States choose smart, cost-effective approaches to achieve EPA's targets.

A multi-state, market-based program like RGGI provides the most cost-effective means of reducing emissions to comply with the Clean Power Plan. The multi-state market enables regulated facilities in the participating states to take advantage of the most cost-effective compliance strategies across the participating states. In addition, states that choose to auction allowances can use the proceeds, as we have done in RGGI, to provide economic benefit and reduce energy costs to their residential and industrial energy consumers. One of the advantages of the Clean Power Plan is that EPA leaves those policy decisions to the states.

Conclusion

Our choice as a nation is straightforward. We can invest in clean energy, creating jobs as a result, at little or no net cost, and reap the benefits of better health, lower health costs and reduced risks of climate change. Or we can ignore the science and expect more frequent storm events causing tens of billions of dollars in damages. To New York, the answer is clear: we can use energy more efficiently, stimulate economic growth, provide healthier air, and reduce the potential damage from climate change. Other states can reap the same benefits.

Senator CAPITO. Thank you.

Our final witness is Mary B. Rice, M.D., MPH, Instructor in Medicine, Harvard Medical School, Division of Pulmonary, Critical Care and Sleep Medicine. Welcome.

STATEMENT OF MARY B. RICE, M.D., MPH, INSTRUCTOR IN MEDICINE, HARVARD MEDICAL SCHOOL, DIVISION OF PULMONARY, CRITICAL CARE AND SLEEP MEDICINE

Dr. RICE. My name is Dr. Mary Rice. I am an adult pulmonologist and critical care physician at Beth Israel Deaconess Medical Center and Harvard Medical School in Boston.

I care for adults with lung disease, most of whom have asthma or emphysema. I also care for critically ill adults in the intensive care unit.

My message is simple. Climate change is becoming the worst public health crisis of modern medicine. Hundreds of research studies have demonstrated that greenhouse gas emissions have already changed our climate over the past several decades, causing heat waves that last longer and happen more frequently, dangerous spikes in ground level ozone, increased wildfire activity and longer, more potent pollen seasons. These effects hurt American families.

My physician colleagues and I are already seeing these health effects among our patients. The American Thoracic Society recently conducted a survey of our U.S. members who are doctors from all around the Country, caring for children and adults.

We found that the vast majority of doctors said climate change is affecting their patients today. Let me describe just a few of the health effects that my colleagues and I see.

Consider heat waves. Several doctors commented that their patients with emphysema, already struggling to breathe, cannot handle extreme heat. Studies have found that people with asthma and emphysema visit their doctors more often and get hospitalized more often during heat waves. The elderly, who may already be weakened by heart and lung disease, die during heat waves.

Extreme heat also increases ozone to levels that are harmful to the lungs of people, not only people with asthma and emphysema but also the lungs of babies and young children, and even healthy adults. Ozone spikes during heat waves have been found to contribute to premature mortality.

The hot conditions promoted by climate change favor forest fires and grassland fires, which are at a great cost to human health. During a heat wave in May 2014, for example, multiple wildfires broke out simultaneously in San Diego County, causing $60 million in damage.

This estimate does not capture the damage to the health of families who were affected by those fires. Wildfires can travel great distances and release a mixture of toxins that are especially irritating to the lung making it harder for people to breathe.

A colleague of mine in San Diego told me that he advised all his patients to stay inside and keep the air conditioning on. Is this the future we want for American families, one where it is not safe to go outside? There is no doubt that wildfires increase hospitalization for asthma in children and adults and for respiratory illness among the elderly.

Climate change is also bad for people with seasonal allergies, about 30 percent of all Americans and for the roughly 10 percent of Americans with asthma. Warmer temperatures lengthen the pollen season because plants bloom earlier in the spring and also higher levels of carbon dioxide increase the amount of pollen that is produced.

In the northern States of the U.S., pollen seasons have lengthened by more than 2 weeks to date than they were in 1995. They are also more powerful. Studies have found that when pollen levels are higher, people use more medications, visit their doctors more for allergies and emergency room visits for asthma among children and adults go up.

One of my patients, a single mother with a teenage son, both of whom have severe asthma, called me on a weekly basis this spring because of trouble breathing. Between the missed days of school for her son and missed days of work for her, this allergy season was a disaster for her family.

I am a physician and a researcher, but my most important job is my role as a mother to three children under the age of 6. My 1-year-old son has had two emergency room visits and a hospitalization for respiratory illness.

When my son develops a cough or wheeze, I am terrified because this could mean the next ambulance ride. When he is sick, I cannot go to the hospital and take care of my patients or my husband cannot work.

We are more fortunate than many Americans, many of whom risk losing their job or struggle to pay for the next emergency room visit when they or a loved one suffers an acute respiratory illness. My son and every American deserves clean air.

I have only described a few of the threats to the health of Americans from climate change. Experts predict that we can avoid the most frightening scenarios if we reduce greenhouse gas emissions and better yet, when we address climate change, we redeem immediate health benefits right here in the U.S. When we reduce greenhouse gas emissions, we also reduce air pollutants that trigger heart attacks, asthma and emphysema attacks, stroke and death.

As a mom, a doctor and a representative of the American Thoracic Society, I favor taking firm steps to address climate change because I support clean air and a healthy future for all Americans.

Thank you.

[The prepared statement of Dr. Rice follows:]

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Comments from the American Thoracic Society
Presented by Mary B. Rice MD MPH
Before the Senate Environment and Public Works Committee
Subcommittee on Clean Air and Nuclear Safety
on
EPA's Proposed Carbon Regulations
June 23, 2015

Ms. Chairwoman, Mr. Ranking member, my name is Dr. Mary Rice. I am an adult pulmonologist and critical care physician at Beth Israel Deaconess Medical Center and Harvard Medical School in Boston, and also Vice-Chair of the Environmental Health Policy Committee of the American Thoracic Society. When I am not caring for patients, I am engaged in research on the respiratory health effects of ambient air pollution exposure among children and adults. On behalf of the American Thoracic Society, I want to thank the Committee for the opportunity to testify regarding the proposed carbon regulations of the Environmental Protection Agency (EPA). The American Thoracic Society is a medical professional organization with over 15,000 professionals and patients who are dedicated to the prevention, detection, treatment and cure of respiratory disease, critical care illnesses and sleep-disordered breathing. We pursue our mission through research, clinical care, education and advocacy. The American Thoracic Society has identified climate change as one of the most important health issues facing our patients, who are children and adults across the United States, most of whom suffer from critical illness or lung disease(1, 2).

The 2013 Intergovernmental Panel on Climate Change (IPCC) report concluded that carbon dioxide concentrations have risen by 40% since pre-industrial times, primarily due to fossil fuel emissions, and have reached levels "unprecedented in at least the last 800,000 years"(3). The report concluded that global warming is "unequivocal" and that with 95-100% certainty, the observed warming since the 1950's is primarily due to human activity(3). In the past decade, an accumulation of scientific evidence has shown that climate change is not only an environmental and economic problem, it is a human health problem of enormous proportions. Some of the most well-described human health consequences of climate change are caused by:

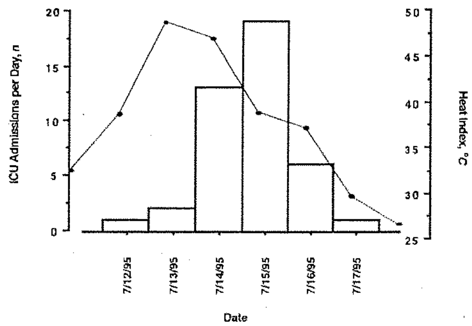
(1) heat waves
(2) spikes in ozone pollution
(3) forest fires
(4) longer and more potent pollen seasons

Last year, the American Thoracic Society Environmental Health Policy Committee collaborated with George Mason University to conduct a survey of United States American Thoracic Society members about climate change and health(4). The survey respondents were predominantly clinicians (89% held an M.D. or other clinical professional degree). Overall, 89% of member respondents judged that climate change is presently happening and 68% indicated that climate change is mostly or entirely caused by human activity. What may be especially surprising to many, is that **most physicians responding to the survey reported that they have already observed symptoms among their patients that they attribute to climate change.** For example, 77% of respondents have noted increases in the severity of chronic illness resulting from spikes in air pollution as a consequence of climate change, such as ozone or wildfires. Also, 58% noted increases in allergic disease symptoms and 48% observed heat-related health effects among patients. Of the many clinical anecdotes provided, several respondents commented about regional wildfire activity and urban high ozone events affecting their patients with asthma or chronic obstructive pulmonary disease, and many noted increases in allergic disease symptoms and injuries due to changes in weather.

Our patients and their families are already suffering as a result of greenhouse gas emissions, and the healthcare system is already paying the cost of hospitalizations, doctor visits and drug prescriptions to treat these problems. Without efforts to reduce greenhouse gas emissions, the human health toll for American families will continue to rise. I will review some of the human health consequences of climate change for which there is a high level of confidence and scientific evidence of health effects, with a focus on cardiopulmonary health.

1. Heat Waves

Heat waves have well-documented adverse health effects. It is therefore highly concerning that climate models predict up to a 50% increase in the frequency in the hottest (ie, the top 5th percentile based on historical records) days by mid-century(5, 6). Extreme heat increases mortality, especially among the elderly and those with chronic disease(7, 8). The heat wave that hit western Europe in August 2003 resulted in an excess of 15,000 deaths in France alone(9). In July 1995, Chicago experienced a heat wave that resulted in more than 600 excess deaths, 3,300 excess emergency department visits, and a large number of intensive care unit admissions for near-fatal heat stroke(10). Heat stroke patients admitted to the intensive care unit suffered from brain impairment, kidney failure and derangement of the clotting system, and 21% died during their hospital admission(10). The chart below demonstrates the increase in intensive care unit admissions for near-fatal heat stroke in 12 Chicago-area hospitals during the 1995 heat wave:



Relation between admissions to the intensive care unit (ICU) for near-fatal heat stroke (bar graph) and the heat index (line chart) during the height of the heat wave. Admissions increased 24 hours after the peak heat index on 13 July 1995. The peak admission rate occurred 2 days later, on 15 July 1995. Intensive care unit admissions coincided with heat-related deaths reported by the Cook County Medical Examiner's office. From: Dermatte et al. Ann Intern Med. 1998;129(3):173-181

Extreme heat events are linked to higher rates of hospitalization for respiratory and heart disease. Acute increases in temperature and humidity are associated with increased emergency department visits and hospitalizations for asthma in children and adults (11, 12). For example, a study of 12.5 million Medicare beneficiaries found that each 10°F increase in daily temperature was associated with a 4.3% increase in same-day emergency hospitalizations for respiratory diseases(13). A study examining hourly temperature and incidence of heart attacks found that when temperatures exceeded a threshold of 68 °F, people's risk of heart attack increased 1-6 hours later(14). There is also evidence that extreme heat may trigger exacerbations of congestive heart failure(12).

People living in cities, particularly low income families living in neighborhoods with large buildings and little open space, are especially vulnerable to extreme heat(15), because of an urban "heat island" effect. As average temperatures increase, populations will adjust to a higher temperature range, but they will continue to be vulnerable at temperature extremes(16). Recent studies have examined the effect of adaptation (including air conditioning use) on heat-related mortality, and have concluded that adaptation does reduce premature mortality due to extreme heat(17, 18). If greenhouse gas emissions continue without abatement, the need for measures such as widespread subsidies for air conditioning for low income families, the construction of cooling centers, and surveillance programs for the frail and elderly to prevent premature death and hospitalization due to extreme heat is likely to become an essential public health priority in cities across the United States.

Extreme heat also impairs outdoor worker productivity, because unprotected outdoor work in extreme heat can lead to heat stroke and heat exhaustion, electrolyte disturbances and dehydration. A number of indexes have been developed, including indices from the Occupational Safety & Health Administration (OSHA) and the US army, to establish safe temperature ranges for outdoor work of varying work intensities(19, 20). Greenhouse gas emissions increase the frequency of days with heat levels that are unsafe for continuous outdoor work, mandating more breaks and reducing worker productivity. Emissions also increase the frequency of days that are unsafe for any heavy outdoor work, such as occupational lifting, carrying and digging(21). One study estimated that global warming since the pre-1960 baseline has decreased global working capacity by 3 % during the peak summer season, and predicts that if greenhouse gas emissions rates continue along their historical trajectory, future global working capacity will drop to below 40 percent during the peak summer season (21). Workers in mid-latitude regions such as the US east of the Rockies, are expected to be exposed to dangerous environmental heat stress, experienced today only by the most extremely hot regions of the Earth, if greenhouse gas emissions continue along their historical trajectory(21).

2. Ozone Pollution

Ground-level ozone is a major component of photochemical smog that is formed through atmospheric reactions of nitrogen oxides and volatile organic compounds (both emitted by motor vehicles and fossil fuel burning) in the presence of sunlight. Ozone formation increases with more sunlight and higher temperature(22).

The frequency and intensity of ozone episodes during summer months are projected to increase as a result of rising temperatures(23, 24). Recent heat waves have been associated with ozone levels that exceeded air quality standards(25). Because ozone is a lung and airway irritant(26, 27), people with pre-existing lung disease like asthma or chronic obstructive pulmonary disease are particularly susceptible to adverse health effects of ozone exposure. A substantial body of evidence has shown that modest short-term increases in ground-level ozone increase risk of acute care visits and hospitalization for asthma (28–31) and chronic obstructive pulmonary disease(32, 33). Ozone exposure also been associated with deterioration in asthma control, resulting in increased medication use and missed school and work days (34, 35).

Spikes in ozone have been associated with increases in all-cause mortality(36). The deadly heat wave of 2003 in Europe was accompanied by high levels of ozone that are thought to have contributed to excess mortality in addition to the mortality caused by the heat itself(25, 37).

3. Forest Fires

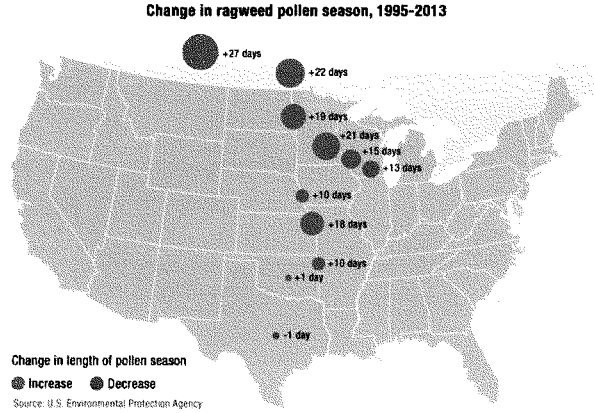
Climate models indicate that with 1°C of warming, wildland fire risk may increase 2- to 6-fold over the 1950-2003 baseline in most of the continental U.S. west of the Mississippi(38). When forests burn they release a range of pollutants, from particulate matter and acrolein (a respiratory irritant) to carcinogens such as formaldehyde and benzene. For example, wildfire in the Pocosin Lakes National Wildlife refuge in North Carolina produced smoke and haze intermittently for a number of weeks in 2008. Maximum daily smoke-related fine particulate matter levels reached as high as 129 $\mu g/m^3$, which is nearly 4 times the current EPA daily standard of 35 $\mu g/m^3$ for fine particulate matter(39). Studies suggest that particles in wildfire smoke are more toxic to the lung than particulate matter from other sources of pollution(40).

The number of wildfires over 1,000 acres in size in the region stretching from Nebraska to California increased by a rate of seven fires a year and 88,000 acres burned per year from 1984 to 2011(41). Although forest fires may ignite in only certain regions, their smoke plumes may extend over great distances. During the Russian heat wave of 2010, for instance, smoke from more than 500 wildfires stretched across more than 1800 miles – roughly the distance from San Francisco to Chicago (42). Exposure to wildland fire smoke has been associated with asthma and chronic obstructive pulmonary disease emergency room visits and hospitalizations(43–45), congestive heart failure episodes(39) and overall mortality(46). For example, the 2008 wildfires in North Carolina increased risk of asthma hospitalization by 66% for every 100 $\mu g/m^3$ increase in fine particulate matter(39).

4. Pollen Season

Higher levels of carbon dioxide and a warming climate worsen the global burden of allergic disease, which has been increasing in prevalence in the industrialized world for more than 50 years(47). Worldwide, between 10 and 30% of people suffer periodically from seasonal allergies and up to 40% show evidence in their blood of sensititivity to allergens in the environment(47). Warmer temperatures lengthen the pollen season because plants bloom earlier in the spring. Between 1995 and 2009, the pollen season lengthened 13-27 days above 44 degrees north in the U.S.(48). Ragweed pollen season has lengthened by 24 days in the Minnesota-North Dakota region between 1995 and 2011 (49). Higher levels of carbon dioxide in the atmosphere have also been found to increase pollen productivity and the allergic potency of pollen(50, 51).

Change in ragweed pollen season, 1995-2013



Higher pollen levels are linked to allergic sensitization in the blood(52) and more healthcare utilization for allergic disease, measured in terms of over-the-counter allergy medication use(53), and emergency room and physician office visits for allergic disease(54, 55).

Longer, more potent allergy seasons are especially detrimental to people with asthma. Numerous studies have found increases in asthma and wheeze-related emergency room visits when pollen levels are higher(56–59)

In 2010, Americans with seasonal allergies spent approximately 17.5 billion on health-related costs, lost more than 6 million work and school days, and made 16 million visits to their doctors(60). Seasonal allergies already exert a huge toll on the health of the American public. Rising carbon dioxide emissions are expected to continue to worsen this problem by lengthening the pollen season and further increasing pollen production across the United States.

Conclusion

People across the United States with lung, heart and allergic disease, and especially the frail and elderly, are already suffering the health consequences of climate change. Physicians of the American Thoracic Society are observing these symptoms among our patients in our clinics, emergency departments and intensive care units nationwide. There is an urgency to reduce greenhouse gas emissions for the sake of human health.

I would be happy to answer any questions.

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Senator CAPITO. Thank you, Doctor.

I want to thank you all. We will begin the questions and I will begin.

Mr. Trisko, you mentioned in your remarks the impacts of the conservation building block of the Clean Power Plan and how elderly citizens and those on fixed incomes would probably be least likely to be the ones to benefit from that or be able to afford to make those changes.

It says the Energy Information Administration projects that consume energy prices will go up by 4 percent by 2020 which seems rather low since we just had a 16 percent rise in our prices in West Virginia.

How do you see these two converging, the rising price and the lack of the conservation and deficiency aspects of this Clean Power Plan for the elderly citizen and those on fixed incomes?

Mr. TRISKO. Let me first address the observation I offered with respect to senior citizens being least likely to benefit from the energy efficiency aspects of the Clean Power Plan.

That observation derives from two facts. First is the payback period that is required to support major investments in energy efficiencies such as replacement of windows and heating and ventilating systems.

Those payback periods typically are too long to be economically feasible for lower income senior citizens. It is also true in general for the population that American houses tend to be owned for a period of about 7 years on average.

If you are a homeowner looking at a $10,000 window replacement project that is going to save a few hundred dollars a year on your energy bills, that payback period is not consistent with the period that typical homeowners expect to live in those dwellings.

Second, I have heard this from senior utility executives as well. One of the difficulties in securing energy efficiency gains from lower income consumers is the quality of the housing stock, the relatively poor quality of the housing stock, will not support investments in fairly high cost energy efficiency upgrades such as windows and HVAC systems.

Certainly lower cost options, the simple things such as better attic insulation, weather stripping and the like have short payback periods and are feasible. The magnitude of the energy efficiency investments EPA is projecting in the Clean Power Plan, which NERA estimates to cost some $500 billion for American consumers, those investments simply will not be made by the elderly and the lower income consumers.

I hope that is responsive to your question.

Senator CAPITO. Thank you.

Mr. Alford, the Energy Information Administration recently concluded the Clean Power Plan could reduce the GDP by $1 trillion. Based on the analysis that you just did and explained, could you reemphasize for us how you think that is going to impact low income or even minority citizens across the Country?

Mr. ALFORD. It is going to be very critical and tragic. As far as the 2.1 million Black-owned businesses we represent, their customer base is going to whither and I think the quality of life is going to hurt in our communities. I think people will start to shortshrift moneys that would be used for health care or education. I think people who would resort to crime and violence because they are poor and broke would increase.

I think it would hurt our communities severely.

Senator CAPITO. A final question very quickly, Mr. Trisko. Part of the ARENA Act says we should not move forward with these regulations until all the legal aspects are settled. As you know, States are challenging this and will challenge when the final rule comes out.

If States begin to make changes in the meantime, what kind of scenario does that present to you in terms of how States are going to be able to react not knowing whether the legal issues have been settled as yet?

Mr. TRISKO. Senator, you have hit upon one of the most desirable aspects of the ARENA Act. Let me put it in the context of the current situation that the electric utility industry faces.

With respect to EPA's 2011 Mercury and Air Toxic Standard Rule or the MATS rule, the MATS rule is currently before the Supreme Court. A decision is expected shortly within a matter of days.

It is possible the Supreme Court decision could result in vacating the rule. And yet, utilities, in order to comply with that rule already have retired dozens of power plants across the United States and are scheduled to retire even more over the course of the next year.

Wouldn't it be advisable as a matter of public policy before implementation of the most expensive rule ever imposed on the electric utility sector, $9.5 billion a year, to know up front whether the rule is legal?

Senator CAPITO. Thank you.

To our Ranking Member, Senator Carper, a fellow West Virginian, I want to say welcome and also ask if he could do his opening statement and then do questions which I say most certainly you can.

Senator Carper.

OPENING STATEMENT OF HON. THOMAS R. CARPER, U.S. SENATOR FROM THE STATE OF DELAWARE

Senator CARPER. Thank you, Madam Chairman. Thanks for holding the hearing.

To all of our witnesses, it is great to see you and thank you for joining us, some of you not for the first time.

Dr. Rice, I will think about your son and hope he grows up to be 101 or 102 years old and has a great life.

One of the issues we always wrestle with here is, is it possible to have cleaner air, cleaner water and at the same time, have a strong economy. For most of my life after the Navy, I focused on job creation and job preservation and what we do to foster a nurturing environment for job creation and job preservation.

If you go back to January 2009, the week Barack Obama and Joe Biden were sworn into office, that week 628,000 people filed for unemployment insurance. Think about that, 1 week in January 2009. In the last 6 months of 2008, we lost 2.5 million jobs. The first 6 weeks in 2009, we lost another 2.5 million jobs. That is 5 million jobs literally in a 12-month period of time.

Since 2010, we have adopted new mercury regulations on power plants. We have adopted new carbon pollution or fuel economy standards on cars and trucks. We have also adopted across State air pollution standards. Since 2010, we have added 762,000 manufacturing jobs and millions other jobs, but three-quarters are manufacturing jobs.

This leads me to believe that maybe it is possible to have cleaner air and cleaner water and at the same time actually do better by virtue of our economy and economic growth. I would ask that we keep that in mind.

As the Chairman said, I was born in Beckley, West Virginia, a coal mining town. I grew up there in Roanoke and Danville, Virginia. Now I represent the State of Delaware, the lowest lying State in the Country. We see every day the effects of climate change and global warming. Sea level rise creeps up higher and higher on the east coast of my State. It is very, very real to us.

For decades, the fear of the cost to combat climate change prevented any real action on this issue in Congress. Since coming here, I have tried to work with my colleagues on a climate compromise that would harness market forces to reduce carbon pollution and reduce the cost of compliance.

As part of that compromise, I worked with Senator Byrd and a handful of other coal State Senators on language that would have provided more than $10 billion in incentives to support the deployment of clean coal power plants.

This language, along with other language, intended to buffer impacts to the coal industry, was included in the Kerry-Boxer bill which regrettably was not enacted into law. Instead, in coming to a compromise on climate change, Congress came to a stalemate. All the while, it is becoming clear that the price of inaction is much greater than the price of action.

The EPA just released a comprehensive report that outlines the alarming truth that failure to act on climate change will result in dramatic costs for our environment and for our economy. Findings are pretty clear concerning low lying States like Florida, Delaware and others up and down the east coast.

Without action on climate change, we are going to need to spend billions of dollars in this century to protect States from rising sea levels and extreme storms.

The study also projects that inaction on climate change could lead to extreme temperatures and cause thousands of deaths throughout the northeast and the mid-Atlantic regions of our Country.

At least it is clear to me that as each year passes without action, the more severe, the more costly and perhaps more irreversible the effects of climate change are becoming. For those of us who come from States already being impacted by climate change, I think the message is clear and that is, we can no longer afford inaction.

Many States such as New York, represented here today and welcome, and Delaware have already taken action to reduce the emissions of the largest emitters of carbon pollution, power plant.

As we will hear today, the economics of these States continue to grow at a faster rate than the States that have yet to put climate regulations in place. However, we need all States to do their fair share to protect the air we breathe and stem the tide of climate change.

The EPA's Clean Power Plan attempts to do that. Under the Clean Power Plan, States are given their own carbon pollution targets and allowed to find the most cost effective way to find reductions. In fact, it sounds similar to the compromise I tried to foist on my colleagues here a number of years ago.

I believe instead of undercutting the Clean Power Plan, we should be working in good faith with the agency to find ways to improve the regulation. For example, the regulation could be improved in several ways.

One, to ensure early action, States are not penalized for being climate inefficiency leaders. Two, ensure that all clean energy, including nuclear, is treated equitably. Three, ensure we meet our carbon reduction goals.

No compromise is ever perfect. The worse thing we can do is to do nothing while we try to find the perfect solution. We must act now while the ability to mitigate the most harmful impact is still within our grasp.

The choice between curbing climate change and growing our economy is, as I have suggested here many times, a false one. Instead, we must act on curbing climate change in order to protect the future economy prosperity of our Country.

[The prepared statement of Senator Carper follows:]

STATEMENT OF HON. THOMAS R. CARPER,
U.S. SENATOR FROM THE STATE OF DELAWARE

Thank you, Chairman Capito, for holding this hearing today. I want to welcome the witnesses to the subcommittee. In today's hearing we will focus on the costs and benefits of the Environmental Protection Agency's (EPA's) proposed carbon regulations, known as the Clean Power Plan.

I was born in Beckley, West Virginia, and have spent most of my adult life in Delaware. As a native of a small town supported by coal mining, and now as a Senator representing the lowest-lying State in the Nation, I have a unique perspective on the balance that we must strike to make climate regulations work for each State.

The debate on the costs and benefits of climate change action is not a new one. For decades, fears of the costs to combat climate change have prevented any real action on this issue in Congress.

Since coming to the Senate I have tried to work with my colleagues on a climate compromise that would use market forces to reduce carbon pollution and reduce the costs of compliance. As part of a compromise, I worked with Senator Byrd and a handful of other coal-State Senators on language that would have provided more than $10 billion in incentives to support the deployment of clean coal power plants. This language—along with other language intended to buffer impacts to industry—was included in the Kerry-Boxer bill, which regrettably did not pass into law.

Instead of coming to a compromise on climate change, Congress came to a stalemate. All the while, it is becoming clearer that the price of inaction is much greater than the price of action.

The EPA just released a comprehensive report that outlines the alarming truth that failure to act on climate change will result in dramatic costs for our environment and for our economy. The findings are particularly concerning for low-lying coastal States like Delaware. Without action on climate change, we will need to spend billions of dollars in this century to protect our State from rising sea levels and extreme storms. The study also projects that inaction on climate change could lead to extreme temperatures and cause thousands of deaths throughout the Northeast and Mid-Atlantic regions.

It is clear that as each year passes by without action the more severe, the more costly, and perhaps irreversible, the effects of climate change are becoming. For those of us from States that are already being impacted by climate change, the message is clear—we can no longer afford inaction.

Many States, such as New York and Delaware, have already taken action to reduce the largest emitter of carbon pollution—power plant emissions. As we will hear today, the economies of these States continue to grow at a faster rate than the States that have yet to put climate regulations in place. However, we need all States to do their fair share to protect the air we breathe and stem the tide of climate change. The EPA's Clean Power Plan attempts to do just that.

Under the Clean Power Plan, States are given their own carbon pollution targets and allowed to find the most cost-effective way to find reductions. In fact, it sounds similar to the compromises I tried to find with my colleagues.

I believe instead of undercutting the Clean Power Plan we should be working in good faith with the agency to find ways to improve the regulation. For example, the regulation could be improved to:

(1) ensure early action States are not penalized for being climate and efficiency leaders;

(2) ensure all clean energy is treated equitable; and

(3) ensure we meet our carbon reduction goals.

No compromise is ever perfect, but the worst thing we can do is to do nothing while we try to find the perfect solution. We must act now while the ability to mitigate the most harmful impacts is still within our grasp. The choice between curbing climate change and growing our economy is a false one. Instead, we must act on curbing climate change in order to protect the future economic prosperity of our Country. Thank you.

Senator CARPER. Madam Chairman, thank you for letting me give my statement and ask some questions.

I was delayed today because we had a caucus lunch. Part of our caucus lunch discussion, you would be interested to know, was about the transportation bill, the 6-year transportation bill authored by Chairman Inhofe, Senator Boxer, Senator Vitter and myself which I think is going to be well received. We are excited about that. We had a discussion about that and I got here a little late and I apologize for that.

I like to joke around a bit and I thought I was going to come in and say I had taken a call from the Pope but I am not Catholic and he rarely calls me. I must say I am impressed with this guy.

I am impressed with him because I think he actually read the New Testament and has a real commitment to the least of these in our society. You know, when I was hungry, did you feed me? When I was thirsty, did you give me drink? When I was naked, did you clothe me? When I was sick in prison, did you come to visit me? He gets that and really calls on all of us to do the same.

The other thing that he gets, for those of you familiar with Scripture, most of you probably more than me, is we have a moral obligation to make sure we have a planet with a decent quality of life. He believes and a lot of folks believe that there is a real serious problem here. We have a moral imperative to do something about it.

We can talk about all these other studies and everything until the cows come home, but I would have us keep that thought in mind. Now I have a couple of questions.

First, I ask unanimous consent to submit for the record two items. One is the latest report from the Lancet and the University College London Commission on Health and Climate Change entitled Health and Climate Change Policy, Responses to Protect Public Health.

I would also ask unanimous consent to submit the EPA's peer-reviewed report entitled Climate Change, the United States Benefit of Global Action.

Senator CAPITO. Without objection.

[The referenced information follows:]

Health and climate change: policy responses to protect public health

Nick Watts, W Neil Adger, Paolo Agnolucci, Jason Blackstock, Peter Byass, Wenjia Cai, Sarah Chaytor, Tim Colbourn, Mat Collins, Adam Cooper, Peter M Cox, Joanna Depledge, Paul Drummond, Paul Ekins, Victor Galaz, Delia Grace, Hilary Graham, Michael Grubb, Andy Haines, Ian Hamilton, Alasdair Hunter, Xujia Jiang, Moxuan Li, Ilan Kelman, Lu Liang, Melissa Lott, Robert Lowe, Yong Luo, Georgina Mace, Mark Maslin, Maria Nilsson, Tadj Oreszczyn, Steve Pye, Tara Quinn, My Svensdotter, Sergey Venevsky, Koko Warner, Bing Xu, Jun Yang, Yongyuan Yin, Chaoqing Yu, Qiang Zhang, Peng Gong, Hugh Montgomery*, Anthony Costello**

Executive summary

The 2015 *Lancet* Commission on Health and Climate Change has been formed to map out the impacts of climate change, and the necessary policy responses, in order to ensure the highest attainable standards of health for populations worldwide. This Commission is multi-disciplinary and international in nature, with strong collaboration between academic centres in Europe and China.

The central finding from the Commission's work is that tackling climate change could be the greatest global health opportunity of the 21st century. The key messages from the Commission are summarised below, accompanied by ten underlying recommendations to accelerate action in the next 5 years.

The effects of climate change are being felt today, and future projections represent an unacceptably high and potentially catastrophic risk to human health

The implications of climate change for a global population of 9 billion people threatens to undermine the last half century of gains in development and global health. The direct effects of climate change include increased heat stress, floods, drought, and increased frequency of intense storms, with the indirect threatening population health through adverse changes in air pollution, the spread of disease vectors, food insecurity and under-nutrition, displacement, and mental ill health.

Keeping the global average temperature rise to less than 2°C to avoid the risk of potentially catastrophic climate change impacts requires total anthropogenic carbon dioxide (CO_2) emissions to be kept below 2900 billion tonnes ($GtCO_2$) by the end of the century. As of 2011, total emissions since 1870 were a little over half of this, with current trends expected to exceed 2900 $GtCO_2$ in the next 15–30 years. High-end emissions projection scenarios show global average warming of 2·6–4·8°C by the end of the century, with all their regional amplification and attendant impacts.

Tackling climate change could be the greatest global health opportunity of the 21st century

Given the potential of climate change to reverse the health gains from economic development, and the health co-benefits that accrue from actions for a sustainable economy, tackling climate change could be the greatest global health opportunity of this century. Many mitigation and adaptation responses to climate change are "no-regret" options, which lead to direct reductions in the burden of ill-health, enhance community resilience, alleviate poverty, and address global inequity. Benefits are realised by ensuring that countries are unconstrained by climate change, enabling them to achieve better health and wellbeing for their populations. These strategies will also reduce pressures on national health budgets, delivering potentially large cost savings, and enable investments in stronger, more resilient health systems.

The Commission recommends that over the next 5 years, governments:

1 Invest in climate change and public health research, monitoring, and surveillance to ensure a better understanding of the adaptation needs and the potential health co-benefits of climate mitigation at the local and national level.
2 Scale-up financing for climate resilient health systems world-wide. Donor countries have a responsibility to support measures which reduce the impacts of climate change on human wellbeing and support adaptation. This must enable the strengthening of health systems in low-income and middle-income countries, and reduce the environmental impact of health care.
3 Protect cardiovascular and respiratory health by ensuring a rapid phase out of coal from the global energy mix. Many of the 2200 coal-fired plants currently proposed for construction globally will damage health unless replaced with cleaner energy alternatives. As part of the transition to renewable energy, there will be a cautious transitional role for natural gas. The phase out of coal is proposed as part of an early and decisive policy package which targets air pollution from the transport, agriculture, and energy sectors, and aims to reduce the health burden of particulate matter (especially $PM_{2.5}$) and short-lived climate pollutants, thus yielding immediate gains for society.
4 Encourage a transition to cities that support and promote lifestyles that are healthy for the individual and for the planet. Steps to achieve this include development of a highly energy efficient building stock; ease of low-cost active transportation; and

Published Online
June 23, 2015
http://dx.doi.org/10.1016/S0140-6736(15)60854-6

See Online/Comment
http://dx.doi.org/10.1016/S0140-6736(15)61080-7,
http://dx.doi.org/10.1016/S0140-6736(15)60931-X, and
http://dx.doi.org/10.1016/S0140-6736(15)61043-1

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increased access to green spaces. Such measures improve adaptive capacity, whilst also reducing urban pollution, greenhouse gas emissions, and rates of cardiovascular disease, cancer, obesity, diabetes, mental illness, and respiratory disease.

Achieving a decarbonised global economy and securing the public health benefits it offers is no longer primarily a technical or economic question—it is now a political one

Major technical advances have made buildings and vehicles more efficient and renewable energy sources far more cost effective. Globally, there is plentiful financial resource available, however much of it is still being directed towards the fossil-fuel industry. Bold political commitment can ensure that the technical expertise, technology, and finance to prevent further significant climate change is readily available, and is not a barrier to action.

The Commission recommends that over the next 5 years, governments:

5 Establish the framework for a strong, predictable, and international carbon pricing mechanism.
6 Rapidly expand access to renewable energy in low-income and middle-income countries, thus providing reliable electricity for communities and health facilities; unlocking substantial economic gains; and promoting health equity. Indeed, a global development pathway that fails to achieve this expansion will come at a detriment to public health, and will not achieve long-term economic growth.
7 Support accurate quantification of the avoided burden of disease, reduced health-care costs, and enhanced economic productivity associated with climate change mitigation. These will be most effective when combined with adequate local capacity and political support to develop low-carbon healthy energy choices.

The health community has a vital part to play in accelerating progress to tackle climate change

Health professionals have worked to protect against health threats, such as tobacco, HIV/AIDS, and polio, and have often confronted powerful entrenched interests in doing so. Likewise, they must be leaders in responding to the health threat of climate change. A public health perspective has the potential to unite all actors behind a common cause—the health and wellbeing of our families, communities, and countries. These concepts are far more tangible and visceral than tonnes of atmospheric CO_2, and are understood and prioritised across all populations irrespective of culture or development status.

Reducing inequities within and between countries is crucial to promoting climate change resilience and improving global health. Neither can be delivered without accompanying sustainable development that addresses key health determinants: access to safe water and clean air, food security, strong and accessible health systems, and reductions in social and economic inequity. Any prioritisation in global health must therefore place sustainable development and climate change front and centre.

The Commission recommends that over the next 5 years, governments:

8 Adopt mechanisms to facilitate collaboration between Ministries of Health and other government departments, empowering health professionals and ensuring that health and climate considerations are thoroughly integrated in government-wide strategies. A siloed approach to protecting human health from climate change will not work. This must acknowledge and seek to address the extent to which additional global environmental changes, such as deforestation, biodiversity loss, and ocean acidification, will impact on human health and decrease resilience to climate change.
9 Agree and implement an international agreement that supports countries in transitioning to a low-carbon economy. Whilst the negotiations are very complex, their goals are very simple: agree on ambitious and enforceable global mitigation targets, on adaptation of finance to protect countries' rights to sustainable development, and on the policies and mechanisms that enable these measures. To this end, international responsibility for reducing greenhouse gas emissions is shared: interventions that reduce emissions and promote global public health must be prioritised irrespective of national boundaries.

Responding to climate change could be the greatest global health opportunity of the 21st century.

To help drive this transition, the 2015 *Lancet* Commission on Health and Climate Change will:

10 Develop a new, independent Countdown to 2030: Global Health and Climate Action, to provide expertise in implementing policies that mitigate climate change and promote public health, and to monitor progress over the next 15 years. The Collaboration will be led by this Commission, reporting in *The Lancet* every 2 years, tracking, supporting, and communicating progress and success along a range of indicators in global health and climate change

Introduction

In 2009, the UCL–*Lancet* Commission on Managing the Health Effects of Climate Change called climate change "the biggest global health threat of the 21st century".[1] 6 years on, a new multidisciplinary, international Commission reaches the same conclusion, whilst adding that tackling climate change could be the greatest global opportunity of the 21st century.

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

The Commission represents a collaboration between European and Chinese climate scientists and geographers, social and environmental scientists, biodiversity experts, engineers and energy policy experts, economists, political scientists and public policy experts, and health professionals—all seeking a response to climate change that is designed to protect and promote human health.

The physical basis

The Intergovernmental Panel on Climate Change (IPCC) has described the physical basis for, the impacts of, and the response options to climate change.[2] In brief, short-wave solar radiation passes through the Earth's atmosphere to warm its surface, which emits longer wavelength (infrared) radiation. Greenhouse gases (GHGs) in the atmosphere absorb this radiation and re-emit it, sharing it with other atmospheric elements, and with the Earth below. Without this effect, surface temperatures would be more than 30°C lower than they are today.[3] One such GHG is carbon dioxide (CO_2), primarily released when fossil fuels (ie, oil, coal, and natural gas) are burned. Others, such as methane (CH_4) and nitrous oxide (N_2O), are generated through fossil-fuel use and human agricultural practice. GHG emissions have steadily climbed since the industrial revolution.[4] CO_2 remains in the atmosphere for a long time, with a part remaining for thousands of years or longer.[5] As a result, atmospheric GHG concentrations have risen steeply in the industrial age, those of CO_2 reaching more than 400 parts per million (ppm) in 2014, for the first time since humans walked the planet. Every additional ppm is equivalent to about 7·5 billion tonnes of atmospheric CO_2.[6,7]

In view of their proven physical properties, such rising concentrations must drive a net positive energy balance, the additional heat distributing between gaseous atmosphere, land surface, and ocean. The IPCC's 2014 report confirms that such global warming, and the role of human activity in driving it, are unequivocal. The oceans have absorbed the bulk (90% or more) of this energy in recent years and ocean surface temperatures have risen.[8] However, temperatures at the Earth's surface have also risen, with each of the last three decades being successively warmer than any preceding decade since 1850. Indeed, 2014 was the hottest year on record. Overall, the Earth (global average land and ocean temperature) has warmed

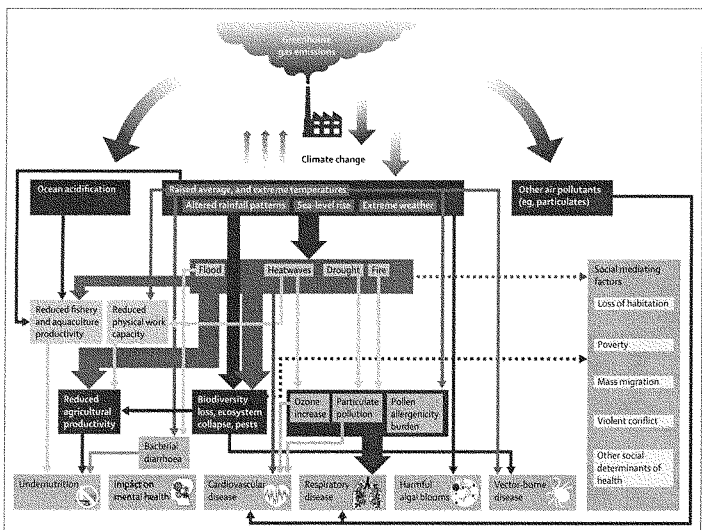

Figure 1: **An overview of the links between greenhouse gas emissions, climate change, and health**
The causal links are explained in greater detail in the section about climate change and exposure to health risks.

by some 0·85°C between 1880 and 2012.[8] Arctic sea ice is disappearing at a rate of up to 50 000 km^2 per year, the Antarctic ice sheet is now losing 159 billion tonnes of ice each year, and sea levels are rising inexorably.[9]

Much of past emissions remain in the atmosphere and will drive continued warming in the future. GHG concentrations in the atmosphere are continuing to rise at a rate that is incompatible with limiting warming to 2°C in the coming 35 years (by 2050), and which exceeds the IPCC's "worst case scenario".[10] We are on track for a global average temperature rise of more than 4°C above pre-industrial temperatures in the next 85 years, at which point global temperature will still be increasing by roughly 0·7°C per decade (due to the lag in reaching equilibrium). This distribution will not be even: the so-called polar amplification phenomena might cause temperatures in parts of the Arctic to increase by 11°C in this timeframe.[8]

The health impacts of climate change

The resultant climate change poses a range of threats to human health and survival in multiple, interacting ways (figure 1). Impacts can be direct (eg, heatwaves and extreme weather events such as a storm, forest fire, flood, or drought) or indirectly mediated through the effects of climate change on ecosystems (eg, agricultural losses and changing patterns of disease), economies, and social structure (eg, migration and conflict). After only 0·85°C warming, many anticipated threats have already become real-world impacts. Table 1 summarises the evidence attributing climate change to specific extreme weather events, outlining the role that climate change is playing in the present day (2013). It demonstrates increasing certainty that climate change significantly alters the probability of extreme weather, most often in directions that have dangerous health consequences.

	Summary statement	Anthropogenic influence increased event likelihood or strength	Anthropogenic influence decreased event likelihood or strength	Anthropogenic influence not found or uncertain	Number of papers
Heat	Long-duration heatwaves during the summer and prevailing warmth for annual conditions are becoming increasingly likely because of a warming planet	Europe heat, 2003 (Stott et al, 2004[11]); Russia heat, 2010 (Rahmstorf and Couman, 2011;[12] Otto et al, 2012[13]); USA heat, 2012 (Diffenbaugh and Scherer, 2013;[14] Knutson et al, 2013);[14] Australia heat, 2013 (Arblaster et al, 2014; King et al, 2014; Knutson et al, 2014; Lewis et al, 2014; Perkins et al, 2014);[15] Europe heat, 2013 (Dong et al, 2014);[15] China heat, 2013 (Zhou et al, 2014);[15] Japan heat, 2013 (Imada et al, 2014);[15] Korea heat, 2013 (Min et al, 2014)[15]	..	..	14
Cold	Prolonged cold waves have become much less likely than they were previously, such that the probability of reoccurrence of the 2013 severely cold winter in the UK might have fallen by 30 times because of global warming	..	UK cold spring, 2013 (Christidis et al, 2014)[15]	UK extreme cold, 2010–11 (Christidis and Stott, 2012)[16]	2
Heavy precipitation and flood	Extreme precipitation events were found to have been much less influenced by human-induced climate change than extreme temperature events	UK floods, 2011 (Pall et al, 2011);[17] USA seasonal precipitation, 2013 (Knutson et al, 2014);[15] India precipitation, 2013 (Singh et al, 2014)[15]	USA Great Plains drought, 2013 (Hoerling et al, 2014)[15]	Thailand floods, 2011 (Van Oldenborgh et al, 2012);[16] UK summer floods, 2012 (Sparrow et al, 2013);[14] north China floods, 2012 (Tett et al, 2013);[14] southwest Japan floods, 2012 (Imada et al, 2013);[14] southeast Australia floods (2012); (King et al, 2013,[14] Christidis et al, 2013);[14] southern Europe Precipitation, 2013 (Yiou and Cattiaux, 2014);[15] central Europe precipitation, 2013 (Schaller et al, 2014)[15]	14
Drought	Droughts are highly complex meteorological events and research groups have analysed different factors that affect droughts, such as sea surface temperature, heat, or precipitation	East African drought, 2011 (Funk et al, 2012);[16] Texas drought, 2011 (Rupp et al, 2012);[16] Iberian Peninsula drought, 2011 (Trigo et al, 2012);[16] east African drought 2012, (Funk et al, 2012);[16] New Zealand drought, 2013 (Harrington et al, 2014);[15] USA California drought, 2013 (Swain et al, 2014)[15]	..	Central USA drought, 2012 (Rupp et al, 2013);[14] USA California drought, 2013 (Funk et al, 2014);[15] (Wang and Schubert, 2014)[15]	9
Storms	No clear evidence of human influence was shown for any of the four very intense storms examined	..	..	USA hurricane Sandy, 2012 (Sweet et al, 2013);[14] cyclone Christian, 2013 (von Storch et al, 2014);[15] Pyrenees snow, 2013 (Anel et al, 2014);[15] USA south Dakota blizzard, 2013 (Edwards et al, 2014)[15]	4
Number of papers	..	23	2	18	43

References are in Peterson et al, 2012;[16] Peterson et al, 2013;[14] Herring et al, 2014;[15] or listed separately. Adapted from the Bulletin of the American Meteorological Society.

Table 1: **Detection and attribution studies linking recent extreme weather events to climate change**

Some population groups are particularly vulnerable to the health effects of climate change, whether because of existing socioeconomic inequalities, cultural norms, or intrinsic physiological factors. These groups include women, young children and older people, people with existing health problems or disabilities, and poor and marginalised communities. Such inequalities are often also present in relation to the causes of climate change: women and children both suffer the majority of the health impacts of indoor air pollution from inefficient cookstoves and kerosene lighting, and so mitigation measures can help to reduce existing health inequities such as these.

Non-linearities, interactions, and unknown unknowns

The magnitude and nature of health impacts are hard to predict with precision; however, it is clear that they are pervasive and reflect effects on key determinants of health, including food availability. There are real risks that the effects will become non-linear as emissions and global temperatures increase. First, large-scale disruptions to the climate system are not included in climate modelling and impact assessments.[18] As we proceed rapidly towards 4°C warming by the end of the century, the likelihood of crossing thresholds and tipping points rises, threatening further warming and accelerated sea-level rise. Second, small risks can interact to produce larger-than-expected chances of catastrophic outcomes, especially if they are correlated (panel 1).[22,23]

Such impacts (and their interactions) are unlikely to be trivial and could be sufficient to trigger a discontinuity in the long-term progression of humanity.[24] Whilst the poorest and most vulnerable communities might suffer first, the interconnected nature of climate systems, ecosystems, and global society means that none will be immune. Indeed, on the basis of current emission trajectories, temperature rises in the next 85 years may be incompatible with an organised global community.[25]

Panel 1: Teeth in the tails

Tail risks are those whose probability of occurring is low (ie, >2 or 3 SDs from the mean). The size of the tail and the combination of tails will decide the chance of extreme or catastrophic outcomes. Interactions between tail risks greatly affect the risk of several happening at once—eg, interactions between crop decline and population migration, or between heatwaves, water insecurity and crop yields. The 2008 global financial crisis is an example. Here, rating agencies catastrophically mispriced the risks of pooled mortgage-related securities. For example, Nate Silver showed that if five mortgages, each with a 5% risk of defaulting, are pooled, the risks of a default of all five is 0·00003% as long as the default is perfectly uncorrelated.[19] If they are perfectly correlated (as almost happened with the housing crash) the risk is 5%. In other words, if rating agencies assumed no interaction, their risk would be miscalculated by a factor of 160 000.[19]

We must not assume that individual climate tail risks will be uncorrelated. In complex systems, individual events might become more highly correlated when events place the whole system under stress. For example, in the UK in 2007, flooding threatened electricity substations in Gloucestershire. The authorities requested the delivery of pumps and other equipment to keep one of these substations, Walham, from flooding. Loss of the substation would have left the whole county, and part of Wales and Herefordshire without power, and many people without drinking water. Equipment had to be delivered by road. Parts of the road system in the region of the substation flooded, which almost prevented the delivery of equipment. Under normal conditions, disturbances to the three subsystems—roads, electricity, and the public water supply—are uncorrelated and simultaneous failure of all three very unlikely. With extreme flooding they became correlated under the influence of a fourth variable, resulting in a higher than expected probability of all three failing together.[20,21] Indeed, these extremes of weather, which will occur more frequently with unmitigated climate change, are the ones that are often most important for human health.

The health co-benefits of emissions reduction

Acting to reduce GHG emissions evidently protects human health from the direct and indirect impacts of climate change. However, it also benefits human health through mechanisms quite independent of those relating to modifying climate risk: so-called health co-benefits of mitigation.[26]

Reductions in emissions (eg, from burning fossil fuels) reduce air pollution and respiratory disease, whilst safer active transport cuts road traffic accidents and reduces rates of obesity, diabetes, coronary heart disease, and stroke. These are just some of the many health co-benefits of mitigation, which often work through several causal pathways via the social and environmental determinants of health. Protecting our ecosystems will create the wellbeing we gain from nature and its diversity.[27]

Affordable renewable energy will also have huge benefits for the poorest. WHO found that in 11 sub-Saharan African countries, 26% of health facilities had no energy at all and only 33% of hospitals had what could be called "reliable electricity provision", defined as no outages of more than 2 h in the past week.[28] Solar power is proposed as an ideal alternative energy solution, providing reliable energy that does not harm cardiovascular or respiratory health in the same way that diesel generators do. Clean cookstoves and fuels will not only protect the climate from black carbon (a very short-lived climate pollutant), but also cut deaths from household air pollution—a major killer in low-income countries. Buildings and houses designed to provide better insulation, heating efficiency, and protection from extreme weather events will reduce heat and cold exposure, disease risks from mould and allergy, and from infectious and vector-borne diseases.[29]

Many other co-benefits exist across different sectors, from agriculture to the formal health system. The cost savings of the health co-benefits achieved by policies to cut GHG emissions are potentially large. This is particularly important in a context where health-care expenditure is growing relative to total government expenditure globally. The health dividend on savings must be factored into any economic assessment of the costs of mitigation and adaptation. The poorest people are also most vulnerable to climate change, meaning that the costs of global development will rise if we do nothing, and poverty alleviation and sustainable development goals will not be achieved.

This Commission

6 years ago, the first *Lancet* Commission called climate change "the biggest global health threat of the 21st century".[1] Since then, climate threats continue to become a reality, GHG emissions have risen beyond worst-case projections, and no international agreement on effective action has been reached. The uncertainty around thresholds, interactions and tipping points in climate change and its health impacts are serious enough to mandate an immediate, sustained, and globally meaningful response.

This report further examines the evidence of threat, before tabling a prescription for both prevention and symptom management. We begin in section 1 by re-examining the causal pathways between climate change and human health, before offering new estimates of exposure to climate health risks in the coming decades. The changes in the spatial distribution of populations, and their demographic structure over the coming century, will put more people in harm's way.

Given that the world is already locked in to a significant rise in global temperatures (even with meaningful action to reduce GHG emissions), section 2 considers measures that must be put in place to help lessen their unavoidable health impacts. Adaptation strategies are those that reduce vulnerability and enhance resilience—ie, the capacity of a system to absorb disturbance and re-organise—so as to retain function, structure, identity, and feedbacks.[30] We identify institutional and decision-making challenges related to uncertainty, multicausal pathways, and complex interactions between social, ecological, and economic factors. We also show tangible ways ahead with adaptations that provide clear no-regret options and co-benefits for food security, human migration and displacement, and dynamic infectious disease risks.

Symptomatic intervention and palliation must, however, be accompanied by immediate action to address the cause of those symptoms: the epidemiology and options for scaling up low-carbon technologies and technical responses are discussed in section 3, in addition to the necessary measures required to facilitate their deployment. This section also explores the health implications of various mitigation options, with particular attention to those which both promote public health and mitigate climate change.

Transformation to a global low-carbon economy requires political will, a feasible plan, and the requisite finance. Section 4 examines the financial, economic, and policy options for decarbonisation. The goal of mitigation policy should be to reduce cumulative and annual GHG emissions. Early emissions reduction will delay climate disruption and reduce the overall cost of abatement by avoiding drastic and expensive last-minute action. Immediate action offers a wider range of technological options, allows economies of scale and prospects for learning, and will reduce costs over time. The window of opportunity for evolutionary and revolutionary new technologies to develop, commercialise, and deploy is also held open for longer.

In section 5, we examine the political processes and mechanisms that might play a part in delivering a low-carbon economy. Multiple levels are considered, including the global response (the UN Framework Convention on Climate Change), national and subnational (cities, states, and provinces) policy, and the role of individuals. The interaction between these different levels, and the lessons learnt from public health are given particular attention.

Finally, in section 6 we propose the formation of an international Countdown to 2030: Global Health and Climate Action. We outline how an international, multidisciplinary coalition of experts should monitor and report on: the health impacts of climate change; progress in policy to reduce GHG emissions, and synergies used to promote and protect health; and progress in health adaptation action to reduce population vulnerability to build climate resilience and to implement climate-ready low-carbon health systems. A Countdown process would complement rather than replace existing IPCC reports, and would bring the full weight and voice of the health and scientific communities to this critical population health challenge.

Section 1: climate change and exposure to health risks

No region is immune from the negative impacts of climate change, which will affect the natural world, economic activities, and human health and wellbeing in every part of the world.[31] There are already observed impacts of climate change on health, directly through extreme weather and hazards and indirectly through changes in land use and nutrition. Lags in the response of the climate system to historical emissions means the world is committed to significant warming over coming decades.

All plausible futures resulting from realistic anticipated emissions trajectories expose the global population to worsening health consequences. In 2014, WHO estimated an additional 250 000 potential deaths annually between 2030 and 2050 for well understood impacts of climate change. WHO suggest their estimates represent lower bound figures because they omit important causal pathways. The effects of economic damage, major heatwave events, river flooding, water scarcity, or the impacts of climate change on human security and conflict, for example, are not accounted for in their global burden estimates.[32] Without action to address continued and rising emissions, the risks, and the number of people exposed to those risks, will likely increase significantly. WHO emphasises that the importance of the interactions between climate change and many other trends affecting public health, stressing the need for interventions designed to address climate change and poverty—two key drivers of ill health.[32] Similarly, the authors of the IPCC assessment of climate change on health emphasise that the health impacts become amplified over time.[21]

This report provides new insights into the potential exposure of populations, showing that when demographic trends are accounted for, such as ageing, migration, and aggregate population growth, the populations exposed to climate change that negatively affect health risk are more seriously affected than suggested in many global assessments. It involves new analysis on specific and direct climate risks of heat, drought and heavy precipitation that directly link climate change and wellbeing. The number of people exposed to such risk is amplified by social factors: the distribution of population density resulting from urbanisation, and changes in population demographics relating to ageing.

Thus, human populations are likely to be growing, ageing, and migrating towards greater vulnerability to climate risks. Such data emphasise the need for action to avoid scenarios where thresholds in climate greatly increase exposure, as well as adaptation to protect populations from consequent impacts.

How climate affects human health

Mechanisms linking climate and health

The principal pathways linking climate change with health outcomes are shown in figure 2, categorised as direct and indirect mechanisms that interact with social dynamics to produce health outcomes. All these risks have social and geographical dimensions, are unevenly distributed across the world, and are influenced by social and economic development, technology, and health service provision. The IPCC report documents in expansive detail the scientific knowledge on many individual risks.[11] Here, we discuss how these risks could change globally as a result of a changing climate and of evolving societal and demographic factors.

Changes in extreme weather and resultant storm, flood, drought, or heatwave are direct risks. Indirect risks are mediated through changes in the biosphere (eg, in the burden of disease and distribution of disease vectors, or food availability), and others through social processes (leading, for instance, to migration and conflict). These three pillars, shown in figure 2, interact with one another, and with changes in land use, crop yield, and ecosystems that are being driven by global development and demographic processes. Climate change will limit development aspirations, including the provision of health and other services through impacts on national economies and infrastructure. It will affect wellbeing in material and other ways. Climate change will, for example, exacerbate perceptions of insecurity and influence aspects of cultural identity in places directly affected.[11]

Thus, in figure 2, climate risks might be both amplified and modified by social factors. The links between food

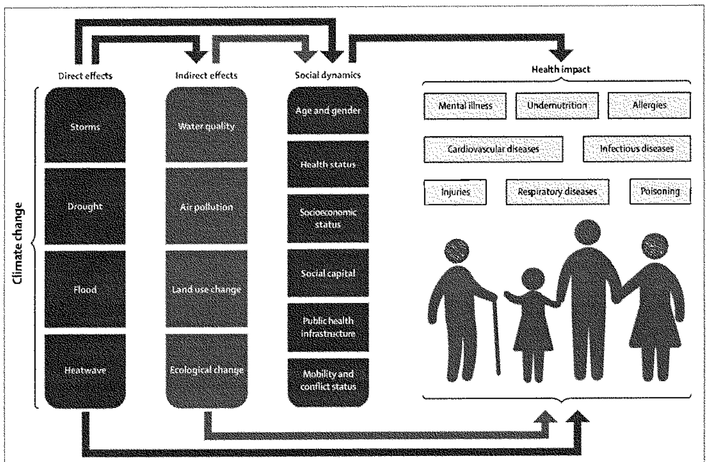

Figure 2: **The direct and indirect effects of climate change on health and wellbeing**
There are complex interactions between both causes and effects. Ecological processes, such as impacts on biodiversity and changes in disease vectors, and social dynamics, can amplify these risks. Social responses also ameliorate some risks through adaptive actions.

production and food security in any country, for instance, are strongly determined by policies, regulations and subsidies to ensure adequate food availability and affordable prices.[34] Vulnerabilities thus arise from the interaction of climatic and social processes. The underpinning science shows that impacts are unevenly distributed, with greater risks in less developed countries, and with specific subpopulations such as poor and marginalised groups, people with disabilities, the elderly, women, and young children bearing the greatest burden of risk in all regions.[31]

In many regions, the consequences of lower socio-economic status and cultural gender roles combine to increase the health risks that women and girls face as a result of climate change relative to men and boys in the same places, although the converse might apply in some instances. Whilst in developed countries, males comprise approximately 70% of flood disaster fatalities (across studies in which sex was reported), the converse is generally true for disaster-related health risks in developing country settings, in which the overall impacts are much greater.[35,36] For example, in some cultures women may be forbidden from leaving home unaccompanied, are less likely to have learnt how to swim, and may have less political representation and access to public services. Additionally, women's and girls' nutrition tends to suffer more during periods of climate-related food scarcity than that of their male counterparts, as well as starting from a lower baseline, because they are often last in household food hierarchies.[37]

Direct mechanisms and risks: exposure to warming and heatwaves

While societies are adapted to local climates across the world, heatwaves represent a real risk to vulnerable populations and significant increases in the risks of extreme heat are projected under all scenarios of climate change.[38] On an individual basis, tolerance to any change is diminished in those whose capacity for temperature homoeostasis is limited by, for example, extremes of age or dehydration. There is a well-established relationship between extreme high temperatures and human morbidity and mortality.[39] There is also now strong evidence that such heat-related mortality is rising as a result of climate change impacts across a range of localities.[31]

Evidence from previous heatwave events suggests that the key parameters of mortality risk include the magnitude and duration of the temperature anomaly and the speed of temperature rise. The risks are culturally defined, even temperate cities experience such mortality as it is deviation from expectations that drives weather-related risks. This is especially true when hot periods occur at the beginning of summer, before people have acclimatised to hotter weather.[38] The incidence of heatwaves has increased in the past few decades, as has the area affected by them.[40,41]

The most severe heatwave, measured with the Heat Wave Magnitude Index, was the summer 2010 heatwave in Russia.[40] More than 25 000 fires over an area of 1·1 million hectares[42] raised concentrations of carbon monoxide, nitrogen oxides, aerosols, and particulates (PM_{10}) in European Russia. The concentration of particulate matter doubled from its normal level in the Moscow region in August, 2010, when a large smoke plume covered the entire capital.[43] In combination with the heat wave, the air pollution increased mortality between July and August, 2010, in Moscow, resulting in more than 11 000 additional deaths compared with July to August, 2009.[44] Projections under climate scenarios show that events with the magnitude of the Russian heatwave of 2010 could have become much more common and

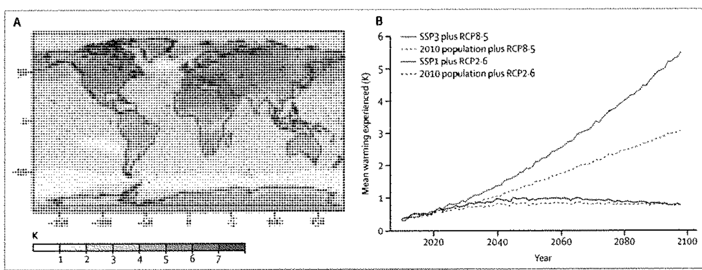

Figure 3: Exposure to warming resulting from projections of 21st century climate and population change
Changes in summertime temperatures (June–July–August for the northern hemisphere, and December–January–February for the southern hemisphere) between 1995 and 2090, for the RCP8.5 scenario, using the mean of the projections produced by the CMIP5 climate models (A). Change in the mean warming experienced by a person under RCP8.5 (red lines) and RCP2.6 (blue lines), calculated using the 2010 population (dashed lines), and time-varying future population scenarios (continuous lines; B). To encompass the range of possible exposures, we have paired the high-growth SSP3 population scenario with RCP8.5 and the low-growth SSP1 population scenario with RCP2.6. RCP=Representative Concentration Pathway.

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

with high-end climate scenarios could become almost the summer norm for many regions.[40,45]

Rising mean temperatures mean that the incidence of cold events is likely to diminish. The analysis here focuses on the heat-related element because the health benefits of reductions in cold are not established. Whilst there is an increase in deaths during winter periods in many climates, the mechanisms responsible for this increase are not easily delineated. Most winter-related deaths are cardiovascular, yet the link between temperature and cardiovascular mortality rates is weak. There is a stronger link between respiratory deaths and colder temperatures but these account for a smaller percentage of winter deaths.[46]

The impact of cold temperatures can be measured considering seasonal means, extreme cold spells, and relative temperature changes. Seasonal means and extreme cold spells (or absolute temperature) have relatively small or ambiguous relationships with numbers of winter deaths, however temperature cooling relative to an area's average temperature does more clearly correlate with mortality rates.[46,47] There may be modest reductions in cold-related deaths; however, these reductions will be largely outweighed at the global scale by heat-related mortality.[46] Whilst climate change will have an impact on cold-related deaths, particularly in some countries with milder climates, the overall impact is uncertain.[48,49]

Population growth, urbanisation trends, and migration patterns mean that the numbers exposed to hot temperature extremes, in particular, will increase, with major implications for public health planning. Urban areas will expand: urban land cover is projected to triple by 2030 from year 2000 levels.[50] Many assessments of climate risks, including those for heat, do not consider the detail of demographic shifts, in effect, overlooking the location of vulnerable populations as a part of the calculus. We have produced models that consider both climate and population projections. We use Shared Socioeconomic Pathway (SSP) population projections to

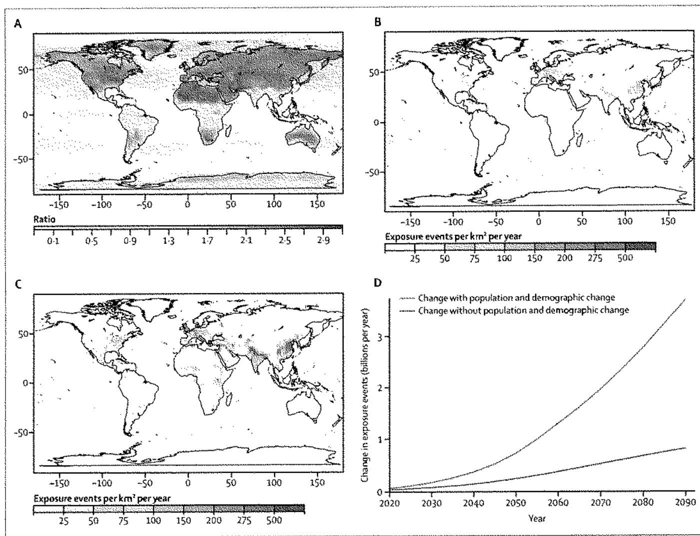

Figure 4: Changing exposure to heatwave resulting from projections of 21st century climate and population and demographic change
Change in heatwave frequency between 1995 and 2090 for the RCP8.5 scenario, in which a heatwave is defined as more than 5 consecutive days for which the daily minimum temperature exceeds the summer mean daily minimum temperature in the historical period (1986–2005) by more than 5°C (A). Change in the mean number of heatwave exposure events annually per km² for people older than 65 years as a result of the climate change in panel A and assuming the 2010 population and demography (B). The same scenario as for panel B, but for the 2090 population and demography under the SSP2 population scenario (C). Time series of the change in the number of annual heatwave exposure events for people older than 65 years with (red line) and without (blue line) population and demographic change (D).

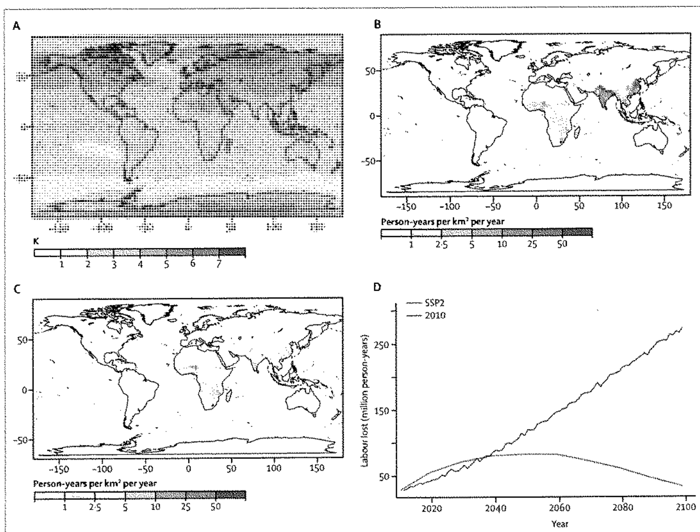

Figure 5: Change in outdoor labour productivity resulting from projections of 21st century climate and rural population change
Change in summer mean (June–July–August for the northern hemisphere, and December–January–February for the southern hemisphere) wet-bulb globe temperature[65] for the RCP8.5 scenario (A). Annual loss of outdoor labour productivity due to the climate change in panel A and assuming the 2010 rural population (B). The same scenario as for panel B, but for the 2090 rural population under the SSP2 population scenario (C). Time series of the annual loss of outdoor labour with (red line) and without (blue line) rural population change (D).

calculate future demographic trends alongside Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models (as used in the IPCC 5th Assessment report) and projected emission pathways (so-called Representative Concentration Pathways [RCPs]).[51–54] Appendix 1 outlines assumptions, together with the data and the climate and population scenarios used to estimate the scale of various health risks for the 21st century, shown in figures 3–7.

See Online for appendix 1

The projected global distribution of changes in heat in the coming decades is shown in figure 3A using the high-emission projections of RCP8.5, as explained in appendix 1. This focuses on summer temperatures, hence the graph represents the summer months for both the northern (June to August) and southern (December to February) hemispheres. Climatic impact will not be experienced uniformly across the globe. At such levels of warming, the return period of extreme heat events, such as those experienced in 2003 in western Europe, is significantly shortened. Figure 3B makes clear that future health risks arising from exposure to warming (measured as the mean temperature increase experienced by a person) might also be extensively driven by demographics, shown as the divergence between red and blue lines driven by different warming and population scenarios across the incoming decades. In other words, population change in areas of the world where population growth is significant, fundamentally affects the increase in numbers of people exposed to the impacts of climate change.

Whilst hotter summers increase vulnerability to heat-related morbidity, heatwaves in particular have a negative impact on health. Figure 4 re-analyses projections from the latest climate models (the CMIP5 models as used in the IPCC 5th Assessment report) in terms of the number of exposure events per year for heatwaves. Heatwaves here are defined as 5 consecutive days of daily minimum night-time temperatures more than 5°C greater than the presently observed patterns of daily minimums. Although heatwaves have different characteristics, this definition focuses on health impacts based on deviation from normal temperature, duration, and extent.

Elderly populations are especially vulnerable to heatwaves, and demographic and climatic changes will

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

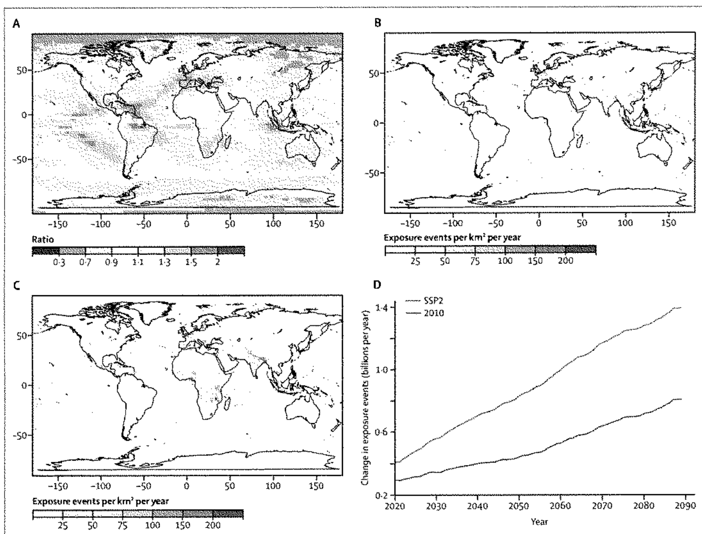

Figure 6: Changing exposure to drought resulting from projections of 21st century climate and population change

Change in drought intensity between 1995 and 2090 for the RCP8.5 scenario, defined as the ratio of the mean annual maximum number of consecutive dry days (2080–99, 1986–2005), in which a dry day is any day with less than 1 cm of precipitation (A). Change in the mean number of drought exposure events annually per km^2 as a result of the climate change in panel A and assuming the 2010 population (B). The same scenario as for panel B, but for the 2090 population under the SSP2 population scenario (C). Time series of the change in the number of annual drought exposure events with (red line) and without (blue line) population change (D).

combine to shape population heatwave vulnerability in coming decades (figure 4).[55] We use populations projected over 65 years of age rather than a frailty index, recognising the underlying health of elderly populations and the cultural context of ageing are both likely to change over time.[56] Educational levels and other demographic factors are also important in the ability of societies to cope with extreme events.[57] Allowing for these caveats, figure 4D shows growing exposure in global projections of the number of people older than 65 years exposed to heatwave risks. The numbers of events of elderly people experiencing high temperatures reaches more than 3 billion towards the end of the century. A key message is that demographic change added to climate changes will expose increasing numbers of elderly people to increasing numbers of heat waves, especially in the developed and transition economies.

Heat also poses significant risks to occupational health and labour productivity in areas where people work outdoors for long hours in hot regions.[58] Heavy labour in hot humid environments is a particular health and economic risk to millions of working people and their families in hot tropical and sub-tropical parts of the world.[59] These have been documented in young and middle-aged men in France 2003,[60] agricultural workers in the USA,[61] and sugar-cane harvesters in Central America.[62] The Climate Vulnerability Monitor 2012 estimated the annual costs in China and India at US$450 billion in 2030.[63] The percentage of GDP losses due to increasing workplace heat is greater than the current spending on health systems in many low-income and middle-income countries.[64]

Impacts of heat on labour productivity will be compounded in cities by increased urbanisation and the corresponding heat island effect, but will also be offset by reductions in populations working outdoors in sectors (eg, construction and agriculture).[58] Tolerance to any given temperature will be influenced by humidity, which alters the capacity for thermoregulation through the evaporation of sweat. These measures are combined in an index known as wet-bulb globe temperature (WBGT), used to determine how long an individual can work before a break, with work capacity falling substantially after WBGT 26–30°C.[58]

Using projections from RCP8.5 and SSP2, figure 5 estimates the extent of lost labour productivity (on the hasis of the response function between temperature and productivity used by Dunne et al, 2012[65]) across the coming decades, focusing on proportion of the labour force in rural and urban areas. Again the impact of climate change is greater in regions such as sub-Saharan Africa and India. But some trends offset the potential impact, including the trend towards employment in service and other sectors where exposure is reduced (assumed in the SSP2 used here; figure 5C, D). As demographic trends towards urban settlement and secondary and tertiary sector employment progress, increasing urbanisation may reduce the negative impacts of warming on total outdoor labour productivity, depending on the population scenario (SSP2 in figure 5D).

Loss of agricultural productivity through impaired labour will be amplified by direct climate change impacts on crop and livestock production.[66] The impact of increasing temperatures on labour productivity can be mitigated—eg, by use of air conditioning or by altering working hours. However, these actions are predicated on affordability, infrastructure, the suitability of a job to night labour, and energy availability.[67]

Indirect and complex mechanisms linking climate change and health

Most climate-related health impacts are mediated through complex ecological and social processes. For risks associated with transmission vectors and water, for example, rising temperatures and changes in precipitation pattern alter the viable distribution of disease vectors such as mosquitoes carrying dengue or malaria. Climate conditions affect the range and reproductive rates of malarial mosquitoes and also affect the lifecycle of the parasitic protozoa responsible for malaria. The links between climate change, vector populations and hence malarial range and incidence may become significant in areas where the temperature is currently the limiting factor, possihly increasing the incidence of a disease that causes 660 000 deaths per year.[68] In some highland regions, malaria incidence has already been linked to warmer air temperatures although successful control measures in Africa have cut the incidence of malaria in recent decades, and there are long established successes of managing malaria risk in temperate countries including in southern USA and in Europe.[69,70] There are equally complex relationships and important climate-related risks associated with dengue fever, cholera and food safety.[54,71,72] Dengue fever for example has 390 million recorded infections each year, and the number is rising.[54,73]

Changing weather patterns are also likely to affect the incidence of diseases transmitted through infected water sources, either through contamination of drinking water or by providing the conditions needed for bacterial growth.[74] Cholera is transmitted through infected water sources and often occurs in association with seasonal algal blooms with outbreaks sometimes experienced following extreme weather events such as hurricanes that result in the mixing of wastewater and drinking water, and in association with El Niño events.[72] Such extreme weather events are likely to increase in frequency in the coming decades and waterborne epidemics need to be planned for and monitored carefully.

In effect, all health outcomes linked to climate variables are shaped by economic, technological, demographic, and governance structures. Institutions and social norms of behaviour and expectation will play a significant part in how new weather patterns impact health.[38,71] Changes in temperature, precipitation frequency, and air stagnation also affect air pollution levels with significant risks to health. Climate affects pollution levels through pollutant formation, transport, dispersion, and deposition. In total, fine particulate air pollution is estimated to be responsible for 7 million additional deaths globally in 2012, mainly due to respiratory and cardiovascular disease.[75] Its effect is amplified by changes in ambient temperature, precipitation frequency, and air stagnation—all crucial for air pollutant formation, transport, dispersion and deposition.

Ground-level ozone (GLO) and particulate air pollutants are elements that will be most affected by climate change. Whilst the net global effect is unclear, regional variation will see significant differences in local exposure.[31,76] GLO is more readily created and sustained in an environment with reduced cloudiness and decreased precipitation frequency, but especially by rising temperatures.[77] Thus, ozone levels were substantially elevated during the European heatwave of summer 2003.[76,78] Climate change is predicted to elevate GLO levels over large areas in the USA and Europe, especially in the summer, although the background of GLO in the remote areas shows a decreased trend.[77,79–82] In the USA, the main impact of future climate change on GLO is centred over the northeast and mid-west where the future GLO are expected to increase by 2–5 ppbv (about 3–7%) in the next 50–90 years under the IPCC A1 scenario.[79,81] Knowlton and colleagues estimated that ozone-related acute mortality in the USA would rise by 4·5% from 1990 to 2050, through climate change alone.[83] Likewise, climate change is predicted to increase concentrations of fine particulate matter (2·5 micron particles [$PM_{2.5}$]) in some areas.[80,84]

The interactions between air pollution and climate are highly differentiated by region. In China, for example, the interactions between climate and a range of pollutants is especially acute. While action on carbon emissions dominate energy policy in China, climatic changes will have a significant impact on air pollutants in all regions of the country.[84,85] Chinese ozone concentrations in 2050 have been projected to likely increase beyond present levels under many climate scenarios through the combined effects of emissions and climate change. The greatest rises will be in eastern and northern China.[85]

Compared with ozone, $PM_{2.5}$ levels rely more on changes in emissions than temperature. The concentrations of SO_4^{2-}, black carbon and organic carbon are projected to fall, but those of NO_3^- to rise, across China under many possible climate futures.[84] Levels of aerosols (especially NO_3^-) in the eastern Chinese spring will be especially affected by 2030. Falling emissions would reduce overall $PM_{2.5}$ concentrations by 1–8 μg/m³ in 2050 compared with those in 2000 despite a small increase (10–20%) driven by climate change alone.[84] Although emission changes play a key part in projections, climate-driven change should not be ignored if warming exceeds 2°C. $PM_{2.5}$ is sensitive to precipitation and monsoon changes and global warming will alter Chinese precipitation seasonally and regionally, thereby changing the regional concentration of $PM_{2.5}$.[76,86] Independent of climate change, China's air pollution has already come at great cost, with an annual pollution-related mortality of 1·21 million in 2010.[87]

Climate change has important implications for livelihoods, food security, and poverty levels, and on the capacity of governments and health systems to manage emerging health risks. Crops and livestock have physiological limits to their health, productivity, and survival, which include those related to temperature. For every degree greater than 30°C, the productivity of maize production in Africa might be reduced by 1% in optimum conditions and 1·7% in drought, with a 95% chance of climate change-related harm to the production of South African maize and wheat in the absence of adaptation.[88,89]

Sensitivity of crops and livestock to weather variation has a substantial impact on food security in regions that are already food insecure, pushing up food prices and ultimately affecting food availability and affordability to poor populations and contributing to malnutrition.[90] This effect is amplified by polices on food stocks, reactions to food prices by producer countries, and by the global demand for land to hedge against climate shifts. The increased volatility of the global food system under climate change has impacts on labour, on farmer livelihoods and on consumers of food, with attendant health outcomes for all these groups.[66]

Within this complex relationship between climate and food security, the availability of water for agricultural production is a key parameter. Figure 6 shows very significant changes in exposure to drought-like meteorological conditions over the coming decades. The analysis shows that the population changes (from SSP2) alongside climate change could lead to 1·4 billion additional person drought exposure events per year by the end of the century. Importantly, the geographical distrihution of this exposure is highly localised and variable (eg, across Asia and Europe), acutely degrading water supply and potentially quality. But all such estimates focus on availability of surface water, whereby both long-term water availability and supply for specific regions are also affected by groundwater resources, which have been shown to be in a critical state in many regions.[91,92]

Increased frequency of floods, storm surges, and hurricanes will have a substantial effect on health. Extreme events have immediate risks, exemplified by more than 6000 fatalities as a result of typhoon Haiyan in the Philippines in late 2013. Floods also have long-term and short-term effects on wellbeing through disease outbreaks, mental health burdens, and dislocation.[93]

Risks related to water shortages, flood, and other mechanisms involve large populations. Projections suggest, for example, that an additional 50 million people and 30 000 km² of land could be affected by coastal storm surges in 2100, with attendant risks of direct deaths and of infectious diseases.[94,95] Involuntary displacement of populations as a result of extreme events has major public health and policy consequences. In the longer term, flooding affects perceptions of security and safety, and can cause depression, anxiety, and post-traumatic stress disorder.[93,96]

Figure 7 shows estimates of extreme precipitation events (events exceeding 10 year return period) under the RCP8.5 (high-emission) scenario. We estimate that there would be around 2 billion additional extreme rainfall exposure events annually (individuals exposed once or multiple times during any year), partly due to population growth in exposed areas and partly due to the changing incidence of extreme events associated with climate change. Whilst not all extreme rainfall events translate into floods, such extreme precipitation will inevitably increase flood risk. Regions of large population growth dominate changes in the number exposed to flood risk (especially in sub-Saharan Africa and South Asia).[97]

All these climate-related impacts are detrimental to the security and wellbeing of populations around the world. Whilst there is, as yet, no definitive evidence that climate change has increased the risk of violent civil conflict or war between states, there are reasons for concern. The IPCC concludes that climate change will directly affect poverty, resource uncertainty and volatility, and the ability of governments to fulfil their obligations to protect settlements and people from weather extremes.[33,98] These factors are important correlates of violent conflict within states, suggesting that climate change is detrimental to peaceful and secure development, even if they do not directly enhance conflict risks.[99] Similarly, migration has significant complex consequences for human security. The continued movement of migrant populations into cities, the potential for climate hazards in high-density coastal mega-cities, and impaired air quality create significant public health challenges, not least for migrants themselves.[100,101]

The direct and indirect effects of climate change outlined here represent significant risks for human health. The precautionary case for action is amplified with three additional dimensions: (1) interventions to adapt to evolving climate risks as discussed in section 2 might not be as effective as required; (2) unforeseen

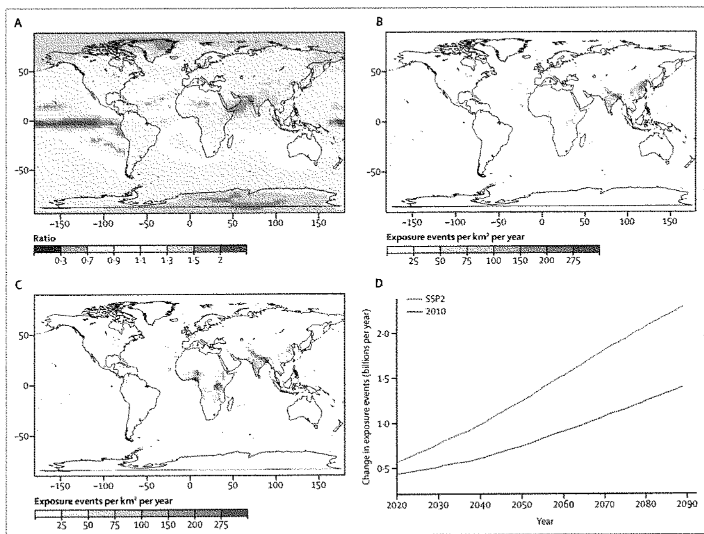

Figure 7: Changing exposure to flood resulting from projections of 21st century climate and population change
Change in flood frequency between 1995 and 2090 for the Representative Concentration Pathway (RCP) 8.5 scenario, in which a flood event is defined as a 5 day precipitation total exceeding the 10 year return level in the historical period (1986–2005; A). Change in the mean number of flood exposure events annually per km² due to the climate change in panel A and assuming the 2010 population (B). The same scenario as for panel B, but for the 2090 population under the SSP2 population scenario (C). Time series of the change in the number of flood exposure events with (red line) and without (blue line) population change (D).

interactions and amplifications of climate risks are possible (eg, emerging zoonotic and other diseases being affected through complex ecological changes, covered in more detail in the *Lancet* Commission on Planetary Health); (3) the risk that tipping elements in the climate system could rapidly accelerate climate change at regional or global scale. Lags in warming and climate impacts mean that irrespective of the mitigation pathway taken, many impacts and risks will increase in the coming decades.

Section 2: action for resilience and adaptation

Adaptation measures are already required to adapt to the effects of climate change being experienced today. As shown in section 1, these risks will increase as worsening climate change affects more people, especially in highly exposed geographical regions and for the most vulnerable members of society.

This section outlines possible and necessary actions to limit the negative impacts and burden on human health, including direct and indirect impacts within and beyond the formal health system. Responses aim to reduce the underlying vulnerability of populations; empower actors to cope or adapt to the impacts; and whenever possible support longer-term development. The health sector has a central part to play in leading climate change adaptation and resilience efforts.[102,103] However, effective adaptation measures must cross multiple societal sectors, identify ways to overcome barriers to achieve co-benefits, and target vulnerable groups and regions.

Early action to address vulnerability allows for more options and flexibility before we face indispensable and involuntary adaptation.[104,105] Panel 2 provides definitions of vulnerability, adaptation, and resilience.

Adaptation to the direct health impacts of climate change

The direct health impacts result from extreme weather events such as storms, floods, droughts, and heatwaves. Many responses centre on the importance of health system strengthening; however, actions in other sectors are also needed.

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

Early warning systems for extreme events

Approaches to the health management of extreme weather events involve improved early warning systems (EWS), effective contingency planning, and identification of the most vulnerable and exposed communities.[111] They include forecasting, predicting possible health outcomes, triggering effective and timely response plans, targeting vulnerable populations, and communicating prevention responses. Public health authorities need to upgrade existing emergency programmes and conduct exercises to enhance preparedness for anticipated health risks due to new extreme events such as sea level rise, saline water intrusion into drinking water courses, and severe flooding from storm surges. These efforts to improve disaster preparedness must also run in parallel with efforts to strengthen local community resilience.

Actions to reduce burdens of heatwaves

The frequency, intensity, and duration of extreme heat days and heatwaves will increase with climate change, leading to heat stress and increased death rates (see section 1). The effects are worsened by the so-called urban heat island effect, which results from greater heat retention of buildings and paved surfaces, compared with reflective, transpiring, shading, and air-flow-promoting vegetation-covered surfaces. Evidence suggests that effective adaptation measures would reduce the death rates associated with these heat waves. The 2003 European heatwave, which killed up to 70 000 people led France to introduce a heatwave warning system and a national action plan.[111] Health worker training was modified, urban planning altered, and new public health infrastructure developed. The 2006 heatwave suggested that these measures had been effective, with 4400 fewer anticipated deaths.[112]

Adaptation options within health care include training of health-care workers and integrated heatwave early warning systems (HEWS), especially for the most vulnerable populations.[111,113] Adaptation measures also include increasing green infrastructures and urban green spaces, improving the design of social care facilities, schools, other public spaces, and public transport to be more climate-responsive.[113,114] This also entails mitigating effort to reduce air pollutants, which in turn reduces air quality related morbidity and mortality.[115]

Floods and storms

In general, adaptive measures to floods can be classified as structural or non-structural. Infrastructure such as reservoirs, dams, dykes, and floodways can be used to keep flooding away from people and property. In some areas there is also the possibility to incorporate floodable low-lying areas into the urban design that can be temporarily under water during an extreme event. Structural programmes are considered by many flood managers as a priority and are also the principal source of funds for efforts to control floods. However, the construction of flood control works may have a maladaptive effect, encouraging more rapid economic development of the flood plains, and hence ultimately increasing flood losses.[116]

Adaptation to flood risk requires comprehensive approaches (panel 3). Non-structural measures include flood insurance, development policies, zoning laws, flood-plain regulations, building codes, flood proofing, tax incentives, emergency preparedness, flood forecasting, and post-flood recovery.[116,121] Non-structural flood

Panel 2: Vulnerability, adaptation, and resilience

Vulnerability is here defined as the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change.[106] This definition considers demographics, geographical circumstances, effectiveness, and coverage of the health-care system, pre-existing conditions, and socioeconomic factors such as inequity.[107]

Adaptation to climate change is here defined as "the process of adjustment to actual or expected climate and its effects, in human systems in order to moderate harm or exploit beneficial opportunities, and in natural systems human intervention may facilitate adjustment to expected climate".[108]

Resilience is here defined as the capacity of a system to absorb disturbance and reorganise while undergoing change, so as to still retain essentially the same function, structure, identity and feedbacks.[30] Resilience has also been referred to the ability of human communities to withstand external shocks to their social infrastructure.[109] Resilience includes the capacity of a system to not only absorb a disturbance, but to innovate and transform.[110]

Panel 3: Adaptation to floods and storms in Bangladesh

In a mid-range climate-sensitivity projection, the number of people flooded per year globally is expected to increase by 10–25 million per year by 2050.[117] Bangladesh is one of the most vulnerable countries to climate change in south Asia, regularly suffering from events such as flooding, cyclones, or coastal erosion, which cause inundation of farmlands, affect migration, and lead to displacement.[118] More than 5 million Bangladeshis live in areas highly vulnerable to cyclones and storm surges, and more than half the population lives within 100 km of the coast.[119] In 2007, cyclone Sidr killed roughly 4000 people in Bangladesh. By comparison, an equivalent storm in 1970 killed 300 000 people.[120] Bangladesh achieved this reduction in mortality via collaborations between governmental and non-governmental organisations and local communities. Together, these groups improved general disaster reduction, deployed early warning systems, and built a network of cyclone shelters.[31]

adaptation options aim to reduce flood damages and enhance the ecological functions of flood plains. Many opportunities to increase resilience to extreme weather events are found in improved planning, zoning, and the management of land use. These have the additional advantage of providing multiple co-benefits (see ecosystem-based adaptation below).

Action for resilience to indirect impacts

Adaptation to indirect effects poses difficult challenges to policy making due to complex causal chains and limited predictibility.[122] These complex interactions can result in "surprises"—situations in which the behaviour in a system, or across systems, differs qualitatively from expectations or previous experiences. These indirect impacts pose serious obstacles for climate adaptation, especially where health responses require integrated and cross-sectoral interventions.[123]

Food insecurity

Food insecurity and its health impacts play out at the local level, but have clear links to drivers and changes at the national and international level. The compounded impacts of climate change and ocean acidification will affect both agricultural production and fisheries, including food availability and prices.[124–126] Adaptation policies should consider agro-food systems and fisheries and aquaculture alike.

Resilience to increased food insecurity and price volatility is of great importance to human health. Food security could be enhanced while simultaneously ensuring the long-term ability of ecosystems to produce multiple benefits for human wellbeing (panel 4). Issues such as improved local ecosystem stewardship (see section on ecosystem-based adaptation), good governance, and international mechanisms to enhance food security in vulnerable regions are of essence.[130,131] Even though the drivers of increased food prices and price volatilities are contested, investment in improved food security could provide multiple co-benefits and no-regret options.[132,133]

> *Panel 4*: Food security, climate change, and human health
>
> Today, agriculture uses 38% of all ice-free land areas and accounts for 70% of freshwater withdrawals and roughly a third of global greenhouse gas emissions.[127] The provision for global food demand by 2050 cannot assume improved crop yields through sustainable agricultural intensification because of the negative effects on crop growth from an increased frequency of weather extremes. Multifunctional food production systems will prove important in a warmer world. These systems are managed for benefits beyond yield, and provide multiple ecosystem services, support biodiversity, improve nutrition, and can enhance resilience to shocks such as crop failure or pest outbreaks.[128,129]

Important adaptation options for food security action include:

- Enhancement of food security through improved ecosystem based management and ecosystem restoration. Case studies show the benefits of implementing strategies to improve ecosystem management as a means to increase not only food security, but also to achieve other social goals. Examples include collaborative management of mangrove forests to promote conservation, mitigation of climate change and alleviation of poverty among people dependent on the mangroves and adjacent marine ecosystems.[125] Such strategies require supportive institutions, partnerships, collaboration with farmers' innovation networks, and connections from sustainable farms to markets.[129,131] Similar strategies have recently been explored for fisheries and aquaculture.[134]
- Increased investments in agricultural research and human capital are often raised as an important strategy to improve yields and long-term food security.[131] Agricultural research and development (R&D) has proven to have high economic rates of return.[135] Innovative crop insurance mechanisms, new uses of information technology, and improved weather data also hold promise for increased agricultural production.[136] Education in agricultural areas is critical to enhance the diffusion of technologies and crop management, and as a means to increase household incomes and promote gender equality.[131,137]
- Increased investments in rural and water infrastructure. Investment is essential for situations in which underdeveloped infrastructure results in poor supply chains and large food losses. Investments could boost agricultural production, reduce price volatilities, and enhance food security in the long term. The investments required in developing countries to support this expansion in agricultural output have been estimated to be an average annual net investment of US$83 billion (not including public goods such as roads, large scale irrigation projects, and electrification).[131]
- Enhanced international collaboration. International collaboration is critical for food security in food insecure regions. Early warning systems, financial support, emergency food and grain reserves, the ability to scale up safety nets such as child nutrition schemes, and capacity building play a key part in emergency responses to food crises, and can be supported by international organisations.[131,138]

Environmental migration

Changes in human mobility patterns have multiple drivers,[139] and range from large-scale displacement (often in emergency situations), to slow-onset migration (in which people seek new homes and livelihoods over a lengthy period of time as conditions in their home communities worsen).[140] The efficacy of national and international policies, institutions, and humanitarian responses also influence whether people are able to cope with the after-effects of natural hazard in a manner that allows them to recover their homes and livelihoods.[141]

Displacement occurs when choices are limited and movement is more or less forced by land loss, for example due to extreme events.[142] Population displacement can further affect health through increased spread of communicable diseases and malnutrition, resulting from overcrowding and lack of safe water, food, and shelter.[143] Additional impacts on economic development and political instability could develop, generating poverty and civil unrest that will exacerbate the population burden of disease.[1,143]

Existing vulnerabilities will determine the degree to which people are forced to migrate.[144] The availability of alternative livelihoods or other coping capacities in the affected area generally determines the scale and form of migration that may take place. Conflict undermines the capacity of populations to cope with climate change, leading to greater displacement than might have been the case in a more stable environment. Conflicts have also been shown to reduce mobility and trap populations in vulnerable areas, exposing politically marginalised populations to greater environmental risks.[145]

Migration from both slow and rapid-onset crises is likely to be immediately across borders from one poor country into another. Receiving countries could have few resources and poor legal structures or institutional capacity to respond to the needs of the migrants. Destination areas may face similar environmental challenges (eg, drought or desertification) and may offer little respite. In rural areas, drought particularly affects rural to urban migration.[143] Urbanisation can be beneficial for health and livelihood, but also entails many risks.[121,142] The social disruption provoked by migration can lead to a breakdown in traditional institutions and associated coping mechanisms.[146] Furthermore, the lack of mobility and risks entailed by those migrating into areas of direct climate-related risk, such as low-lying coastal deltas, presents a further hazard.[121] The mental health implications of involuntary migration are often downstream effects, seen as a result of multiple interacting social factors (panel 5).

No or low-regret policies to reduce environmental migration

Effective public health and adaptation strategies to reduce environmental migration or reduce the negative impact of environmental migration should entail the coordinated efforts of local institutions, national and international governments and agencies.[100] There are several no or low-regret practices that generate both short-term and long-term benefits if integrated with existing national development, public health and poverty reduction strategies.

1 Slowing down the rate of environmental change, including mitigation policies and reducing land degradation.[121,154]

Panel 5: **Mental health impacts and interventions**

Climate change affects mental health through various pathways by inflicting natural disasters on human settlements and by causing anxiety-related responses, and later chronic and severe mental health disorders, and implications for mental health systems.[147,148] These effects will fall disproportionately on individuals who are already vulnerable, especially for indigenous people and those living in low-resource settings.[147] Additionally, individuals might feel a distressing sense of loss, known as solastalgia, that people experience when their land is damaged and they lose amenity and opportunity.[149]

Elevated levels of anxiety, depression, and post-traumatic stress disorders have been reported in populations who have experienced flooding and during slow-developing events such as prolonged droughts;[93,96] impacts include chronic distress and increased incidence of suicide.[150,151] Even in high-income regions where the humanitarian crisis might be less, the impact on the local economy, damaged homes, and economic losses can persist for years after natural disasters.[152] Government and agencies now emphasise psychological and psychosocial interventions within disaster response and emergency management. Social adaptation processes can mediate public risk perceptions and understanding, psychological and social impacts, coping responses, and behavioural adaptation.[153]

2 Reducing the impact of environmental change through early warning systems, integrated water management, rehabilitation of degraded coastal and terrestrial ecosystems, and robust building standards.[154,155]

3 Promoting long-term resilience through enhanced livelihoods, increased social protection, and provision of services. These include ecosystem-based investments, and processes that decrease marginalisation of vulnerable groups—eg, by increased access to health services.

Limitations of migration as a means of adaptation

Migration has been proposed as a transformational adaptive strategy or response to climate change. The policy response is often referred to as "managed retreat".[121,156] With changes in climate, resource productivity, population growth, and risks various governments have now, as part of their adaptation strategies, engaged in planning to move settlement.[33] As an example, five indigenous communities in Alaska have planned for relocation with government funding support. Research on experience of migration policy concludes that a greater emphasis on mobility within adaptation policies could be effective.[100,156]

Using migration as a strategy to cope with environmental stress might however create conditions of increased (rather than reduced) vulnerability.[100,144,156] Even though migration is used as a strategy to deal with imminent risks to livelihoods and food security, many vulnerable low-income groups do not have the resources to migrate in order to avoid floods, storms, and droughts.[157] In addition, studies of resettlement programmes demonstrate negative social outcomes, often analysed as breaches in individual human rights.[154] There are significant perceptions of cultural loss and the legitimacy, and success depends on incorporating cultural and psychological factors in the planning processes.[158]

Dynamic infectious disease risks

Interactions and changes in demographics, human connectivity, climate, land use, and biodiversity will substantially alter disease risks at local, national and international scales.[159] For example, vector-borne infectious disease risks are affected by not only changing temperatures, but also sea level rise.[160] The geographical distribution of African trypanosomiasis is predicted to shift due to temperature changes induced by climate change.[161] Biodiversity loss may to lead to an increase in the transmission of infectious diseases such as Lyme disease, schistosomiasis, Hantavirus and West Nile virus.[162] Infectious disease risks are dynamic and subject to multiple and complex drivers. Adaptation responses therefore must consider multiple uncertainties associated with dynamic disease risks, which include a focus on co-benefits, no regrets and resilience.[113,163–165]

Adaptation policy options for infectious disease risks

1 *Investing in public health*

Determinants of health, such as education, health care, public health prevention efforts, and infrastructure play a major part in vulnerability and resilience.[166] Adapting to climate change will not only be beneficial in reducing climate change impacts, but also have positive effects on public health capacity.[163] Furthermore, health improvements account for 11% of economic growth in low-income and middle-income countries.[167] The UN Framework Convention on Climate Change (UNFCCC) estimates the costs of health-sector adaptation in developing countries to be US$4–12 billion in 2030. However, the health consequences of not investing would be more expensive, and it is clear that there are several health impacts that we will not be able to adapt to.[168]

2 *One-health approaches*

These approaches involve collaboration across multiple disciplines and geographical territories to protect the health for people, animals and the environment. 70% of emerging infectious diseases are zoonotic[169] and have multiple well-established links to poverty.[170] They also pose considerable global risks (eg, avian influenza, Ebola). Effective responses to emerging infectious diseases require well-functioning national animal and puhlic health systems, reliable diagnostic capacities, and robust long-term funding. Critical gaps are present in existing health systems, including poor reporting, severe institutional fragmentation, and deficient early response capacities.[171,172]

Zoonosis outbreaks are costly: the economic losses from six major outbreaks of highly fatal zoonoses between 1997 and 2009 cost at least US$80 billion.[173] Implementing a one-health approach is, by contrast, economically sensible: the World Bank values its global benefits at $6·7 billion per year.[173] It provides no-regret options because investments will contribute to reduced vulnerability applicable across climate futures, and it enhances resilience by linking government and civil society partners, facilitating early warning and building capacities to respond to multiple disease risks.

3 *Surveillance and monitoring*

Strengthening the capacity of countries to monitor and respond to disease outbreaks is vital, as shown by the ongoing Ebola epidemic in West Africa. Climate-change adaptation for human health requires a range of data, including on health climate risks or vulnerabilities, and specific diseases related to climate change impacts. Information and data collected from public health surveillance or monitoring systems can be used to determine disease burdens and trends, identify vulnerable people and communities, understand disease patterns, and prepare response plans and public health interventions.[174,175]

Health co-benefits from climate adaptation

Even though many climate-related health effects are beset by uncertainties, policy makers and communities can prepare if they focus on measures that: 1) create multiple societal and environmental benefits; 2) are robust to multiple alternative developments, and 3) enable social actors to respond, adapt and innovate as a response to change. [164,165]

Ecosystem-based adaptation (EbA)–co-benefits for indirect effects

Ecosystem services contribute to human health in multiple ways and can act as buffers, increasing the resilience of natural and human systems to climate change impacts and disasters.[155]

Ecosystem-based Adaptation (EhA) utilises ecosystem services, biodiversity, and sustainable resource management as an adaptation strategy to enhance natural resilience and reduce vulnerability (covered in more detail in a forthcoming *Lancet* Commission on Planetary Health).[176,177] Natural barriers can act as a defence against climatic and non-climatic events—eg, restoration of mangroves for protecting coastal settlements and conservation of forests to regulate water flow for vulnerahle communities.[178,179] EbA is considered to be more cost effective than many hard-engineered solutions, and thought to minimise the scope for maladaptation.[155,180] It can be combined with engineered infrastructure or other technological approaches. EbA interventions can be effective in reducing certain climate change vulnerability as it provides both disaster risk reduction functions, and enables improvements in livelihoods and food security, especially in poor and vulnerable settings.[181] However, the

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

scientific evidence about their role in reducing vulnerabilities to disasters is developing, and the limits and timescales of EbA interventions need further evaluation. Drawbacks can include the amount of land they require, uncertainty regarding costs, the long time needed before they become effective, and the cooperation required across institutions and sectors.[180]

Ecosystem-based adaptation in urban areas

EbA also has the potential to yield benefits for highly urban areas, through the development of green infrastructure.[180] The evidence comes mainly from the northern hemisphere, in high-income settings with a dense city core. In many cases enhancement of urban ecosystems provides multiple co-benefits for health such as clean air and temperature regulation.[182] EbA can further create synergies between adaptation and climate-change mitigating measures by assisting in carbon sequestration and storage, and enhancing various ecosystem services considered beneficial for human health.[176,183] Trees are particularly considered to be efficient in reducing concentrations of pollutants, although the capacity can vary by up to 15 times between species.[184]

Green urban design can reduce obesity and improve mental health through increased physical activity and social connectivity.[164] Increased neighbourhood green spaces reduces both morbidity and mortality from many cardiovascular and respiratory diseases and stress-related illnesses.[31] Tree canopies have a higher albedo effect than other hard surfaces and can work to reduce the urban heat island effect, lowering heat mortality by 40–99%.[185] Whilst resulting in improved public health and community resilience, many of these measures will also act to mitigate climate change.

Overcoming adaptation barriers

Globally, relatively few national strategies bring climate change into public health decision-making processes. The health impacts of climate change are often poorly communicated and poorly understood by the public and policy makers. Barriers to health climate adaptation include competing spending priorities, widespread poverty, lack of data to inform adaptation policies, weak institutions, a lack of capital, distorted economic incentives, and poor governance. Here, we elaborate these barriers and discuss some ways to overcome them.

Institutional collaboration

Health-adaptation policies and programmes require engagement of numerous agencies and organisations, including government agencies, non-governmental organisations (NGOs), informal associations, kinship networks, and traditional institutions.[186] At the same time, institutional fragmentation, lack of coordination and communication across levels of government, and conflicts of interest between ministries are overly common.[186,187] Strengthening institutions at multiple levels is vital, and institutional capacity needs-assessment and collaboration are critical for health adaptation to climate change.[188] The support of bridging organisations, as well as partnerships through networks, are critical as a means to overcome fragmentation and improve collaboration, information flows, and learning.[189]

Finance

Lack of finance is commonly cited as a major obstacle to adaptation, especially in the poorest regions and communities. This might result in economic incentives for investment in adaptation appearing small, individuals or firms lowering initial costs by avoiding expensive adaptation technologies or options, and the fact that the long-term benefits of health risk reduction, health improvements, and other societal benefits (reduced public health care costs) are heavily discounted.

Community and informal networks may provide financial support, but regional, national, and international funds as well as private sector funding will be required for adaptation responses at a larger scale.[190] To date, adaptation funding is inadequate compared to the risks and hazards faced. This is covered in more detail, in section 4 of the Commission.

Communication

Public awareness of the health risks of climate change, even from heatwaves and other extreme weather events, is currently low.[191] Innovative media strategies are needed to enhance awareness of such risks and improve public adaptive skills and effectiveness.[192] health professionals, being knowledgeable and trusted, are in a strong position to communicate the risks posed by climate change and the benefits of adaptation.[192]

Monitoring indicators for adaptation to indirect impacts

Several indicators can serve as proxies for investments in adaptation and resilience to the indirect health effects of climate change.

National adaptation programmes of action

National adaptation programmes of action (NAPAs) are designed for low-resource countries to communicate their most urgent adaptation needs to the UNFCCC for funding.[193] Health projects are more often included in the NAPAs and they typically address current disease (eg, malaria) control issues.[168] To this end, there is a need to provide ongoing assessment of the number of countries that integrate health aspects in their NAPA, as well as the extent to which health is integrated. This indicator should assess adaptation for both direct and indirect health impacts.

Early warning systems

This indicator should include the number of countries that have upgraded early warning systems for extreme weather events, climate-change-sensitive diseases, food security, and migration movements. Early warning systems have proved to be a critical and co-beneficial investment and, if matched with response capacities, could help societies adapt more promptly to changing circumstances that affect human health.

Ecosystem-based adaptation

Investments in ecosystem based adaptation for both direct (eg, flood risk) and indirect (eg, food security, disease mitigation) health impacts could create multiple co-benefits and provide no-regret options for several of the indirect effects discussed above.

Conclusion

This section has outlined interventions available to enhance community resilience and adapt to the health effects of climate change. Many of these are no-regret options that could provide co-benefits across several dimensions including food security, disease prevention, and sustainability in general. Adaptation will provide both short-term and long-term benefits beyond human health. Effective adaptation requires institutional collaboration across levels, integrated approaches, appropriate long term funding, and institutions flexible enough to cope with changing circumstances and surprise. Urgent mitigation efforts must accompany the recommendations provided in section 2, a subject covered in section 3 of this Commission.

	Potential mitigation effects
Energy efficiency	
Supply-side efficiency	Save 14% of primary energy supply (121 EJ by 2050)[194]
End-user efficiency	1·5 Gt of CO_2-equivalent in 2020[195]
Carbon sequestration	
Land carbon sequestration	
Afforestation and reforestation	183 Gt of carbon by 2060[194]
Biochar	0·55 Gt of carbon per year[194]
Upstream oil and gas industry methane recovery	570 Mt of CO_2-equivalent in 2020[195]
Ocean carbon-sink enhancement	
Increase ocean alkalinity	0·27 Gt of carbon per year after 100 years[196]
Iron fertilisation	3·5 Gt of carbon per year for first 100 years[196]
Carbon capture and storage	
Carbon capture during energy generation	Can reduce lifecycle CO_2 emission from fossil-fuel combustion at stationary sources by 65–85%[195]
Direct air capture	3·6 Gt CO_2 per year with 10 million units[197]
Carbon intensity reduction	
Renewable energy*	
Geothermal	0·2–5·6 Gt of CO_2 per year by 2050[198]
Bioenergy	2·0–5·3 Gt of CO_2 per year by 2050[198]
Ocean energy (thermal, wave, tidal)	0·0–1·4 Gt of CO_2 per year by 2050[198]
Solar energy	0·4–15·0 Gt of CO_2 per year by 2050[198]
Hydropower	0·6–4·5 Gt of CO_2 per year by 2050[198]
Wind energy	1·2–9·8 Gt of CO_2 per year by 2050[198]
Nuclear energy	1·5–3·0 Gt of CO_2 per year with current capacity[199]

*We obtained the values of CO_2 emission mitigation for renewable energy from figure 10. 20 of the Intergovernmental Panel on Climate Change (IPCC) special report on renewable sources and climate change mitigation.[198] The ranges represented the minimum and maximum values from four future energy scenarios.

Table 2: **List of high-impact technologies for climate mitigation**

Section 3: transition to a low-carbon energy infrastructure

It is technically feasible to transition to a low-carbon infrastructure with new technologies, the use of alternate materials, changing patterns of demand, and by creating additional sinks for GHGs. This requires challenging the deeply entrenched use of fossil fuels. Any significant deployment to meet demanding CO_2 targets will require the reduction of costs of mitigation options, carbon pricing, improvement in the research and development process and the implementation of policies and regulations to act as enabling mechanisms, as well as recognition of the strong near-term and long-term co-benefits to health.

The technologies for reducing GHG emissions related to energy and many energy-related end-uses have been in existence for at least 40 years (table 2), and several key technologies have their roots deep in the 19th century. The technologies are available now. We have a reasonable grasp of their performance, economics and side-effects (unintended impacts). They treat the causes of the problem (fossil fuel GHG emissions) rather than the symptoms (climate change). Other technologies, such as those described under geo-engineering have a high degree of uncertainty as to their effectiveness and also their side effects. We view these technologies as being highly risky but also (at this time) unnecessary, as we have the tools needed to achieve emission targets to avoid catastrophic climate change. Geo-engineering is analogous to using unlicensed drugs to treat Ebola when public health and hygiene could have prevented the problem in the first place. It is also important to recognise that for an energy source to be renewable, it must satisfy a low-carbon requirement, and consider the use of scarce resources such as copper, silicon, and rare earth metals.

Public health has much to gain from the mitigation of short lived climate pollutants (SLCPs) such as methane, black carbon, hydrofluorocarbons, and tropospheric ozone. The benefits for health, climate change, and crop yields are covered in great detail in a report by WHO and the Climate and Clean Air Coalition.[200]

Main sources of GHG emissions

In 2010, annual global GHG emissions were estimated at 49 $GtCO_2e$.[201] The majority (about 70%) of all GHG emissions can be linked back to the burning of fossil fuel for the production of energy services, goods or energy extraction (figure 8).[202] Global emissions from heat and electricity production and transport have tripled and doubled respectively since 1970, whereas the contribution from agriculture and land-use change has slightly reduced from 1990 levels.[203]

When upstream and electricity sector emissions are allocated on an end-use basis, most emissions (about 61%)

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

are related to the built environment (ie, buildings, transport, and industry). These emissions are related to providing services such as cooling and heat in buildings, power for lights, appliances, electronics and computing, and motive power for moving to and within largely urbanised places, while industrial manufacturing of products feeds into the built environment system through movement of goods, economic activity and employment.

The global energy system

We know that the global energy system is heavily dependent on the extraction, availability, movement, and

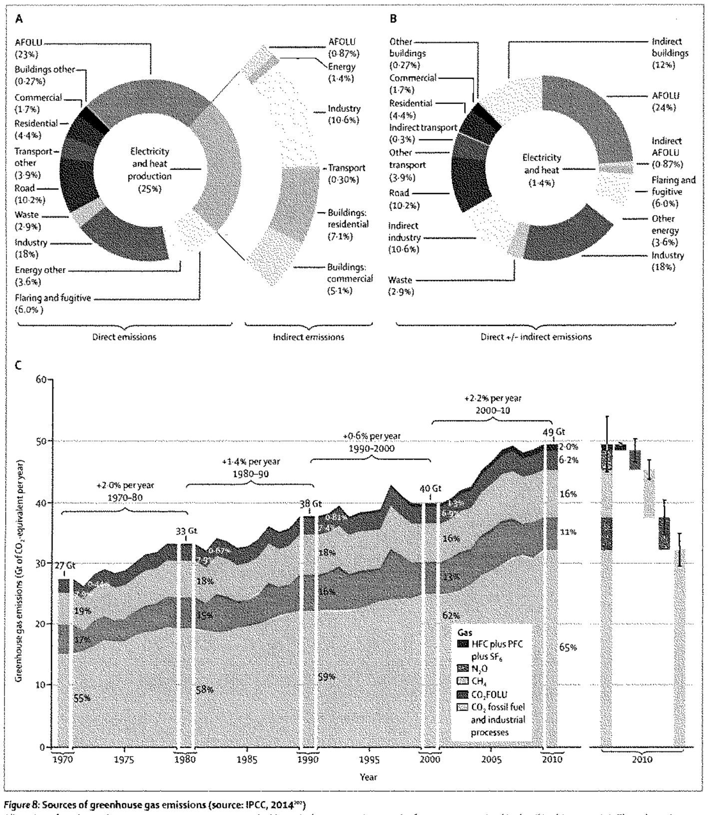

Figure 8: **Sources of greenhouse gas emissions (source: IPCC, 2014[202])**

Allocation of total greenhouse gas emissions in 2010 (49·5 Gt CO_2 equivalent per year) across the five sectors examined in detail in this report (A). The enlarged section of panel A allocates indirect CO_2 emission shares from electricity and heat production in the sectors of final energy use. Panel B allocates total emissions (49·5 Gt of CO_2 equivalent per year) to show how the total from each sector increases or decreases when adjusted for indirect emissions. Total annual greenhouse gas emissions by groups of gases 1970–2010, and estimated uncertainties for 2010 (whiskers; C). The uncertainty ranges are illustrative, given the limited literature in the field.[201] AFOLU=agriculture, forestry, and other land uses. FOLU=forestry, and other land uses.

consumption of fossil fuels, and this system shows vulnerabilities when stressed. For example, the 1972 Organization of the Petroleum Exporting Countries (OPEC) oil embargo (which resulted in a cut of global production by 6·5% over 2 months) or the first Persian Gulf War (which caused a doubling of global oil prices over 3–4 months) each caused major pressure on the access and security of global energy supplies.[204] Furthermore, many of the world's largest actual and potential conventional oil reserves are in areas of historic volatility and civil unrest.[205]

Climate change poses a risk to the existing energy system. Under a changing climate, these vulnerabilities could result in disruption in both supply and production of power under extreme weather events, operations (eg, water availability for cooling towers), viability of infrastructure (eg, location of power lines or hydroelectric systems), impact on transmission (eg, high temperatures or wind damage), and higher demand for cooling and building system performance.[206,207]

The usefulness of fossil fuels relates to their power and energy density, portability, and relative cost compared with other forms of energy. These attributes have acted as challenges to the transition to low-carbon energy sources and vectors, such as renewable and nuclear electricity and hydrogen. Maintaining power supply based on intermittent electricity sources such as wind power is a complex system integration problem.[208] Practical solutions will involve combinations of energy stores (hydroelectric, thermochemical), demand-side management, and the harnessing of geographical diversity with respect to demand and supply. Cross-continental power grids can play a significant part in reducing low-carbon systems costs because greater diversity of demand and supply reduces the need for expensive energy storage.

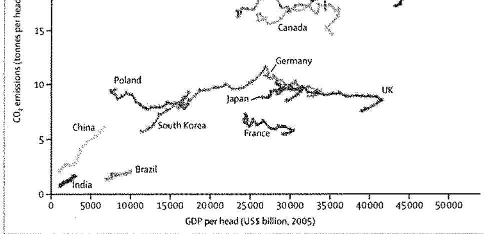

Figure 9: **Per head CO_2 emission trends in relation to income for a selection of countries (1990–2008)[212,213]**
*Based on purchasing power parity.

The growth in energy demand

Global energy demand has grown by 27% from 2001–10, largely concentrated in Asia (79%), the Middle East and Africa (32%), and Latin America (32%), but with near stable but high demand (on a territorial accounting basis) in the 1990 Organisation for Economic cooperation and Development (OECD) group of countries.[203] China doubled its energy demand during this period and represented the single largest proportion of the global increase (44%).[209] Most global growth in energy was in coal (44%) for use in electricity production, a dangerous reality for human health.[210]

Economic productivity has risen alongside global energy demand. Whilst fossil fuel-based energy demand has grown slowly in OECD countries since 1970, gains were made in GDP terms that were largely a result of de-industrialisation of the economy (largely exported to Asia). As a result, Asia has made a significant leap in energy consumption, emissions and GDP. The energy intensity of large global economies (ie, the USA, China, EU, India) have fallen progressively over the period of industrialisation.[211] Figure 9 shows that economic gains need not be strongly coupled to CO_2 emissions, though the association is partly obscured by the export of CO_2 emissions. Moving energy-intensive industries offshore (most of which remain fossil-fuel powered) allows for territorial emissions to fall, but at the cost of increased emissions elsewhere.

Growth in demand for energy will probably continue over the coming 25 years, particularly in lower-middle and low-income economic regions, where most citizens lack access to safe and affordable energy. The growth in global per capita energy demand is linked to improvements in the standard of living in developing regions and directly supports development goals. Expected energy demand in non-OECD countries may double by 2035 (107%) from 2010, while OECD countries may increase by 14% over the same period.[209] However, this growth in demand will continue to directly benefit high-income regions through exported production of goods.

Meeting our future energy needs

Access to energy is a key enabler of economic development and social wellbeing. In recognition of energy being a key determinant of economic and social development, and of health and wellbeing, the UN has declared that 2014–24 is the UN Decade of Sustainable Energy for All. The world's population must be able to access clean forms of energy that can provide these basic needs, which can minimise the health burden from both direct exposure and indirect from future climate change risks. The Sustainable Development Goals (SDGs) have emphasised the role that energy plays in securing a sustainable future for a global 9 billion population by 2050, and has outlined four targets to support, which could act as progress metrics. The indicators measuring

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

progress on the proposed SDGs for securing sustainable energy for all by 2030 include: ensuring universal access to affordable, sustainable, reliable energy services; doubling the share of renewable energy in the global energy mix; doubling the global rate of improvement in energy efficiency; phasing out fossil-fuel production and consumption subsidies that encourage wasteful use, while ensuring secure affordable energy for the poor.[214]

The health burden of the current energy system

Although linked to a historical transformation in health, a fossil-fuel-based energy system also imposes significant health burdens (figure 10). The direct burden occurs through emissions of particulates and solid wastes (coal, oil, gas, biomass), risk of flooding (hydroelectricity), accidents and injuries (all), and emission of radioactive materials (coal, nuclear). But as the main driver of anthropogenic climate change, an energy system based on fossil fuels will also have indirect effects through climate change and the increase in temperatures, extreme weather, heatwaves, and variable precipitation (see section 1).

The immediacy of this burden varies with the inertia built into the emission to exposure pathways and exposure to health-effect pathways. Compared with climate change, the locality and visibility of fossil fuel emissions are more apparent today as poor air quality and toxic discharges, such as smog in Beijing or Delhi. A coal-fired power plant will emit particulates that result in immediate exposure for the local population with consequent increased risk of developing respiratory disease and lung cancer. The exposure to emissions can result in immediate health effects for the local population, such as respiratory tract infections, or take many years or decades to have an effect. A coal-fired station will produce immediate CO_2 emissions, but these emissions do not result in immediate health impact. Instead, GHG emissions that accumulate in the atmosphere over the long term will result in global climate change. The long-term nature of climate change means that these exposures build towards a more dangerous level. Another dimension is locality of the emissions-exposure, exposure-health effect pathways. Locally generated emissions will affect both the population surrounding the point of discharge and in some cases more widely, as in burning coal in north Asia. Climate change, however, will affect all areas to varying degrees.

The global increased use of energy per capita is highly related to considerable improvements in quality of life across much of the world. The majority of this energy use is derived from fossil-fuel use, but mainly coal. Coal's wide availability and economic attractiveness has made it the fuel of choice for use in power generation. The recent expansion of coal use, mainly in the newly industrialising countries, effectively reverses the global pattern through most of the 20th century towards less carbon intensive and less polluting fossil fuels–the progressive displacement of coal by oil, and of both by natural gas. However, the time when fuel switching could decarbonise the global economy sufficiently quickly to avoid dangerous climate change has almost certainly passed. It is increasingly difficult to justify

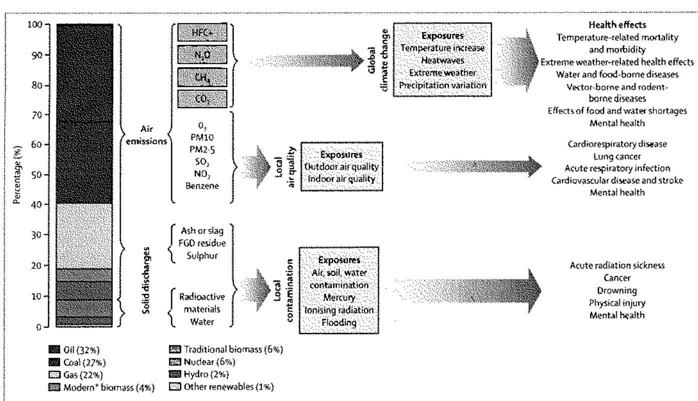

Figure 10: Connections between the global energy system and health impacts
Length of arrows denotes time to impact; width denotes inertia of impact. FDG=flue gas desulphurisation. *Does not include other renewables.

large-scale investment in unabated gas-fired infrastructure. The dangerous impacts of coal on health from exposure to air pollution in the form of noxious particulates and heavy metals, the environmental degradation (eg, contaminating water courses and habitat loss) from the extraction and processing of coal, and the major contribution that burning coal and the release of GHGs has in changing the long-term climate almost certainly undermines the use of coal as a long-term fuel. Although the use of coal as a fuel source for power generation will be linked to economic growth and (sometimes precarious) improvements in quality of life, the risk that coal has on our global health through climate change and habitat loss means that moving to low-emission fuels in areas of high coal demand is a major part of the global low-carbon energy transition. Whilst the use of technologies such as carbon capture and storage (CCS) are consistently cited in reducing the impact of coal-based power generation, at present, these technologies have many major unknowns and are without substantial government investment or the use of carbon pricing.

One important strategy to protect against the health burdens of local and national energy choices, is to ensure that health impact assessments are built in to the planning, costing, and approval phases of a new project. By developing the tools and capacity to enforce this, policy makers can better understand the broader consequences of their decisions.

Actions, technologies, and health outcomes

Actions that seek to mitigate climate change have the potential to be beneficial to health, both directly and indirectly.[1,29] Across a number of sectors, the potential health benefits of switching to low-carbon technologies include a reduction in carhon emissions from power generation,[215,216] improved indoor air quality through clean household cooking technologies in low-income settings and housing thermal efficiency in high-income settings, and lowered particulate-matter exposure from low-emission transport.[217,218]

Decarbonising the power supply sector holds both risks and benefits for health. The direct benefits centre on reducing exposure to air pollutants from fossil-fuel burning.[216] In the UK, the associated burden of air pollution from the power sector is estimated to account for 3800 respiratory related deaths per year.[216] In China, air pollution is thought to result in 7·4 times more premature deaths from PM2.5 than in the EU.[215] It has been estimated that current ambient concentrations of particulate matter led to the loss of about 40 months from the average life expectancy in China, but that this loss could be cut by half by 2050 if climate mitigation strategies were implemented. The risks to health from decarbonisation are more likely to he indirect; if the deployment and adoption of technologies that aim to reduce carbon emissions, reduce energy demand, or switch fuels are not undertaken with care, there are risks of unintended consequences through, for example, poor housing ventilation.[219] Besides air quality, several links between climate mitigation practices and technologies and potential health benefits have been established (figure 11).[220,221] Using active transport as an example, the shift from car driving to walking and cycling not only reduces the air pollutant emissions, but also increases levels of exercise, which in turn can lead to reduced risks of several health outcomes, including cardiovascular diseases, diabetes, and some cancers.[218]

The formal health sector itself also has a role to play in reducing its emissions. Hospitals and health systems, particularly in more industrialised settings, account for around 10% of GDP and have a significant carbon footprint. While the full extent of health care's climate impacts is not known, emerging data confirms its significance and the need for mitigation strategies. For instance, the NHS in England calculated its carbon footprint at more than 18 million tonnes of CO_2 each year—25% of total public sector emissions.[222] 72% of the NHS's carbon footprint is related to procurement and the remaining split between travel and energy use in buildings.[223] In the USA, the health-care sector is responsible for 8% of the country's total GHG emissions.[224] With among the largest sectoral purchasing power globally, the health sector could reduce its impact through the products it purchases and through investment in its infrastructure (ie, hospitals, ambulatory services, and clinics).

By moving toward low-carbon health systems, health care can mitigate its own climate impact, become more resilient to the impacts of climate change, save money, and lead by example. For instance, in South Korea, Yonsei University Health System is targeting reducing GHG emissions by 30% by 2020. Energy efficiency measures saved the system $1·7 million and reduced GHG emissions by 5316 tonnes of CO_2 in 2011 alone.[225] In the USA, Gunderson Health has increased efficiency by 40%, saving $2 million annually, while deploying solar, wind, geothermal, and biomass to significantly reduce its carbon footprint and end its dependence on fossil fuels.[226] In England, the NHS Public Health and Social Care System has similarly committed to reducing their carbon footprint by at least 34% by 2020.[227]

Conversely, accounting for the health co-benefits of climate change mitigation, can help to bring down the overall cost of greenhouse gas mitigation. Jensen and colleagues have shown that the incorporation of health co-benefits of cleaner vehicles and active travel can make those mitigation practices cost effective.[228] The health benefits of reducing methane emission in industrialised nations could exceed costs even under the least aggressive mitigation scenario between 2005 and 2030.[229] For example, in the UK, retrofits aimed at improving energy performance of English dwellings have the potential to

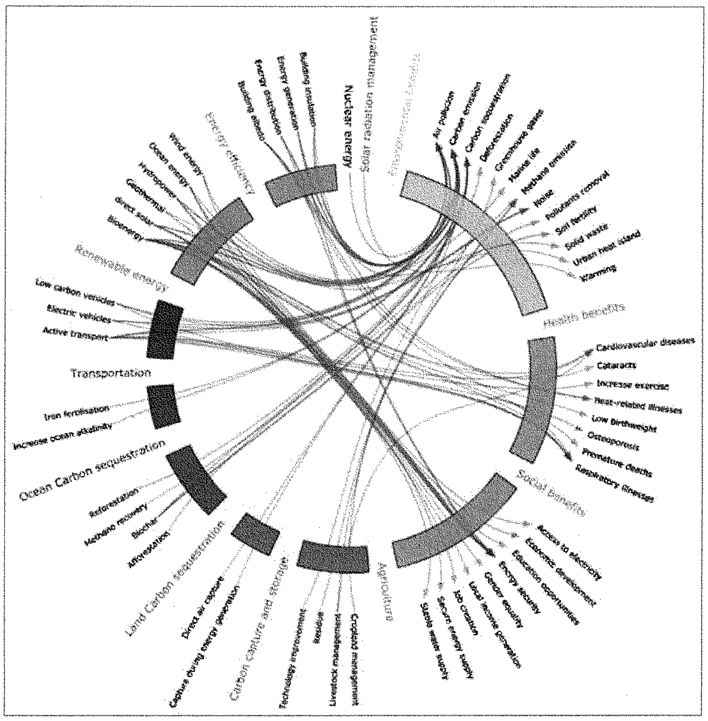

Figure 11: **Frequently cited co-benefits of major mitigation techniques**
Red arrows between a mitigation technology and an effect indicate that the technology will increase the effect; green arrows indicate an opposite trend.

offer substantial health benefit over the long-term, providing ventilation to control indoor pollutants is installed (see appendix 2).

See Online for appendix 2

Pathways to (GHG emissions reduction) pathways

Over the last two centuries, the prevailing pattern of national development has involved dramatic increases in productive capacity, supporting transformations in nutrition and housing, underpinned by development of fossil-fired energy supply, conversion, and distribution systems. Three overlapping stages of development can be identified:

- Stage 1: typically low technology, relatively inefficient and with little regard for damage due to pollution and other externalities.
- Stage 2: locally clean. As countries become wealthier, they can afford to invest in the longer term and deal with the local health problems associated with burning fossil fuels.
- Stage 3: regionally and globally clean. This involves the development of energy systems that address transboundary pollution problems including that of anthropogenic climate change. Stage 3 is generally associated with high GDP and indices of public health.

Importantly, improvements in technology and efficiency have historically accompanied and assisted, but have not been primarily driven by the goal of pollution control. The patterns of development associated with stages 1 and 2 are complex and multi-dimensional, and stage 3 is unlikely to be different. Stages 1 and 2 have historically been associated with increasing income and health.

This pattern of development has resulted in emission of about 1600 $GtCO_2$ since 1870, with a consequent rise in global mean temperature anomaly of +0·85°C (1870–2010). To have a better than 66% probability of keeping the rise in global temperatures to below 2°C, cumulative greenhouse gas emissions from 2011 on would need to be limited to around 630–1180 $GtCO_2$eq.[201,230,231] At the current global emission rate, this budget would be used up in between 13 and 24 years.

The last 30 years of OECD data have shown that significant changes to global energy systems are possible. Indeed, the whole of the 20th century has been characterised by a succession of transitions in energy technologies. However, this process has not been inevitable and decisions on energy systems have been aligned with other national objectives—eg, enhanced security of supply or reduced air pollution. This suggests that the transition to low-carbon energy will need to be predicated on achieving multiple objectives, including climate change, health, equity, and economic prosperity.

Many trajectories that are consistent with such a budget (panel 6 shows those of the UK and China) are in principle possible. Such trajectories necessarily involve emissions in the second half of the century in the region of 90% lower than emissions between 2011–50.[232] All would require an unprecedented global commitment to change, and none appears easy. To stabilise CO_2-equivalent concentrations in the range 450–650 ppm (consistent with 2–4°C of warming) will require the global emission rate to fall by between 3–6% per year, a rate that so far has only been associated with major social upheaval and economic crisis.[25] Postponing deep cuts in emissions may allow for new policies and technologies, but at the cost of significant impacts (eg, for land use and food production) in the second half of the century.

Achieving a 2°C warming target

Many technologies exist or have been proposed to mitigate climate change. But they vary in their potential

Panel 6: Decarbonisation pathways for the UK and China[226]

The Deep Decarbonisation Pathways Project (DDPP) aims to understand and show how major emitting countries can transition to low-carbon economies and, in doing so, move towards the internationally agreed 2°C target by 2050. The project comprises representatives of 15 countries contributing to more than 70% of current global greenhouse gas emissions, and is led by the UN Sustainable Development Solutions Network (SDSN), and the Institute for Sustainable Development and International Relations (IDDRI), Paris.[227]

The project's interim report describes pathways that achieve a 45% decrease of total CO_2-energy emissions over the period (falling to 12·3 Gt by 2050, from 22·3 Gt in 2010). Although the interim pathways do not reach a 50% probability of restricting climate change to 2°C, they provide important insights. Three key pillars of decarbonisation are crucial in all the countries studied: energy efficiency and conservation, a shift to low-carbon electricity, and a switch to lower carbon fuels. However, the balance between these pillars depends on national circumstances.

The UK pathway is characterised by early decarbonisation of the power generation sector, and increased electrification of end-use sectors from 2030, leading to an 83% reduction in CO_2-energy emissions by 2050 (see figures 12A and B). The cumulative investment requirements for such a large-scale decarbonisation are in the region of £200–300 billion, and require a strong policy framework, including electricity market reform. After 2030, radical changes in energy vectors are necessary, with heating switching from gas to heat pumps and district heating, and transport increasingly electrified. Greater-than-marginal reductions in emissions (eg, associated with heating) require sustained strategic vision and interdecadal coordination between energy supply and demand sectors of the economy. Challenges to delivery will probably include the scale of infrastructure investment, and public acceptability across end-use sectors.

The challenge in China is to achieve decarbonisation alongside continued rapid economic growth. The pathway shows GDP per head increasing by six times from 2010 to 2050; this increase is offset by a 72% reduction in energy intensity of GDP—a substantial decoupling. Emissions peak by 2030, and fall by 34% by 2050, driven by falling energy intensity and almost complete decarbonisation of power generation. Despite electricity generation more than doubling by 2050, unabated coal is replaced by renewables, nuclear, and carbon capture and storage (figures 13A and B). In industry, carbon capture and storage and higher efficiency could reduce emissions by 57% by 2050. But growth will continue in the transport sector due to an increase of ten times in mobility, only partly offset by higher efficiency and little penetration of low-carbon vehicles.

Key to the transition of the Chinese energy system is rapid development and deployment of low-carbon technologies, and a shift away from unabated coal use, facilitated by energy market reform and carbon pricing.

The project shows the crucial need for large-scale global technology research, development, demonstration, and deployment, and transfer efforts. A common feature of most pathways is the need to decarbonise freight transport and industry. The final DDPP report will review investment levels and policy frameworks to enable the transition.

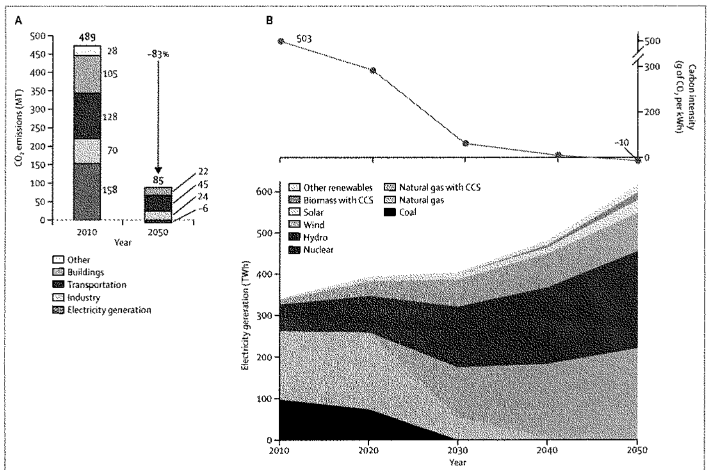

Figure 12: Energy-related CO_2 emissions pathway for the UK in 2010 and 2050 (A), and energy supply pathway for electricity generation for the UK, 2010–50 (B)[239]
CCS=carbon capture and storage.

mitigation impacts, stages of development, costs, and potential risks. Table 2 summarises mitigation technologies. Among them are climate engineering approaches such as land and sea sequestration. Although these have significant potential, they carry significant risks, including the possibility of damage to ecosystems. It is currently uncertain that the necessary international consensus to allow the deployment of such technologies could be achieved. Energy efficiency improvement is considered as the least risky of the options, although on its own it is insufficient to achieve the necessary decarbonisation.[233]

Individual behaviour is an important factor that affects the end-user energy efficiency—eg, using high-efficiency heating and cooling systems, adopting more efficient driving practices, routine maintenance of vehicles and building systems, managing temperatures for heating, and hot water for washing.[234,235] But behavioural changes are not so easily achieved and pose considerable risk as a mitigation strategy. The medical professions have decades of experience with attempts to induce mass changes of behaviour through health promotion. The most prominent campaigns have been targeted at alcohol consumption, smoking, diabetes, and obesity. The overarching lesson is that even when behaviour change yields direct personal benefits, amounting in some cases to a decade or more of life expectancy, it is extraordinarily difficult to achieve through persuasion. In practice, different societies favour divergent approaches to influencing behaviour, ranging from the economic, through the physical to the psychological.[236]

Technologies that have the greatest decarbonisation potential include nuclear power, offshore wind, concentrated solar power (CSP), and CCS.[237,238] Solar photovoltaic (PV) and wind systems have been growing exponentially for decades (wind about 12% per year, PV about 35%), with consequent reductions in costs due to learning and increasing scale of production and deployment, while both CSP and CCS have not yet been deployed at any significant scale and so cannot capture significant learning effects. CCS suffers from similar problems to nuclear—ie, large unit sizes, potential regulatory concerns, and long lead times, which means weak and delayed learning once deployment has begun. But CCS's additional disadvantage compared with nuclear and renewables is that while the latter decouple economies from the threat of future rising and volatile fossil fuel costs, CCS magnifies these threats. Even in the absence of carbon pricing, renewables and nuclear can be justified as a hedge against future increases in fossil fuel prices, whereas CCS cannot.

Attempts to understand the adaptation of the whole energy system in the context of rapid transitions to low-carbon emissions have been predominantly from the

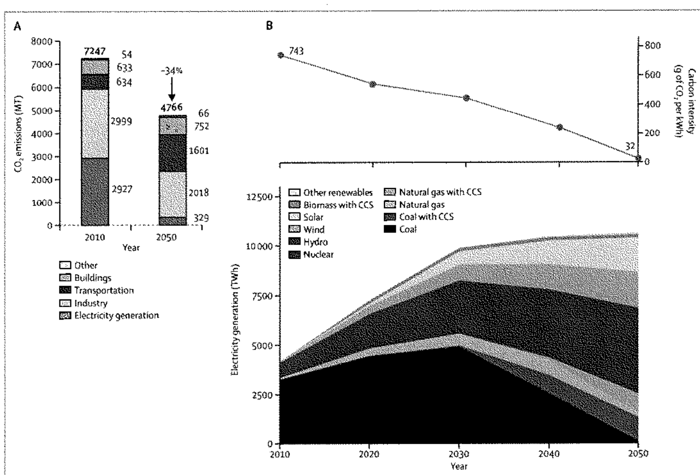

Figure 13: Energy-related CO_2 emissions pathway for China in 2010 and 2050 (A), and energy supply pathway for electricity generation for China, 2010–50 (B)[230]
CCS=carbon capture and storage.

discipline of economics. Among these is the Deep Decarbonization Pathways Project (DDPP), which has developed pathways for 15 countries.[230] Panel 6 provides an example of these technology pathways for the UK and China. Transforming the global economy in anything like the timescale implied by the above discussion requires unprecedented action in both industrialised and developing countries. The former will need to embark more-or-less immediately on CO_2 reduction programmes with a high level of ambition. Developing countries will need to move directly from stage 1 to stage 3 (significantly reduced emissions with associated high GDP and indices of public health) probably with both capital and technical support from developed countries. Delayed emission reduction would lower the possibility to control climate change, raise costs and force the uptake of riskier and unproven mitigation technologies with increased risk of unintended consequences for human wellbeing and ecosystems.[239]

The range of unintended consequences when the technologies are administered to different systems is large, complicated, and in some areas poorly understood. Ultimately, rapid mass deployment of low-carbon technologies requires a better understanding of the drivers and barriers to delivery within different economic sectors, the scale and opportunity of deployment, and the setting and its context including the actors and decision makers involved. The application of low-carbon technologies, their impact, deployment, and co-benefits must be maximised by understanding what works, where it works, and why it works. This understanding is particularly important to support emerging technologies that are yet to reach market-scale deployment. Three key drivers are required to support pathways to a low-carbon future: maximising the efficacy of low and zero carbon technologies, maximising the deployment of these technologies, and maximising and internalising the potential health co-benefits of decarbonisation.

Maximising efficacy

Although significant progress has been made in adopting clean technologies, the resulting impact on energy intensities and carbon emissions has been lower than expected. Barriers to adoption and deployment of mitigation technology include a lack of awareness and access to technical knowledge, segmentation and fragmentation within and amongst sectors, and financial disincentives. These barriers will be particularly acute in developing countries where the benefits of energy efficiency are not necessarily recognised and may be a lower priority compared to many other urgent issues, such as poverty eradication, public health improvement, and crime reduction; this may be further affected by a lack of means of communication. Furthermore, due to a lack of quantitative and reliable measurements of energy performance, many stakeholders are not aware of energy savings potential. We propose three actions to improve efficacy:

1 Understanding the direct and indirect impacts of technologies from an integrated technical, economic, social, health and cultural, and political perspective;
2 Gathering, evaluating, and reporting real-world evidence to support and guide development and implementation of mitigation strategy;
3 Put in place policies and regulations (such as reporting schemes, inspections, and benchmarks) to make performance visible within the market.

Maximising uptake

Minimum deployment of low-carbon technologies poses a significant risk to the transition to a low-carbon future. The International Energy Agency (IEA) has stated that nine out of ten low-carbon technologies that are essential for energy efficiency and decarbonisation are failing to meet their deployment objectives. Limited deployment, particularly early in the process, limits learning and constrains subsequent progress.

Inertia in the technology diffusion process within many sectors means that many off-the-shelf technologies today could take 20 years to achieve significant market penetration without incentives to support their uptake. Overcoming such inertia requires clear guidance on technology potential; robust data on technology performance, impact, and costs; detailed information on existing sectors and historic structures; removal of disincentives and perverse incentives; and strong regulations. For certain technologies, regulation can play a major part in accelerating deployment. Criteria for regulations to be effective in this role may be summarised as follows: that the goal of regulation should be unambiguous; that the technical nature of measures which will achieve the goal should be clear, and they should be easy to apply; that the technical nature of these measures should make it easy for the regulator to confirm that they have been implemented; that the total benefits should outweigh costs; and that both benefits and costs should be a small part of some larger economic transaction.[240] Cities offer opportunities and challenges for technology deployment. For appropriate technologies, economies of scale are quickly achieved with population and economic densities supported by larger tax bases, deployment through existing services and a history of operating large scale infrastructure. Density intensifies local environmental problems (particulates, noise, etc), which can in turn make it politically possible to introduce local regulation favouring low-carbon technologies. Resulting niches and learning can then accelerate the development and wider deployment of key mitigation technologies.[241]

Development status is another important driver of deployment. The bulk of technology transfer occurs between developed countries who dominate the invention of technologies for climate mitigation.[242] This does nothing to overcome the low availability of mitigation technologies in developing countries. Major barriers to technology transfer from developed to developing countries include insufficient local human capital and technology support capabilities, lack of capital, trade and policy barriers, lax intellectual property regimes in developing countries, and the potential lack of commercial viability of the technology itself.[243] These barriers need to be overcome to enable countries seeking to achieve a high quality of life to tunnel from stage 1 to stage 3.

Mechanisms to support low-carbon technology uptake should include:

- Enacting policy regulations to improve deployment of technologies (such as incremental minimum performance standards or delivery obligations)
- Developing strong national-level commitments and sources of funds for investment in low-carbon infrastructure that is accessible to local delivery agents.
- Targeting decision makers who can achieve maximum on-the-ground change and uptake of technologies and changes in practices (ie, sector heads, mayors, and councils).

Maximising co-benefits and avoiding unintended consequences

Many low-carbon technologies provide benefits other than reducing greenhouse gas emissions—eg, increased energy security, improved asset values, improved air quality, greater disposable income, and improved health and comfort. Some low-carbon technologies are primarily deployed because of their co-benefits.

Low-carbon technologies inappropriately deployed can hurt the economic and social development of developing countries. The increased use of expensive low-carbon energy sources could delay essential structural changes and slow down the construction of much needed infrastructure. Higher energy prices can affect economic growth and exacerbate poverty and inequality. However, abstaining from mitigation technologies in developing countries carries the risk of lock-in into a high-carbon-intensity economy.[244] In order to avoid such unintended consequences, a balanced strategy focusing on both human development and climate mitigation in developing countries is needed.

Mechanisms to maximise co-benefits should include:

- Developing compelling arguments for action that emphasise co-benefits (ie, health, quality of life, air quality, a creative and resilient economy).
- Putting in place national and international level mechanisms to support and encourage technology adoption (ie, carbon pricing).
- Putting in place policies and economic tools that can facilitate the technology transfer from developed countries to developing countries (ie, the importance of the Green Climate Fund).

Panel 7: Total external costs of burning fossil fuels

The prices of fossil fuels routinely do not account for their global impacts related to climate change, or their local impacts on human health and ecosystems. These external costs of fossil fuels can be expressed by the following formula:

$$TEC_{ff} = C_{cc} + C_{lap} = (C_{cd} + C_{ad} + C_{mg}) + (C_{pd} + C_{he} + C_{pc})$$

Where TEC_{ff} are the total external economic costs of burning fossil fuels; C_{cc} are the costs related to climate change, which can in turn be regarded as the sum of C_{cd} (the damage costs of unmitigated climate change), C_{ad} (the costs of adapting to climate change, either present or anticipated), and C_{mg} (the costs of mitigating climate change); and C_{lap}—the costs of local air pollution—which can be regarded as the sum of C_{pd} (the pollution damages to buildings, crops and health of such pollution), C_{he} (the health and other expenditures to remedy this pollution damage) and C_{pc} (the costs of controlling this pollution). There is symmetry in these cost terms relating to climate change and local air pollution, between C_{cd} and C_{pd} (the estimated damage costs), C_{ad} and C_{he} (the actual expenditures in response to the pollution), C_{mg} and C_{pc} and (the costs of reducing the extent of the pollution). The components of this formula are also dependent on each other, in conceptually simple if often practically complex ways, as follows:

- C_{cd} is a function of C_{mg}, such that increased mitigation will reduce the costs of climate damage, with a similar relationship between C_{pd} and C_{pc} for local air pollution.
- C_{ad} is also a function of C_{mg}, such that increased mitigation will reduce the costs of adaptation, with a similar relationship between C_{he} and C_{pc} for local air pollution.
- C_{lap} is also a function of C_{mg}, such that increased mitigation will reduce the costs of air pollution.
- C_{cd} is a function of C_{ad}, such that increased adaptation will reduce the costs of climate damage, with a similar association between C_{he} and C_{pd} for local air pollution.

Notably, in each case, the effects of the different variables on each other might act over widely differing timescales. Furthermore, whereas the above equation has been discussed in terms of the combustion of fossil fuels, which make the major contribution to anthropogenic greenhouse gas emissions, for full cost-effectiveness of climate mitigation the equation should be computed over the full range of greenhouse gas emissions to ensure that relatively cheap abatement measures are not overlooked.

Conclusions

Energy systems comprise some of the largest, most complex and enduring capital structures in modern economies. Decarbonisation and reducing energy demand is not a simple challenge of cleaning up pollutants or installing new equipment, it requires systemic transformations of energy infrastructures and associated systems. We need to put in place mechanisms that support the uptake of technologies in an effective manner (ie, support pathways to impact pathways or pathways to pathways). Finally, it should be noted that the full potential of mitigation technologies will only be achieved if the social and political systems around these technologies co-evolve to deliver carbon targets.

There is a clear and compelling need for the industrialised world to achieve faster and much deeper emission reductions than anything delivered to date. At the same time, industrialisation historically has been accompanied by rising greenhouse gas emissions (particularly CO_2) up to income levels of \$10–15 000 per capita. Some of the major emerging economies are already reaching such levels, with concomitant emissions; helping others to avoid doing so, or helping those (like India) still with huge challenges to lift hundreds of millions of people out of extreme poverty, will require international assistance.

Through a multipronged approach that advocates co-benefits, targets decision makers and puts in effective measures that are understood, it might be possible to make real progress towards meeting our emission reduction goals. These mechanisms represent a public health-style approach to developing and implementing mitigation strategies, with the end goal of many co-benefits.

Section 4: financial and economic action

The total economic cost of fossil-fuel use

Past failures to reduce GHG emissions mean that remaining within the required carbon budget is becoming progressively challenging. We are increasingly committed to a certain level of climate disruption, requiring adaptation measures to reduce the impact this is likely to have. Given that the world is already committed to some degree of climate change, and given too that the combustion of fossil fuels also emits a variety of other pollutants, the total external costs of burning fossil fuels (ie, those costs that are not included in the price of fossil fuels) may be expressed as shown in panel 7.

The optimum outcome of this formula is that which minimises TEC_{ff}, computed over the time horizon of interest. Unfortunately, the state of knowledge now, or at any likely point in time in the future, does not permit such a dynamic optimum to be computed. The purpose of this section is to explore the estimates of these different cost categories that appear in the literature to draw conclusions regarding the extent of climate change adaptation and mitigation that should be attempted, and the policies that might be able to deliver it.

The question of what is optimum in economic terms (GDP or welfare per head) for a given level of carbon emissions and discount rate requires the computation of an optimal time path. What is optimum today (without regard for the future) will not be optimal if the future is to be taken into account. And of course the relation between low prevention costs now means very high treatment costs later, compared with high prevention costs now means lower treatment costs later will be subject to very great uncertainty. Higher uncertainty may mean that high prevention costs would be wasted. On the other hand, with higher uncertainty comes the increased probability that high prevention costs are not high enough. However, whatever the answers to these questions, models reviewed in the IPCC's Working Group III Fifth Assessment Report (AR5) indicate with sufficient certainty that more needs to be spent earlier rather than later if even a moderate value is given to the intermediate and long term future.[201]

The health and related economic benefits of adaptation

There are significant research gaps regarding the scientific evaluation of the health benefits of climate-change adaptation due to its highly diffuse and context-specific nature, with only scattered quantitative or semi-quantitative studies on the health costs and benefits of adaptation options.[245] Monetising these costs and benefits is an even more difficult task. However, the studies that do exist present a strong message. Seven of the eight studies on the effectiveness of heatwave early warning systems reported fewer deaths after the systems were implemented. For example, in the summer of 2006, a heatwave in France produced around 2000 excess deaths—4000 less than anticipated based on previous events.[11] A national assessment attributed this to greater public awareness of the health risks of heat, improved health-care facilities, and the introduction of a heatwave early warning system in 2004.[112] A Climate Forecast Applications Network developed in the USA had successfully forecast three major floods in 2007 and 2008 in Bangladesh 10 days in advance, allowing farmers to harvest crops, shelter animals, store clean water, and secure food before the event.[246] Webster also strongly advocates the establishment of a network between weather and climate forecasters in the developed world, and research and governmental and non-governmental organisations in the less-developed world.[246] According to his estimation, such a network could produce 10–15 day forecasts for south and east Asia for a wide range of hydrometeorological hazards (including slow-rise monsoon floods, droughts, and tropical cyclones) at an annual cost of around $1 million, but with prevention of "billions of dollars of damage and protecting thousands of lives". To support assessments such as these, WHO Europe have prepared an economic analysis tool to enable health systems to calculate the health and adaptation costs of climate change, which was in turn tested in their study of seven European countries.[247,248]

The health and related economic benefits of mitigation

Unmitigated climate change presents serious health risks that could reach potentially catastrophic proportions. Mitigating climate change not only significantly reduces this risk, but can also yield substantial health co-benefits against contemporary circumstances.

Panel 8 illustrates the proportion of national GDP directed to health care increasing with wealth, along with the proportion accounted for by government expenditures. This suggests that governments of high and increasing income countries should give significant priority to mitigating climate change to prevent detrimental health impacts, which could result in the need for significant extra health expenditures, from both governmental and personal finances. Indeed, the direct and indirect cost of existing pollution-induced illnesses alone is significant. The OECD estimates the cost of ambient air pollution in terms of the value of lives lost and ill health in OECD countries, plus India and China, to be more than $3·5 trillion annually (about 5% gross world product [GWP]), with India and China combined accounting for 54% of this total.[251] Globally, and with the addition of indoor air pollution, this value is likely to be substantially higher (appendix 3)

See Online for appendix 3

The European Commission has estimated that in the EU alone, reduced air pollution from policies to mitigate climate change could deliver benefits valued at €38 billion a year by 2050 through reduced mortality. From a broader perspective, the European Commission estimates that moving to a low-carbon economy could reduce the control costs of non-CO_2 air pollutants by €50 billion by 2050.[252] With an increase to 36% renewables in global final energy consumption by 2030 (from 18% in 2010), IRENA calculates up to $230 billion of avoided external health costs annually by 2030.[253] In addition, West and colleagues note that if RCP4.5 is achieved, annual global premature deaths avoided reach 500 000 by 2030, 1·3 million by 2050, and 2·2 million by 2100. Global average marginal benefits of avoided mortality are $50–380 per tCO_2, exceeding marginal abatement costs in 2030 and 2050. The greatest benefit is projected for east Asia, with 220 000–470 000 premature deaths avoided per annum by 2030, with marginal benefits of $70–840/$tCO_2$—a range 10–70 times that of the projected marginal cost[254] (see appendix 3 for more about the cost of ambient air pollution in China). In the USA, Thompson and colleagues estimate that human health benefits associated with air quality improvements driven by CO_2 mitigation policies can offset the cost of the policies by up to ten times.[255]

Panel 8: Global expenditure on health care

Figure 14 shows the global range of total expenditure on health care as a proportion of GDP in 2011. Total expenditure is 9·1% gross world product (GWP)—about US$6·8 trillion—with geographical variation ranging from 1·65% GDP in South Sudan, to 17·7% in the USA. At a global level, 59% of expenditure is sourced from government budgets (of which 60% is via social security mechanisms), accounting for more than 15% of total expenditure by governments worldwide. The remaining 41% is sourced from the private sector (of which 38% is in the form of health insurance, with 50% out-of-pocket expense). Total average global health expenditure per capita was $1053, in purchasing power parity (PPP) terms.[247]

Figure 15 shows the variation between the economies of different average income levels against these global totals. Total expenditure per head varies between an average of $64 in low-income countries and $4319 in high-income countries in PPP terms. This increase in expenditure proportional to income is accompanied by the increasing use of insurance mechanisms (either private or social security), and decreased reliance on external (international) resources (principally development assistance and funding from non-governmental-organisations), and private expenditure and out-of-pocket expenses (in proportional terms). Whereas private expenditure and out-of-pocket expenses remain a significant component in all groups, external resources decrease rapidly, from 29% in low-income countries to 2·3% in lower middle-income countries, 0·4% in upper middle-income countries, and 0% in high-income countries.

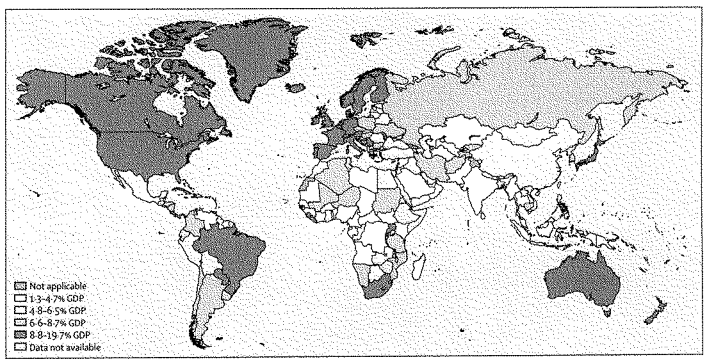

Figure 14: **Total expenditure on health as proportion of GDP (2011)[249]**

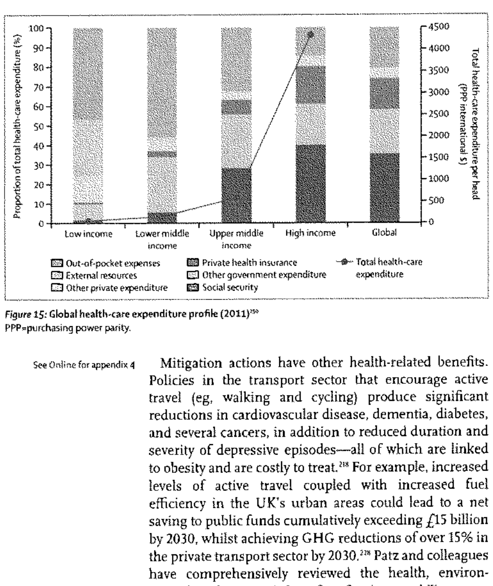

Figure 15: **Global health-care expenditure profile (2011)[250]**
PPP=purchasing power parity.

See Online for appendix 4

Mitigation actions have other health-related benefits. Policies in the transport sector that encourage active travel (eg, walking and cycling) produce significant reductions in cardiovascular disease, dementia, diabetes, and several cancers, in addition to reduced duration and severity of depressive episodes—all of which are linked to obesity and are costly to treat.[218] For example, increased levels of active travel coupled with increased fuel efficiency in the UK's urban areas could lead to a net saving to public funds cumulatively exceeding £15 billion by 2030, whilst achieving GHG reductions of over 15% in the private transport sector by 2030.[228] Patz and colleagues have comprehensively reviewed the health, environmental, and economic benefits of active travel.[256]

In many countries, climate-change mitigation through increased energy efficiency will have the benefit of reducing fuel poverty (a condition in which low-income households have to spend a high proportion of their income to keep warm or cool), and associated impacts on excess winter mortality, respiratory health of children and infants, and the mental health of adults.[257] Nicol and colleagues estimated that improved housing in England alone could save the UK NHS more than €700 million per year in treatment no longer required.[258] In addition, Copenhagen Economics estimates that improvements in housing energy efficiency in Europe would, alongside the production of direct energy and health-care savings, reduce public subsidies for energy consumption hy €9–12 billion per year.[259] Various other health and ancillary benefits exist. Appendix 4 provides information about a recently developed framework to quantity key co-benefits.

It is apparent both that societies spend very large sums on health care and that measures to mitigate climate change would directly reduce existing and projected damages to health from the combustion of fossil fuels, and associated costs. In fact, Markandya and colleagues estimated that in India, if the health benefits of reduced $PM_{2.5}$ emissions alone, resulting from a 50% reduction in CO_2 emissions by 2050 (from 1990 levels) from electricity generation, were valued similarly to the approach used in the EU for air pollution, then they offset the cost of GHG emissions reductions in full.[215] As such, a significant proportion of expenditures for climate-change mitigation (and adaptation) may legitimately be seen as offsetting health expenditures, existing or anticipated, or even put forward itself as expenditure on the treatment and prevention of ill health. If a large part of the costs of climate-change mitigation and adaptation is offset by

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

improved health of the existing population, and if unabated climate change is itself a major health risk, investment in such actions is clearly an attractive and sensible proposition.

Investment required for mitigation and adaptation

In industrialised countries, large-scale investment in energy systems is required simply to maintain existing services as infrastructures age and need to be replaced. Emerging and developing economies will require very large energy system investments to meet growing demand as they develop and to provide increasing proportions of their populations with access to modern energy services. It is estimated that such business-as-usual investments will total around $105 trillion between 2010 and 2050, with average annual investment requirements rising rapidly over time.[260] However, this value excludes the costs of climate damage to the energy system or resilience measures to reduce it. Such costs could be significant.

The IEA estimates that to achieve a trajectory that produces an 80% chance of remaining on a 2°C stabilisation pathway, additional cumulative investment of $36 trillion in the energy system is required by 2050—roughly $1 trillion per year (in the order of 1% GWP under moderate growth assumptions or about 10% of existing expenditure on health care), although recent estimates from the New Climate Economy report suggest that this value may be a much reduced $270 billion per year.[260,261] The insurance premium represented by this additional investment is very modest in relation to the potential costs that are being avoided, even without the offsetting health and other co-benefits such as those described above. To achieve both the requisite level of decarbonisation whilst meeting increasing global demand for energy, the IEA estimates that investments in low-carbon technologies and energy efficiency must account for around 90% of energy system investment by 2035.[262] Currently, this value is around 23%.[262]

Estimates for the investment required for adaptation measures to protect against climate impacts to which the world is already committed are limited. The most comprehensive global estimate thus far was produced by the World Bank (2010), which estimates the annual global cost of adaptation even on a 2°C trajectory to be $70–100 billion by 2050.[171]

Estimating existing expenditure on adaptation actions is not much easier than estimating the possible future costs of adaptation. Buchner and colleagues[263] estimate that in 2012, about $22 billion was invested in activities with an explicit adaptation objective. However, the lack of common agreement on what constitutes an adaptation measure over other investment classifications and objectives mean understanding of existing financial flows to adaptation measures is poor. Even so, whilst the magnitude is difficult to determine, it is reasonable to conclude that existing financial flows for climate change adaptation are not sufficient to match long-term requirements, even for impacts resulting from current and past emissions.

Macroeconomic implications of mitigation and adaptation

The macroeconomic impacts of climate change

Attempts to estimate the marginal social cost of CO_2 emissions in the absence of mitigation or adaptation measures have produced an extremely wide range of results, spanning at least three orders of magnitude.[264] Table 3 illustrates the multifaceted, diverse, and potentially extreme nature of the impacts involved.

The IPCC's AR5 chapter on impacts, adaptation and vulnerability estimates an aggregate loss of up to 2% GDP if global mean temperatures reach 2·5°C above pre-industrial levels.[266] A world of unabated GHG emissions, what might be called a business-as-usual pathway (in which a global mean temperature increase is likely to far exceed 2·5°C, and in which many of the kinds of impacts in the last row and column of table 3 are likely to be experienced) could produce costs equivalent to reducing annual GDP by 5–20% now, and forever, compared with a world with no climate change, according to the Stern Review on the Economics of Climate Change.[267]

It may be noted that these costs are the result of a low discount rate, the validity of which has been questioned.[268] However, the relevant point here is that the physical impacts underlying the upper range of these costs represent a substantial risk to human societies—what Weitzmann[269] has called the "fat tails" of climate-risk distributions. The costs of mitigation may be seen to represent a premium paid to reduce these risks and, hopefully, avoid the worst climate outcomes entirely. In any case, even these large costs derive from economic models built upon climate science and impact models, which themselves necessarily cannot fully characterise all processes and interactions known to be of importance.[270]

The macroeconomic impacts of responding to climate change

The theoretical microeconomics position on the balance to be struck between mitigation and adaptation is clear—there should be investment in mitigation up to the point

	Market	Non-market	Multiple stresses and socially contingent
Projection (trend)	Coastal protection, dry-land loss, energy (heating and cooling)	Heat stress, wet-land loss, ocean acidification, ecosystem, migration and termination	Displacement from coastal zones, regional systemic impacts
Climate variability and (bounded) extremes	Agriculture, water, storms	Loss of life, biodiversity, environmental services	Cascading social effects, environmental migration
System changes and surprises	So-called tipping-point effects on land and resources	High-order social effects, irreversible losses	Regional collapse, famine, war

Adapted from Grubb et al, 2014.[265]

Table 3: Social cost of CO_2 emissions—assessment framework

where the marginal cost of further investment is higher than the marginal cost of adaptation plus that of remaining climate damages. In practice, the robust identification of this point is impossible, because of the uncertainty of the costs concerned and how they will develop over time, the difficulties of valuing non-market costs, and the lack of consensus over the appropriate discount rate for such costs, when they are incurred over long and varied time periods.[271] Given that some climate impacts (such as the phenomena in the bottom-right corner of table 3) cannot be adapted to at any computable cost, mitigation-focused investment would seem to be the prudent priority at a global level. In a globally interdependent world, even regions that might be less negatively affected by climate change itself, could expect considerable economic and social disruption from those regions that were thus affected.

The macroeconomic impacts of reducing CO_2 emissions derive from several sources, all of which need to be taken into account if the overall impact is to be properly evaluated. First, there are the impacts of the various kinds of investments discussed above. Investments in energy efficiency measures and technologies are often cost effective at prevailing energy prices, and there is substantial evidence that opportunities for such investments are considerable.[272] Such investments will themselves tend to increase GDP. Investments in low-carbon energy that are redirected from fossil fuel investments will, where the low-carbon energy is more expensive than fossil fuels and leaving out considerations of avoided climate change and co-benefits, tend to reduce GDP. However, if fossil fuel prices increase from their currently relatively low levels and remain volatile, and the capital costs of renewables (especially solar and wind) continue to fall, then at some point renewable electricity may become economically preferable to fossil-fuel derived power, irrespective of other factors.

Investments in low-carbon energy that are additional—such as the extra $1 trillion required annually as identified above—may increase or reduce GDP depending on whether they employ unutilised resources or, in a situation of full employment, crowd out more productive investment, and whether they can build domestic supply chains and new competitive industries that can substitute for imports. Whilst employment in fossil fuel-related and emission-intensive industries would decline over time, low-carbon technology industries would expand and increase employment. IRENA estimate a net global increase of 900 000 jobs in core activities alone (i.e. not including supply chain activities), if the level of renewable energy in global final energy consumption doubles from 18% in 2010 to 36% of by 2030.[253] Advantages may accrue to those countries or industries that begin investment in decarbonisation quickly, by gaining technological leadership through experience and innovation, affording the first mover a competitive edge in a growing market.

For fossil-fuel importing countries, investment in indigenous low-carbon energy sources will reduce the need to import fossil fuels. In the EU, the trade deficit in energy products in 2012 was €421 billion (3·3% EU GDP),[273] and is projected to rise to €600 billion (in 2010 euros) by 2050, as the EU's dependence on foreign fossil fuels increases.[274] Low-carbon investments that reduce the need to import fossil fuels are macroeconomically beneficial, with the value of these trade effects in the future being uncertain and dependent on the price of oil and other fossil fuels. Such uncertainty is itself a cost, which is amplified when allied with price volatility—a common characteristic of fossil-fuel markets.

Possible sources of finance

In the public sector (aside from the extensive resources to be found in local, regional, national, and supranational government budgets), sovereign wealth funds, as of August 2014, held over $6·7 trillion in assets.[275] However, in the private sector, institutional investors held a global total of $75·9 trillion in assets under management in 2013 (this includes $22·8 trillion with pension funds, $24·6 trillion with insurance companies, and $1·5 trillion in foundations and endowments).[276]

Institutional investors are likely to be critical sources of finance for mitigation and adaptation due to the scale of resources available and the presence of long-term investment obligations. However, only 0·1% of institutional investor assets (excluding sovereign wealth funds) are currently invested in low-carbon energy infrastructure projects ($75 billion).[277] Commercial banks are also a key source of finance and are one of the main existing sources of renewable investment capital. The resources held by non-financial companies are also extensive, with the largest 1000 such companies estimated to hold $23 trillion in cash reserves.[278]

International financial institutions (IFIs) such as the Bretton Woods institutions and other multilateral development banks (MDBs), multilateral finance institutions (MFIs), and regional investment banks (RIBs), whilst not holding collective assets to match those above, are also leaders in existing mitigation and adaptation finance, and are likely to be key in building a low-carbon economy in developing countries; their mandates are explicitly focused on development and poverty reduction promoted through low-interest, long-term loans—suitable for large infrastructure projects. Existing dedicated funds for climate-change mitigation and adaptation under the UNFCCC, such as the Green Climate Fund (GCF), are also important resources. The GCF, established by the UNFCCC in 2010 and launched in 2013, aims to raise $100 billion of new and additional funding per annum from industrialised nations, by 2020 (from both public and private finance), to support mitigation and adaptation pathways in developing countries. In 2012, $125·9 billion of official development assistance (ODA) was delivered by donor countries, equivalent to 0·29% of their combined gross national income (GNI). Were states to meet their ODA commitments of 0·7% of GNI, another $174·7 billion would be mobilised.[279]

Enabling architecture and policy instruments

The mobilisation of such financial resources requires robust policy-generated incentive frameworks, underpinned by credible political commitments. By the end of 2013, 66 countries had enacted 487 climate mitigation and adaptation-related laws (or policies of equivalent status), with a rich diversity of approaches.[280] The Stern Review considered that a policy framework for CO_2 abatement should have three elements: carbon pricing, technology policy, and the removal of barriers to behaviour change.[267] This three-part classification maps closely to three policy pillars, which in turn correspond to three different domains of change.[265] Figure 16 illustrates this framework, which can be applied to develop both mitigation and adaptation policy.

Each of the three domains reflects three distinct spheres of economic decision making and development. The first, satisficing, describes the tendency of individuals and organisations to base decisions on habit, assumptions, and rules of thumb, and, to some extent, the presence of psychological distancing (discussed in section 5). Such occurrences are the subject matter of behavioural and organisational economics, which can explain the significant presence of unutilised opportunities for already cost-effective energy efficiency measures. The first pillar of policy, standards and engagement, seeks to address these issues, resulting in firms and individuals making smarter choices. The second domain, optimising, describes the rational approach that reflects traditional assumptions around market behaviour and corresponding theories of neoclassical and welfare economics. The second pillar of policy, markets and pricing, seeks to harness markets, mainly acting through producers rather than consumers, to deliver cleaner products and processes. The final domain, transformation, uses insights from evolutionary and institutional economics to describe the ways in which complex systems develop over time under the influence of strategic choices made by large entities, particularly governments, multinational corporations and institutional investors. The third pillar of policy arising from such analysis seeks to deliver strategic investment in low-carbon innovation and infrastructure.[265]

Each of the three domains and policy pillars, whilst presented as conceptually distinct, interact through numerous channels. For example, as figure 16 illustrates, whilst the impact of each policy pillar is strongest in one domain, each of the pillars of policy have at least some influence on all three domains. All three pillars of policy have an important role in producing a low-carbon global energy system.[265]

Standards and engagement

Energy efficiency standards may take many forms. However, all act to push a market, product or process to higher levels of efficiency (or lower levels of emission intensity), through regulation. Such regulations help to overcome market failures such as split incentives, a prominent example of which is the landlord–tenant problem, when the interests of the landlord and tenants are misaligned. The problem arises because, whilst the installation of energy efficiency measures would benefit the energy bill-paying tenant, savings do not accrue to the landlord who therefore has no incentive to bear the cost of installing such measures. Instead, standards can require their installation, or other measures to induce the same effect.

The main typologies of standards relating to mitigation are CO_2 intensity standards, energy intensity standards and technology standards. The first two specify a target limit for specific CO_2 emissions or energy consumption. Examples are a cap on CO_2 emissions from passenger cars per kilometre driven (based on the average rating for all cars sold per manufacturer), or on the annual energy consumption of a new building per unit of floor area. Both such policies (and variants) have been successfully implemented in the EU and around the world, and have proven effective. Technology standards may act in a similar manner to CO_2 or energy intensity standards, but may also proscribe the use of certain components in products, or prevent the sale of the least efficient models of a product type. Such standards may be applied with a legal basis, or through the use of voluntary agreements. Standards may also be applied to produce adaptation actions, for example by amending building codes to obligate developers to incorporate resilience measures in new construction.

Processes and mechanisms for targeted communication and engagement between governments, businesses, other organisations, communities and individuals help to overcome issues of psychological distancing,

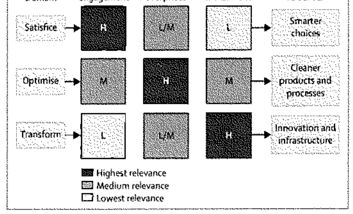

Figure 16: Three pillars of policy
Adapted from Grubb et al, 2014.[265]

motivational issues, split incentives and information asymmetry, and act to pull the market towards higher efficiency, lower emissions and greater resilience. Such mechanisms can take many forms and include training and education campaigns, but also labelling and certification, public reporting and other information disclosure and transparency measures. All these approaches act to provide consumers and investors with information surrounding environmental performance of a product, service, process or organisation at the point of use, or across the product lifecycle or organisational operations and supply chain, in order to help them to make informed decisions regarding investments and purchases. This encourages organisations to mitigate risks by reducing organisational (and possibly supply chain) emissions and to invest in adaptation measures to improve resilience, ensuring they retain a strong customer base and remain a safe investment. The introduction of these instruments may also reveal opportunities for efficiency measures that have an economic rationale independent of environmental considerations.

Markets and prices

The Stern Review called the market externality of GHG emissions in the global economy "the greatest and widest-ranging market failure ever seen".[267] Carbon pricing is the economist's preferred means to address this externality. Such pricing may be achieved through national or regional explicit carbon taxes or cap-and-trade emissions trading systems (ETS), which are increasingly present around the world. A carbon tax sets the carbon price directly, but not the level of abatement, whilst an ETS sets the level of abatement, but the price derives from the carbon market. Regardless of the pricing mechanism, market actors may be expected to factor the existing and expected carbon price into short-term operational and long-term investment decisions. Figure 17 summarises the state of pricing mechanisms around the world. As of June 2014, around 40 national and over 20 subnational jurisdictions were engaged in carbon pricing of varied scope and instrument design, covering about 12% of annual global GHG emissions (the Australian ETS was discontinued in July 2014).[281] The largest ETS is the European ETS, established in 2005, and capping more than 40% of annual GHG emissions from power generation and energy-intensive and emission-intensive heavy industry across the EU-28 (plus Norway, Iceland, and Lichtenstein). This is followed in scale by the aggregate of the seven ETS pilot schemes in China, described in appendix 5. As of 2014, the total value of all explicit pricing mechanisms was around $30 billion.[281]

See Online for appendix 5

For sectors of the economy for which explicit carbon pricing is infeasible or administratively burdensome, taxes on energy products (such as transport fuels) could be realigned to reflect their carbon content (producing an implicit carbon price) By implementing Environmental Tax Reform (ETR) principles, in which the burden of taxation increases on environmentally damaging activities and is reduced on desired inputs, such as labour, the increase in energy prices can be neutralised from a macroeconomic perspective. Parry and colleagues estimate that corrective taxation that internalises CO_2 emissions, local air pollution, and additional transport-related externalities (such as congestion and accidental injury) arising from coal, natural gas, gasoline, and diesel, could raise additional revenues of 2·6% GDP globally, whilst simultaneously reducing CO_2 emissions by 23% and pollution-related mortality by 63%.[282] If this revenue was used to offset labour taxation (eg, by a reduction in payroll or other corporate taxation), revenue neutrality is achieved whilst producing a double dividend effect of employment, as well as environmental improvement.[283] Alternatively, carbon pricing mechanisms can be used to finance, subsidise, or otherwise incentivise investments into other mitigation and adaptation measures, as discussed below.

In addition to pricing pollution, distorting subsidies for the extraction and consumption of fossil fuels should be removed. For consumers, such subsidies (aimed at providing energy at below market price, and principally applied in developing countries) total around $400 billion annually,[284] whilst producer subsidies (aimed at sustaining otherwise uncompetitive production, principally applied in industrialised countries), are around $100 billion annually.[285]

Both fossil-fuel subsidies and the presence of externalities tend disproportionately to benefit the wealthiest in society (in both national and international contexts), as energy consumption (and associated emissions) increases with prosperity, both directly (eg, via additional travel demand, domestic heating and cooling requirements) and indirectly through additional consumption of energy embodied in products and services. Globally, an estimated 80% of such subsidies actually benefit the wealthiest 40% of the population.[286] However, the introduction of carbon pricing and the removal of fossil fuel subsidies may be regressive, as the poorest in society spend a greater proportion of their disposable income on energy. Reduced taxation of the low paid may partly offset this in industrialised economies, although further targeted support, such as the provision of energy efficiency measures for low-income or vulnerable households (funded by carbon price revenues and foregone subsidy), or the introduction of electricity tariffs differentiated by consumption level, is also likely to be required. In developing countries where most consumer fossil-fuel subsidies are provided, and where a greater proportion of the population is not employed in the formal economy or have no access to electricity, more targeted interventions to remove disproportionate effects on low-income households, such as the expansion of social security, health care, and education provision, will be required.

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

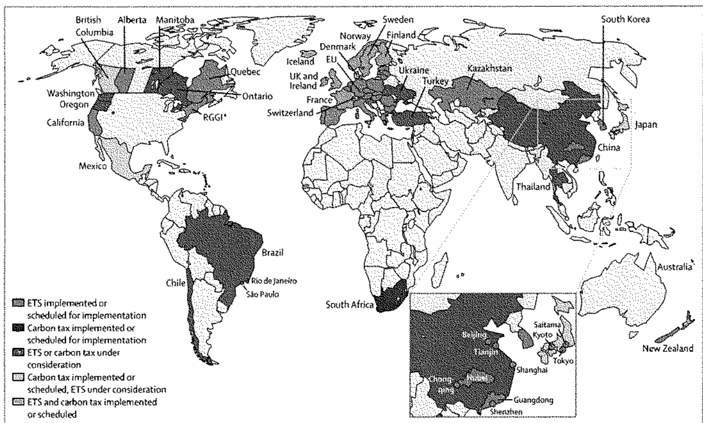

***Figure 17:* Existing, emerging, and potential regional, national, and subnational carbon pricing instruments (ETS and tax)[286]**
*The RGGI (Regional Greenhouse Gas Initiative) is a coordinated cap and trade programme, operating between nine Northeastern and Mid-Atlantic States in the USA and Canada. ETS=emissions trading scheme.

Strategic investment

Whilst a price on carbon is a key component for mitigation, it is technologically agnostic and mainly encourages the adoption of mature low-carbon technologies. To encourage deployment, improvement and cost-reduction of less mature technologies, direct investment is also required. Although various options exist, Feed-in tariffs (FiTs), used in the electricity sector to provide a guaranteed rate of return to low-carbon generators, have been the most effective policy instrument used for this purpose, and have been responsible for a significant majority of installed global renewable power capacity (appendix 6). A FiT-style instrument may also be used to encourage the deployment of non-electric renewable technologies, including heating and cooling options.

However, FiTs and comparable instruments only encourage diffusion and incremental improvements for technologies around the end of the innovation chain (market accumulation and diffusion). For technologies in the earlier stages (applied research to demonstration and commercialisation), concerted R&D efforts are required, comparable to public and private pharmaceutical research that has been shown to produce innovative new drugs.[287] Such efforts may be analogous to the Manhattan Project for nuclear technology, or the Apollo Program for space flight, but focused perhaps on energy storage technologies, which are often seen as crucial for the effective decarbonisation of the global energy system.

Public-led strategic investment is also required in urban low-carbon travel infrastructure (eg, segregated cycle lanes), along with investment in electric-car charging points. This also applies to the electricity transmission network, which is under state ownership in most countries. Such investments may be financed in a number of ways, including directly by governments, multilateral organisations, or other public bodies, through the use of carbon pricing revenues or by the issuance of specialised climate bonds (appendix 7).

See Online for appendix 7

Institutional reform and support

See Online for appendix 6

Beyond the appropriate selection of policy instruments and timeframes for implementation, investments in decarbonisation and adaptation measures will depend on the existence of effective and supportive governance and well-functioning markets. Good governance requires the well-defined division of responsibilities between government departments, agencies and hierarchies, enforcement of standards and regulations, transparency at key stages of the regulatory process and subsequent monitoring and reporting, and effective communication and stakeholder engagement. Additionally, governments are often the largest consumer in the market, with public spending accounting for 15–30% of GDP in any given country.[288] Sustainable public procurement (SPP) policies act to provide a market for efficient, low-carbon goods and services.

Governments may promote well-functioning markets through the kinds of policies described above, and by reducing institutional barriers to low-carbon investment and innovation. For example, many pension funds across the world are barred from investing in infrastructure, including all in China (except the National Social Security Fund) and many in the EU. Whilst these regulations aim to alleviate legitimate concerns (such as preventing pension funds from becoming an extension of government budgets), they are often excessive and increasingly irrelevant as funds gradually become independent of political interference.[276] Reform of such rules is essential in mobilising capital from institutional investors, irrespective of the policy and incentive mechanisms in place to encourage investment in developing the low-carbon economy.

Section 5: delivering a healthy low-carbon future

Central to this Commission's work is the question of whether human societies can deliver a healthy, low-carbon future. Sections 1 and 2 have explained the scientific basis for concern, the potential health dimensions of impacts, and the adaptation responses required. Sections 3 and 4 have demonstrated the technological and economic feasibility of tackling the problem. Yet over the past decade, global emissions have still risen sharply. The evidence to date of humanity's ability to respond effectively is not encouraging. The difficulty, essentially, is ourselves: the tendency of humans to ignore or discount unpleasant facts or difficult choices (something familiar to doctors); the nature of companies and countries to defend their own rather than collective interests (something familiar to those working in global health); and the narrow, short-term horizons of most human institutions, which feed into the difficulties of global negotiations.

Over the past century, the world has made enormous strides in overcoming similar obstacles in the field of health, with international cooperation on health challenges as a shining example. The problem of anthropogenic climate change is more recent, arguably more complex, and the efforts to tackle it more nascent. But there are some promising developments, and a great deal can be learned by examining the history of efforts to date.

One conclusion evident throughout our report is that much of the technical expertise, technology, and finance required to turn climate change from a public health threat into an opportunity is readily available, but politically restricted. In essence, whether we respond to "the biggest global health threat of the 21st century" is no longer a technical or economic question—it is political. This section analyses the politics of climate change and provides suggestions for action. We examine the international regime (under the UN Framework Convention on Climate Change and its Kyoto Protocol); national policy responses; the role of sub-national governance processes, particularly in major cities; and the importance of individuals and public opinion. Importantly, we stress the need for better synergy between top-down and bottom-up approaches. We seek to draw lessons from global health governance mechanisms, and make suggestions for how health-related issues can inform the climate change negotiation process.

Three phases of response—the international regime

It is almost 30 years since climate change emerged onto political agendas, with three phases of response since then, of roughly a decade each.

First phase: understanding the evidence and establishing institutions and broad goals

The first phase established the institutional basis for responding to climate change, including for scientific input into policy processes. Building on long-held concerns of the scientific community, a series of international workshops in the mid-1980s, hosted by the World Meteorological Organisation and the UN Environment Programme, led governments to establish the IPCC in 1988, as the official channel of scientific advice to the international community. In 1990, the IPCC's first report expressed enough concern for governments to formally launch international negotiations aimed at tackling the problem, and 2 years later to agree on the UNFCCC. The UNFCCC now enjoys almost universal membership.

The UNFCCC established the "ultimate objective" of stabilising GHG concentrations at a level that would prevent dangerous human interference in the climate system (UNFCCC, article 2). This objective has been recently interpreted as implying that global temperatures should not rise more than 2°C above pre-industrial levels, an aim reiterated in frequent statements under the UNFCCC and other international fora, such as the G8. The 2°C goal implies a need to roughly halve global emissions by 2050; stabilising the atmosphere at any level ultimately means bringing net emissions (emissions minus removals from forests, oceans, and other carbon sinks) to zero.

The UNFCCC established that industrialised countries would take the lead in curbing GHG emissions, setting them a non-binding goal of returning their emissions to 1990 levels by 2000. All parties, including developing countries, were given general commitments to address climate change, as well as reporting obligations. The UNFCCC also set up a raft of institutions to monitor implementation and pursue ongoing negotiations, under the auspices of the main decision-making body, the Conference of the Parties (COP).

Health concerns feature, albeit in general terms, in the UNFCCC, which lists impacts on human health and wellbeing as part of the adverse effects of climate change (definitions, article 1). The only other reference requires

 www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

parties to consider the broader implications of their mitigation and adaptation actions on human health.[299]

Second phase: leading through top-down international commitments

In 1995, governments accepted the findings of the IPCC's second report and launched negotiations to strengthen the UNFCCC's commitments. The working assumption was that the international response would be led by specific, binding emission targets for industrialised countries, which would then be implemented at a national level. This was the approach adopted in the Kyoto Protocol of 1997, which built mainly on designs proposed by the USA under President Clinton.

However, the fact that developing countries were not subject to any such specific commitments weakened the Protocol's short-term impact and undermined its political viability, particularly in the USA, where strong political forces were opposed to any robust action on climate change. The subsequent US repudiation of the Kyoto Protocol made it clear that the Kyoto-type top-down model was unworkable in these circumstances as the principal way forward.

Third phase: bottom-up initiatives

Global negotiations continued, but with widely varying objectives and perceptions. Whilst the EU and developing countries continued to support a Kyoto-style approach with specific targets, few others believed that to be feasible, or even appropriate. Academics and commentators increasingly argued that action happens from the bottom up, not in response to binding top-down commitments, and pointed to a wide range of initiatives, including at state level in the USA, to argue that a fundamentally different approach was needed.

These divergent views came to a head at a summit in Copenhagen in 2009, which collapsed in acrimony save for two pages of unofficial outline text hammered out as a fallback compromise, initially between the USA and major emerging economies. The so-called Copenhagen Accord did register some landmark achievements, notably confirming the 2°C goal, and a promise to raise $100 billion per year of international finance by 2020 to help developing countries deal with climate change. In terms of emission commitments, however, there were no binding targets; instead, the Copenhagen Accord called on countries to declare domestically-generated voluntary pledges of what they might deliver. Since then, almost all major emitters have registered pledges, although based on varying indicators and with very different levels of precision and ambition.

Negotiations in Durban in 2011 saw the launch of a new round of talks aimed at agreeing a universal framework to deal with climate change from 2020. According to the so-called Durban Platform, this new agreement should be applicable to all parties, and "raise the ambition" of the international community.

Patchy progress in the negotiations

If global emission trends are the only indicator of progress, the results of the negotiations to date have been dismal. The 2014 IPCC report warned that global emissions since 2000 have been rising ever faster at around 2% every year, powered largely by spectacular growth in China, and other emerging economies.[301] Viewed more closely, the picture is more nuanced. Taken together, the industrialised countries did meet the UNFCCC's goal of returning their emissions to 1990 levels by 2000 (helped by massive declines in the former Soviet Union and Eastern Bloc). The industrialised countries that accepted targets under the Kyoto Protocol and remained parties to that agreement also all achieved their official goals. There is no question that in the EU, the Protocol provided the legal framework and impetus for strengthening mitigation policies.

The international process has also had successes in other areas. Through the Kyoto Protocol's Clean Development Mechanism (CDM), many developing countries came forward with new projects that generated cheap emission reductions (that could then be sold on to industrialised countries), and by most accounts contributed to the establishment of renewable energy industries and other low-carbon technologies. Through a levy on CDM transactions, the Kyoto Protocol also established a fund to help finance adaptation measures in developing countries.

The UNFCCC also provides a crucial ingredient of transparency. A major achievement has been in establishing a robust system of reporting and review, for both national emissions data and broader policy actions. In 1992, when the UNFCCC was adopted, many countries had very little knowledge of their emissions profile—ie, what GHGs they were emitting and from what sources. The UNFCCC's provisions, building on the IPCC's methodological work, have been crucial in filling that knowledge gap, which lays the foundation for an effective response to climate change.

Despite patchy progress, the global negotiations continue, and indeed are regaining momentum. It is likely that the hybrid course set out in the Copenhagen Accord, and ratified in 2010 by the Cancun Agreements, of domestic aspirations, policies, and objectives will define the primary ingredients of a future global agreement. Perhaps most importantly, it is also now clear that international agreements must run concurrent with (rather than precede) implementation efforts. The future of the international negotiations will inevitably have to combine elements of top-down and bottom-up policies within the global framework.

One indication of both the opportunities and challenges is found in a joint US–China agreement of 2014, in which the US Administration pledged to reduce its emissions by 26–28% below 2005 levels by 2025, and China offered to cap its emissions growth by 2030, or sooner if possible. On the positive side, this is the first time that any major emerging economy has stated it is willing to cap its emission growth in absolute terms, and interactions between the USA and China helped each to a new level of commitment.

On the negative side, it illustrates the scale of the gap between science and action: if viewed in terms of per-capita emissions, it means that the USA is planning to come down somewhat below 15 tCO_2 per capita, whilst China wants headroom to reach potentially 10 tCO_2 per capita by 2030, before declining. This is a far cry from the scientific goals—a 2°C limit implies the need for a global average close to 2 tCO_2 per capita by mid-century. It emphasises that in isolation, such decentralised policy action also seems unlikely in the aggregate to deliver the necessary global mitigation effort effectively, equitably, and efficiently, and points to the risks of abandoning any collective, science-led direction to the global effort.

There are indeed reasons for concern regarding the international regime's ability to deliver on its promise.[290] The international relations literature has tended to assume that regimes start off weak, but as scientific evidence hardens and political will increases, parties agree to ratchet up their commitments and the regime strengthens; this was clearly the assumption of the early climate change negotiators.[291,292] It is difficult to say, however, whether the climate change regime is now getting stronger or weaker. On the one hand, the regime's coverage is expanding and deepening among the developing countries parties. The voluntary approach of the Copenhagen Accord and Cancun Agreements has engaged a much wider group of countries, including all major emitters, into national target-setting. At the same time, the Durban Platform mandate implies that all countries, not just the industrialised ones, are expected to raise their ambition in the new post-2020 regime. On the other hand, the engagement of industrialised countries is weakening compared with in the 1990s and early 2000s, with major emitters, such as Canada, Japan, Russia and, of course, the USA, now operating only under the Copenhagen Accord and Cancun Agreements, whose targets are voluntary and not subject to common metrics.

See Online for appendix 8

The outlook for future international negotiations is therefore challenging, to say the least. The rest of this section turns to consider reasons why progress on this issue is so difficult (from both a top-down, and bottom-up perspective), and what can be done to change this.

The generic barriers

The technological, investment, and behavioural changes needed to meet ambitious long-term goals, as illustrated in sections 3 and 4, are, in principle, entirely feasible. But they need to be accomplished in the face of highly diverse social, cultural, economic, and political contexts. Opposing national (and vested) interests, clashing views of what constitutes fair distribution of effort, and a model of economic growth that is currently tied to fossil fuel use, can make progress fraught. There are several key issues, as outlined by Hulme, 2009:[293]

- Uncertainty and complexity. The climate is naturally variable and the science that has identified dangerous, anthropogenic climate change to a very high level of probability is complex. This leaves considerable room for public ignorance or misunderstanding of the nature and severity of the issue. Moreover, climate scientists can be ineffective at communicating the issue to the public.[294]
- Climate change is psychologically distant along four dimensions—temporal, social, geographical, and degree of uncertainty—whereas people tend to connect more easily with issues that are close in time, space and social group, and about which there is little uncertainty. These dimensions interact with each other, all tending to dampen concern and willingness to act.[295]
- There is enormous lock-in to current economic patterns.[296] Fossil-fuel use is at the heart of the industrial economy, often operating through long-lived infrastructure (eg, roads, buildings, and power plants) and enabling valued dimensions of modern lifestyles (eg, travel and temperature control in buildings). It is no exaggeration to say that human societies are addicted to fossil fuels, or at least the services they provide. Providing these valued services through alternative, lower-carbon means requires systemic change over a long period.
- These three factors can all come together in a fourth: the active promotion of misinformation, motivated by either ideology or vested economic interests. Here, parallels can be drawn between public health efforts to reduce tobacco consumption (appendix 8). It is estimated that US industry spent close to $500 million in its successful campaign against the 2010 House of Representatives proposal to cap US emissions. A major study of the Climate Change Counter Movement in the USA identifies funding of around $900 million annually.[297]

These obstacles are further compounded by the economic characteristics of responses. Low-carbon technologies are generally more capital-intensive than their fossil-fuel alternatives, albeit with much lower running costs. Their implementation therefore requires more upfront investment and a longer time horizon, resulting initially either in higher energy prices or higher taxes, or some combination of the two. The same is true of most adaptation measures; flood protection defences, for example, are capital-intensive investments with uncertain returns.

A large-scale shift to such technologies will require very large investments over a prolonged period of time. This shift in financial flows will need to be incentivised, in the early periods at least, by strong, consistent, and credible public policies, and a change in financial structures. Such policies are far from easy to introduce

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

and sustain, given other political priorities that may be perceived as more pressing, and the political complexities indicated above.

Cities, states, and provinces: progress at the subnational level

Despite all these obstacles, action does continue in varied ways, at many levels. Local issues have long been part of the broader agenda of international environmental politics, and local governments have an increasingly well-documented track record in climate action.

In the past two decades, cities have been pivotal in producing multiple policy-making frameworks and advocacy coalitions. This has fostered a thick texture of para-diplomatic links and policy action around climate change and environmental health.[298,299] The rise and cross-cutting international spread of cities as actors in climate action also evidences a more refined pattern of transnational connections that are not solely bottom up, but rather offer a level of governance from the middle that cuts horizontally across international and national frameworks, involving an expanding variety of public-private structures and offering a distinct variation on civil society models of climate action.[300,301]

The leaders of cities around the world, from major metropolitan hubs like New York and São Paulo, to smaller centres like Rabat or Medellin, are increasingly using the networked reach of their municipal governments to address climate change in ways that are often more flexible and more directly applied than those of the national or international levels. Evermore city leaders have been leveraging their network power through international networks such as the United Cities and Local Governments (UCLG), ICLEI Local Governments for Sustainability, the World Mayors Council on Climate Change and the Climate Leadership Group (or C40).[299]

These groups are now a well-established presence in the international climate change arena,[302] pointing to the emerging imprint on global environmental governance by city leaders.[301] Their most crucial contribution to climate action is that of leveraging city diplomacy to implement specific actions on the ground via municipal management and multi-city initiatives. In practice, this governance from the middle is about taking advantage of the pooled networked connections of cities to implement a plethora of initiatives aimed at direct and quick implementation, which then injects urban elements in wider international processes.

Among the networks of larger cities, there is an emerging pattern of their local policy priorities becoming aggregated under a single strategic issue, as seen in integrated planning, climate, and sustainability plans such as Sustainable Sydney 2030. Concurrently, climate action has taken place on municipal purview areas such as energy regulation, transport and mobility, building retrofit, or waste management. Major centres like New York or Tokyo, for instance, have implemented building energy retrofit schemes across their city infrastructures.

Taken together, such a two-headed agency can enable cities to collectively attract and therefore release investment capital to execute wide-ranging policy programmes (such as C40's Energy Efficiency Building Retrofit programme). This ability to leverage global capital by effectively generating a large single market can be highly influential insofar as the cities are able to act quickly, often within the space of a year, and increasingly represent a significant proportion of the world's population and energy generation. This stands by contrast with national governments, where climate policy is often subsumed within other priorities rather than as an organising aim across government.

City-level governance may also provide the flexibility and scope to include health in actions on climate change, with city leaders becoming key actors in recognising and responding to the health co-benefits of doing so. It is important that the UN-led international negotiations process takes account of this dimension of multi-level governance, which operates in both formal and informal ways.

Public opinion and behaviour

Ultimately, effective actions by local and national governments, and by businesses, are unsustainable without supportive public opinion. Public support for stronger action on climate change is a necessary, albeit far from sufficient, factor, and is essential if behavioural change is to contribute to solving the problem. In this respect, the evidence is somewhat mixed. Cross-national studies, such as the 2013 survey presented in figure 18, suggest that most people view climate change as a threat, although with some significant variation within regions.[304]

Public understandings of climate change are shaped by broader knowledge and belief systems, including religious convictions and political beliefs.[294] There is evidence that the public recognises that climate change is complex, and interconnected with other environmental and social challenges.[305] Effective communication about climate change requires trust.[306] The most trusted sources vary across time and place, and can include family and friends, environmental groups, scientists, and the media; local and city-level authorities may provide an important conduit for communicating information from trusted sources. For scientists to engage effectively with the public, however, they need to seek a greater understanding of prior knowledge and belief systems, and communication skills radically different from those of academia. They must move beyond traditional scientific discourse to convey a big picture of climate change with which members of the public can engage; this can then provide a context and framing for the discussion of new scientific results and their consequences.[294]

Public responses to climate change

The causes of climate change lie ultimately in human behaviour, in particular in the economies and lifestyles of rich societies.[307] However, it has been science, rather than social science, that has underpinned climate change communication and policy development.[308] There is as yet little evidence on how to change behaviours that contribute to climate change,[309] but taking broader evidence on the determinants of behaviour and behavioural change, four themes stand out.

First, knowledge deficits are not the primary barrier to action; knowing about the causes and consequences of climate change does not, on its own, motivate people to change their lifestyles.[310] Instead, it is emotions—the feelings that accompany thinking—that are central.[311] Negative emotions, including fear, pessimism, and guilt,

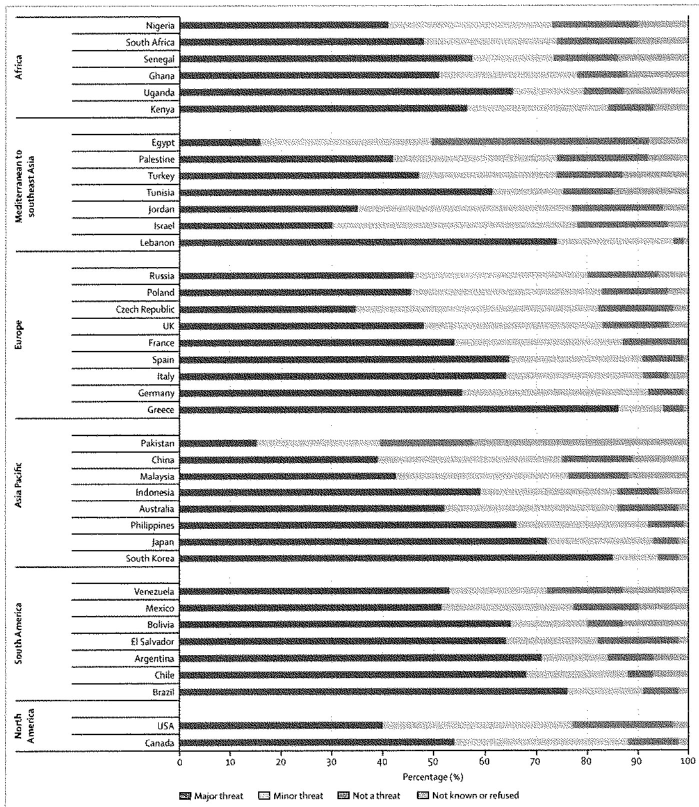

Figure 18: **Perceptions of the threat of climate change, 2013**[304]

www.thelancet.com **Published online June 23 , 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6**

can produce passive and defensive responses, and do little to encourage individuals to change their behaviour and to press for wider social action. So-called fear appeals only work if accompanied by equally strong messages about how to address the problem.[312] Representations of climate change as inexorably heading for catastrophe close off the possibility that individual and collective action can make a difference.[294]

Second, climate change is best represented in ways that anchor it in positive emotions,[313] by framing action in ways that connect with people's core values and identities. Examples include framing climate change as: an ethical and intergenerational issue; about safeguarding ancestral lands and the sanctity of the natural world; or an appreciation of the global injustice of anthropogenic climate change driven by rich countries but paid for by poorer ones.[107,314] Aligning climate change to a range of ethical positions and a core set of identities can offer a way of appealing to diverse social groups, and thus securing a broad and inclusive platform of public support for action. This could be facilitated by avoiding the rhetoric of climate catastrophe, and emphasising, instead, human capacity to steer a way to a sustainable future, including lifting the burdens that unmitigated climate change would otherwise impose on future generations.[313,315]

Third, integral to such an ethical framing of climate change is the implied duty on national and international organisations to take action. A recurrent finding is that the public sees the main responsibility for action lying with governments and other powerful institutions, not least because the options open to individuals to take radical action to cut their own GHG emissions are often sorely limited by cost or availability (eg, poor public transport provision). Public willingness to take action is also contingent on those considered responsible for climate change taking action themselves.[316] The majority of the public in cross-national surveys believe that their country has a responsibility to take action on climate change, and that their government is not doing enough.[317]

Fourth, many climate-affecting behaviours are habitual and resistant to change. Everyday domestic energy use (eg, cooking, heating the home), travel behaviour, and eating patterns are undertaken as part of a daily routine and without conscious thought. Such behaviours are resistant to change, even if alternative options are available, and interventions relying on increasing knowledge have limited effect.[318]

Conclusions

It is clear that in isolation, a top-down approach (international agreement followed by national legislation with which individuals and business must comply) to managing climate change is no longer a sufficient response. Other actors are already taking steps independent of any agreement to reduce their emissions, and a voluntary transformation to a low-carbon economy may already be underway. At the same time, as indicated throughout this report, these bottom-up initiatives have hardly, as yet, taken us any closer to the scale of global action required to protect human health against the risks of climate change, than has the decade of targets under the Kyoto Protocol.

Section 1 has underlined the way in which the continued acceleration of GHG emissions and atmospheric concentrations, mapped on to changing global demographics, is making climate change an increasingly severe risk to global health. Despite the threat that climate change poses to human development, it remains but one of many factors influencing decision makers, and rarely the most important one. Precautionary adaptation is clearly inadequate and prevailing patterns of energy production and consumption are still driving the world towards a dangerous climatic future. Current economic drivers of growth lock communities into patterns of energy use which no amount of reframing can change unless coordinated realignment of these drivers takes place. And the argument that others should be doing more to tackle climate change, because they are more to blame, remains one of the most politically potent excuses for inadequate action.

Thus the challenge, and the crucial test of the international process, will be finding a synthesis of top-down and bottom-up forces. An effective international agreement will be one that supports stronger efforts everywhere and at every level. The diverse worlds of bottom-up initiatives in cities, companies and many others should in turn help overcome the obstacles that impede the ability or willingness of national governments to commit to stronger national actions. To be truly effective, any future agreement will thus need not only to agree goals and aspirations, but also identify what is necessary at the international and national levels to achieve them. This may also require a mechanism, such as a feedback loop, that will motivate increased national ambitions over time. A system of review will be a crucial component, with regular assessments of the effectiveness of national policies, actions, and targets.

Section 6: bringing the health voice to climate change

Our studies point to multiple ways in which the health agenda may help accelerate the response to climate change. First are the positive lessons for international cooperation. No-one would suggest that national action to protect health should depend on a global, all-encompassing treaty. Yet few would deny that WHO and numerous other fora of international cooperation are important in accelerating, coordinating, and deepening responses to health challenges—particularly, but not exclusively, those with transboundary dimensions. The health experience neatly illustrates the falsity of the dichotomy between top-down and bottom-up: one measure of success is how each can reinforce the other. Learning from the health experience may illuminate the most effective actions at a particular level or levels of governance, and how the multi-level governance framework and international negotiation process can mutually reinforce actions at different levels.

Second, political lessons from health have particular, and largely encouraging, resonance for a climate dialogue increasingly characterised by pessimism about the ability to control the problem. The denialism of HIV, responsible for perhaps a million deaths, did eventually give way to global acceptance of the science. 50 years of tobacco industry resistance and obfuscation of the science on lung cancer has to a large extent been overcome, including with recognition embodied in WHO's Framework Convention on Tobacco Control, that governments have a duty to resist such lobbying forces.

Third, the health implications could and should be more effectively harnessed in efforts to build support for a stronger response to climate change. The health impacts of climate change discussed in this Commission are not well represented in global negotiations, but they are a critical factor to be considered in mitigation and adaptation actions. A better understanding of the health impacts of climate change can help to drive top-down negotiations and bottom-up action in many realms. A sophisticated approach is needed, which draws on the universal desire to tackle threats to health and wellbeing (without any particular philosophical slant), in order to motivate rapid action, and a policy framing that is more human than purely environment, technology, or economy focused. This requires making the impact of climate change on people explicit, rather than implicit. By considering directly how climate change will impact on human health, we are naturally drawn to the human component of climate impacts, rather than the environmental (flooding, forest fires) or more abstract effects (the economy, the climate). This supports a human framing of climate change, putting it in terms that may be more readily understood by the public. Fostering such public resonance can act as a powerful policy driver: public pressure is, of course, a crucial factor motivating both national governments and their negotiators in the international arena.

Fourth, local health benefits could in themselves help to drive key adaptation and mitigation actions. The numerous health co-benefits of many adaptation measures were emphasised in section 2, whilst section 3 noted substantial health co-benefits of many mitigation measures. Examples of the latter include the reduced health risks and costs when populations live in well-insulated buildings, and the reduction in air pollution (and other health) damages associated with fossil fuel use, which, as noted, even in strictly economic terms typically amount to several percent of GDP, as well as adding directly to the strain on limited health-care resources. With the direct costs of deep cuts in emissions estimated at around 10% of global expenditure on health, both the direct and indirect health dimensions should be a major driver for mitigation efforts. It is also commonly seen that responding to climate change from a public health perspective brings together both mitigation and adaptation interventions, yielding powerful synergies.

Fifth, analogies in health responses can also help to underline that there is rarely a single solution to complex problems: different and complementary measures are required to tackle different dimensions, and pursuing both prevention (mitigation) and treatment (adaptation) is crucial:

With severely ill or vulnerable patients, the first step is to stabilise the patient and tackle the immediate symptoms. Helping poor countries particularly to adapt to the impacts of climate change is similarly a priority. But as noted in section 2, adaptation cannot indefinitely protect human health in the face of continuing and accumulating degrees of climate change, any more than tackling the symptoms will cure a serious underlying disease.

- For infectious diseases, antimicrobials and a functioning health system to produce, distribute, and administer drugs effectively are essential components. The obvious analogy here is with specific greenhouse gas mitigation policies, such as energy efficiency programmes and technology programmes that span the full spectrum from R&D through to policies to support industrial scale deployment and related infrastructure.
- Deeply-ingrained patterns of behaviour are best addressed by comprehensive approaches and the use of multiple policy levers. Evidence from studies of health behaviour change suggests that, to be sustained, changes in the individual's everyday environments are required. Structural levers are also important for addressing social inequalities in harmful behaviours. Such evidence could be harnessed to inform policies to address climate change—eg, the behaviour change checklists developed to guide policy to reduce tobacco use and tackle harmful alcohol consumption may be particularly useful. Applying lessons from health behaviour change may help to accelerate policy development, building an evidence platform for interventions to promote mitigative and adaptive behaviours.
- As with the evolution of drug-resistant bacteria, the challenges of drug addiction, or the rising health problems of obesity, medical fixes cannot solve all health problems. Similarly, in our energy systems, specific mitigation policies and projects are constantly faced with the ingenuity of the fossil fuel industry in finding and driving down the costs of extracting new fossil fuel resources and marketing them. The long-term antidote is more analogous to programmes of sustained immunisation, education, incentives, and enforcement, all oriented towards supporting healthier lives.

 www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60854-6

The single most powerful strategic instrument to inoculate human health against the risks of climate change would be for governments to introduce strong and sustained carbon pricing, in ways pledged to strengthen over time until the problem is brought under control. Like tobacco taxation, it would send powerful signals throughout the system, to producers and users, that the time has come to wean our economies off fossil fuels, starting with the most carbon intensive and damaging like coal. In addition to the direct incentives, the revenues could be directed to measures across the spectrum of adaptation, low-carbon innovation, and the global diffusion of better technologies and practices. As outlined in section 4, carbon pricing thus has immense potential, particularly when embedded in comprehensive policy packages. This most powerful antidote, however, still faces many political obstacles.

The crux of the matter is that stabilising the atmosphere at any level ultimately requires reducing net emissions to zero. A healthy patient cannot continue with indefinitely rising levels of a toxin in the blood; even nutrients essential to a healthy body (like salt) can become damaging if not stabilised. The climate-change analogy is obvious and focuses global attention on the need to stabilise atmospheric concentrations, which in climate terms, means getting net emissions (that is, emissions minus removals by forests, oceans, and other sinks) to zero. On most scientific indicators, it means getting to zero during the second half of this century. A unifying goal, therefore may be a commitment to achieve zero emissions based on multiple partnerships involving different actors. If any region can achieve net zero, there is no fundamental reason why that should not become global. Getting to net zero also focuses us on a common task: how to get there, which is potentially harder for the societies that have become more dependent on fossil fuels, whilst in developing countries, it sends a clear signal that the sooner their emissions can peak, the better for their own path towards that common goal. If the goal is net zero, all actors in all societies have a sense of the direction of the international framework for action in order to protect everyone's health against the risks posed by continual increases in the global concentration of heat-trapping gases.

A Countdown to 2030: global health and climate action

If we are to minimise the health impacts of climate change, we must monitor and hold governments accountable for progress and action on emissions reduction and adaptation. One might argue that action on climate change is already effectively addressed by the IPCC, World Bank, UNFCCC, WHO, and the G20. We believe, however, that the health dimension of the climate change crisis has been neglected. There are four reasons why an independent accountability and review process is warranted:

1 The size of the health threat from climate change is on a scale quite different from localised epidemics or specific diseases. On current emissions trajectories there could be serious population health impacts in every region of the world within the next 50 years.
2 There is a widespread lack of awareness of climate change as a health issue.[391]
3 Several independent accountability groups have brought energy, new ideas and advocacy to other global health issues. For example, the Institute of Health Metrics and Evaluation in Seattle have led analyses of the Global Burden of Disease, the Countdown to 2015 child survival group has monitored global progress since 2003, and the Global Health 2035 group have stimulated new ideas about global health financing.
4 Perhaps the paramount reason for an independent review is the authority of health professional voices with policy makers and communities. Doctors and nurses may be trusted more than environmentalists. They also bring experience of collating evidence and conducting advocacy to cut deaths as a result of tobacco, road traffic accidents, infectious disease, and lifestyle-related non-communicable diseases.

We propose the formation of an independent international Countdown to 2030: global health and climate action coalition, along the same lines as other successful global health monitoring groups. We recommend that a broad international coalition of experts across disciplines from health to the environment, energy, economics, and policy, together with lay observers, drawn from every region of the world, should monitor and report every 2 years. The report would provide a summary of evidence on the health impacts of climate change; progress in mitigation policies and the extent to which they consider and take advantage of the health co-benefits; and progress with broader adaptation action to reduce population vulnerability and to build climate resilience and to implement low-carbon, sustainable health systems.

A Countdown process would complement rather than replace existing IPCC and other UN reports. UN reports understandably seek cautious consensus. An independent review of progress would add the full weight and voice of the health community and valuable metrics to this critical population health challenge. A Countdown to 2030: global health and climate action coalition would independently decide the structure of their reports and the sentinel indicators they would choose to monitor progress towards key outcomes, policies and practice. Panel 9 outlines one possible framework for monitoring progress in three critical areas: health impacts; progress with action to reduce GHG emissions; and progress with actions to support adaptation, and the resilience of both populations and health systems, to climate change.

Panel 9: Framework of indicators for monitoring progress in three critical areas

Health impacts

An updated review of evidence on the health impacts of climate change:
- Heat stress and heatwaves
- Climate-sensitive dynamic infectious diseases
- Air pollution and allergy
- Climate-related migration
- Food insecurity and crop yields
- Extreme weather events
- Ecosystem service damage

Actions to reduce greenhouse gas emissions that improve public health

International progress and compliance with:
- A strong and equitable international agreement
- Low-carbon and climate-resilient technology innovation and investment
- Climate governance (finance, decision making, coordination, legislation)

Regional and national progress and successes with:
- Phasing out of coal-fired power generation and removal of fossil-fuel subsidies
- Urban planning, spatial infrastructure, and liveable cities
- Government incentives capital for low-carbon, resilient buildings and infrastructure

Adaptation, resilience, and climate-smart health systems

Progress and successes with:
- Poverty reduction and reductions in inequities
- Vulnerability and exposure reduction in high-risk populations
- Food security in poor countries
- Communication of climate risks and community engagement for local solutions
- Development of climate resilient, low-carbon health systems; scale up of renewables and combined heat and power generation in health facilities; use of climate finance for health infrastructure; decentralisation of care

Optimism

We should draw considerable strength in the face of the challenges of climate change from the way in which the global community has addressed numerous other threats to health in the recent past. Although the threats are great and time is short, we have an opportunity for social transformation that will link solutions to climate change with a progressive green global economy, reductions in social inequalities, the end of poverty, and a reversal of the pandemic of non-communicable disease.

There are huge opportunities for social and technological innovation. We have modern communications to share successful local learning. At the highest levels of state, there are opportunities for political leaders to grasp the global challenge with transformative climate initiatives of a scale and ambition to match the Marshall plan, the Apollo and Soyuz space programmes, and the commercial success of mobile telephony. Scalable, low-carbon, and renewable energy technologies require billions of dollars of new investment and ideas. In cities, municipal governments are already bringing energy and innovation to create connected, compact urban communities, better buildings, managed growth, and more efficient transport systems. In local communities transformative action creates greater environmental awareness and facilitates low-carbon transition. And within local government, civil society, and business, many people aim to bring about social and economic transformation. All of us can help cut GHG emissions and reduce the threat of climate change to our environment and health. At every level, health must find its voice. In health systems we can set an example with scale up of renewables, combined heat and power generation in health facilities, decentralisation of care and promotion of active transport, and low-carbon healthy lifestyles. But time is limited. Immediate action is needed. The Countdown to 2030 coalition must begin its work immediately.

Contributors

The 2015 *Lancet* Commission on Health and Climate Change is an international collaboration led by University College London, Tsinghua University, the University of Exeter, the Stockholm Resilience Centre, and Umeå University. The Commission undertook its work within five central working groups, which were responsible for the design, drafting, and review of their individual sections. All commissioners contributed to the overall report structure and concepts, and provided input and expertise in facilitating integration between the five core sections. *Members of Working Group 1 (climate change and exposure to health risks):* W Neil Adger, Mat Collins, Peter M Cox, Andy Haines, Alasdair Hunter, Xujia Jiang, Mark Maslin, Tara Quinn, Sergey Venevsky, Qiang Zhang. *Members of Working Group 2 (action for resilience and adaptation):* Victor Galaz, Delia Grace, Moxuan Li, Georgina Mace, My Svensdotter, Koko Warner, Yongyuan Yin, Chaoqing Yu, Bing Xu. *Members of Working Group 3 (transition to a low-carbon energy infrastructure):* Ian Hamilton, Lu Liang, Robert Lowe, Tadj Oreszczyn, Steve Pye, Jun Yang. *Members of Working Group 4 (financial and economic action):* Wenjia Cai, Paul Drummond, Paul Ekins, Paolo Agnolucci, Melissa Lott. *Members of Working Group 5 (delivering a healthy low-carbon future):* Jason Blackstock, Sarah Chaytor, Adam Cooper, Joanna Depledge, Hilary Graham, Michael Grubb, Yong Luo.

Michael Grubb acted as the integrating editor for mitigation (working across Working Groups 3, 4, and 5), and Maria Nilsson acted as the integrating editor for health (working across all working groups). Peter Byass, Ilan Kelman, and Tim Colbourn provided global health expertise for a number of working groups, and contributed to the Commission's overall direction. Nick Watts, Anthony Costello, Hugh Montgomery, and Peng Gong were responsible for the strategic direction, integration, and editing of the Commission.

Declaration of interests

Five commissioners (PD, MG, MLo, MS, and NW) were compensated for their time whilst working on the Commission's drafting and development. The Commission also covered meeting and travel costs for each author, helping to facilitate improved integration between working groups. NA has received grants from the Natural Environment Research Council UK during the conduct of the study. HG has received an ESRC grant ES/L003015/1 Health of Populations and Ecosystems (HOPE), outside the submitted work. MM is Executive Director and co-founding shareholder of Rezatec. This company uses remote sensing and ground data to provide companies with data on the state of the environment. It does not engage with global health or health related work. HM is a member of the Executive Committee of the UK Climate and Health Council. NW works as a consultant for WHO's Department of Public Health, Environmental, and Social Determinants of Health, and is the Director of the Global Climate and Health Alliance. The UCL Institute for Sustainable Resources receives funding from BHP Billiton, outside of the Commission's work.

Acknowledgments

Central funding for the Commission was provided by ClimateWorks Foundation, the European Climate Foundation, Microsoft Research Asia, the Norwegian Agency for Development Cooperation (NORAD), the National Environment Research Council through an Impact Acceleration award to the University of Exeter (NE/L012782/1), Martin Rushton-Turner, the Stordalen Foundation, and University College London's Grand Challenge for Global Health. In-kind support was also provided from Tsinghua University, University College London (UCL), and the Stockholm Resilience Centre through the Dynamic Drivers of Disease in Africa Consortium (DDDAC). The contributions of WNA and PMC were supported by the National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Environmental Change and Health at the London School of Hygiene and Tropical Medicine in partnership with Public Health England (PHE), and in collaboration with the University of Exeter, University College London, and the Met Office. Whilst carrying out its work, the Commission received invaluable technical advice and input from a number of individuals including Michele Acuto (UCL), John Ashton (E3G), Sukaina Bharwani (Stockholm Environment Institute-Oxford), Isobel Braithwaite (Global Climate and Health Alliance), Michael Depledge (University of Exeter), Helen Fry (University College London), Josh Karliner (Health Care Without Harm), and Duan Maosheng (Tsinsghua University). Olivia Stevenson (University College London) provided ongoing guidance and policy expertise to the Commission. Neil Morisetti (University College London) provided ongoing guidance and strategic input throughout the Commission's process. Elaine Fletcher and Marina Maiero from WHO's Department of Public Health, Environmental and Social Determinants of Health, and Bettina Menne from WHO's Regional Office for Europe provided both formal and informal advice and assistance to the Commission. The Commission also worked with various practitioner commissioners who reviewed its progress independently, and provided policy insight and guidance on how the final report could be most useful to decision makers. The practitioner commissioners included Diarmid Campbell-Lendrum (WHO), Matthew Pencharz (Greater London Authority), Virginia Murray (PHE), and Martin Frick (German Federal Foreign Office). In particular, the Commission would like to thank Diarmid Campbell-Lendrum, who leads WHO's efforts on health and climate change, for his advice and ongoing work in understanding the health impacts and adaptation responses to climate change, which provided a foundation for much of our report. Various experts in the fields of finance and economics provided invaluable guidance during the initial preparation stages for section 4, for which the authors are most grateful. These include Bernie Bulkin (Ludgate Investment), Mark Campanale (Carbon Tracker Initiative), Martin Rushton-Turner (Swiss Re), Michael Mainelli (Z/Yen), Andrew Scott (Overseas Development Institute), Adrian Gault (Committee on Climate Change), Paul Dickinson (CDP, formerly Carbon Disclosure Project), Jim Watson (UK Energy Research Centre), and Simon Buckle (Organization for Economic Cooperation and Development). Administrative, communications, and design support was provided by Ron Finaly, and by Ayesha Ally, Anila Babla, Faye Basset, Rosie Bartlett, Helen Hopkins, Kate Hoyland, and Maxine Lenza at UCL.

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Tackling climate change: the greatest opportunity for global health

Published Online
June 23, 2015
http://dx.doi.org/10.1016/S0140-6736(15)60931-X

See Online/Comment
http://dx.doi.org/10.1016/S0140-6736(15)61080-7 and
http://dx.doi.org/10.1016/S0140-6736(15)61043-1

See Online/The Lancet Commissions
http://dx.doi.org/10.1016/S0140-6736(15)60854-6

"Tackling climate change could be the greatest global health opportunity of the 21st century."[1] This finding, the central message of the second *Lancet* Commission on Health and Climate Change, attempts to answer the stark conclusion of the first *Lancet* Climate Change Commission, published in 2009—namely, that "Climate change is the biggest global health threat of the 21st century."[2]

When climate change is framed as a health issue, rather than purely as an environmental, economic, or technological challenge, it becomes clear that we are facing a predicament that strikes at the heart of humanity. Health puts a human face on what can sometimes seem to be a distant threat. By making the case for climate change as a health issue, we hope that the civilisational crisis we face will achieve greater public resonance. Public concerns about the health effects of climate change, such as undernutrition and food insecurity, have the potential to accelerate political action in ways that attention to carbon dioxide emissions alone do not.

To facilitate action to address the threat of climate change, our 2015 Commission on Health and Climate Change[1] provides nine recommendations for governments to consider. They include: scaling up financing for climate-resilient health systems worldwide; ensuring a rapid phase out of coal from the global energy mix; encouraging a transition to cities that support and promote healthy lifestyles for the individual and the planet; establishing the framework for a strong, predictable, and international carbon pricing mechanism; rapidly expanding access to renewable energy in low-income and middle-income countries; ensuring adequate local capacity and political support to develop low-carbon healthy energy choices; adopting mechanisms to facilitate collaboration between Ministries of Health and other government departments and empowering health professionals; agreeing and implementing an international agreement which supports countries in transitioning to a low-carbon economy; and investing in climate change and public health research.

Despite the optimism of the Commission, we recognise and acknowledge a widespread lack of awareness of climate change as a health issue. To overcome this gap in understanding, the 2015 *Lancet* Commission proposes the formation of an independent, international Countdown to 2030: Global Health and Climate Action coalition to monitor progress and action on the health dimensions of the climate crisis. Health professionals have a vital part to play in tackling the health impacts of climate change. The Commission calls on health professionals to lead the response to the health threats of climate change.

Tackling the health threats of climate change will also need an international multidisciplinary approach. The 2015 *Lancet* Commission represents a unique collaboration between European and Chinese academics, involving climate, social, political, and environmental scientists, geographers, experts in biodiversity and energy policy, engineers, economists, and, of course, health professionals. The *Lancet* Commission on Health and Climate Change has been led by both the University College London Institute for Global Health in the UK and Tsinghua University in China, with working meetings held and launch events planned in both London and Beijing. *The Lancet* has sought to foster collaboration between great universities and research institutes globally to address these neglected but serious threats to human health. We have pledged our long-term support to the work of the two *Lancet* Climate Change

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Commissions. We will continue to engage actively in the campaign to address the health threats of climate change, using the best available science as a platform for our advocacy work. We will also continue our strategic collaboration with Commissioners and report the work of the Countdown to 2030 project every 2 years.

Climate change is the defining challenge of our generation. Health professionals must mobilise now to address this challenge and protect the health and wellbeing of future generations.

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We thank the Co-Chairs of the *Lancet* Commission on Health and Climate Change Anthony Costello, Hugh Montgomery, and Peng Gong, as well as Nick Watts, for their leadership and support in the coordination of the Commission.

1 Watts N, Adger WN, Agnolucci P, et al. Health and climate change: policy responses to protect public health. *Lancet* 2015; published online June 23. http://dx.doi.org/10.1016/S0140-6736(15)60854-62.
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www.thelancet.com **Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)60931-X**

Achieving a cleaner, more sustainable, and healthier future

Published Online
June 23, 2015
http://dx.doi.org/10.1016/S0140-6736(15)61080-7

See Online/The Lancet Commissions
http://dx.doi.org/10.1016/S0140-6736(15)60854-6

In 2009, as countries prepared to negotiate a global climate treaty in Copenhagen, Denmark, the front cover of the first *Lancet* Commission on Health and Climate Change[1] issued a stark warning: "Climate change is the biggest global health threat of the 21st century".[1] This warning was not heeded: the overall agreement fell short of the necessary ambition, and health was noticeable by its absence from the negotiations. However, over the longer term, the Commission made its mark, contributing to a gradual but increasing engagement of the health community. As countries prepare again to reach a global deal on climate change, in Paris, France, in December, 2015, the health voice is louder, clearer, and increasingly listened to by our colleagues leading the negotiations.

The launch of the second *Lancet* Commission on Health and Climate Change[2] is therefore very timely. It is welcome not just for the summary of the evidence, but also for the wider scope, which makes connections between climate, health, economics, and energy decisions. I also congratulate the Commission for a comprehensive, ambitious, and forward looking set of recommendations, and encourage national Ministries of Health, and all health professionals, to consider each of them carefully. I would like to single out three of them where WHO will make a direct and specific contribution.

The first is the Commission's recommendation to scale up financing for climate-resilient health systems worldwide. WHO has estimated, considering only a few of the associated health risks, and assuming continued progress in economic growth and health protection, that climate change would still be likely to cause about 250 000 additional deaths per year by the 2030s.[3] The best defence is the same one that will protect us from outbreaks of infectious disease, and the mounting burden of non-communicable diseases: strong, flexible, and resilient health systems. In February, 2015, the WHO Executive Board endorsed a new workplan on climate change and health.[4] A central goal is to scale up a systematic approach to strengthening health systems, to include specific measures to adapt to a changing climate, such as early-warning systems for more frequent and severe heatwaves, and protection of water, sanitation, and hygiene services against floods and droughts. As doing so will require additional resources, health needs to receive appropriate support from existing international climate finance mechanisms, which has not yet been the case.

The second area is the set of recommendations on assessing the health implications of energy systems, and ensuring that these are factored in to overall government policies. In 2014, WHO documented that more than 7 million deaths every year are attributable to air pollution.[5] This makes it one of the most important health risk factors globally, comparable to tobacco smoking, and the largest killer in some countries. Globally, 88% of the world's population breathes air that does not meet WHO's air quality guidelines.[6] This is partly due to poverty and lack of access to clean energy—but it is also a result of policy choices. The health impacts of air pollution are not reflected in the price of the fuels that cause them, so that the cost is instead borne in lost lives, and health system expenditure. A recent report by researchers at the International Monetary Fund identifies the omission of health damages from polluting fuels as the largest of the subsidies provided to global energy production and use, which will total US$5·3 trillion in 2015.[7] This is larger than total health spending by all of the world's governments. I am pleased to report that in May, 2015, the World Health Assembly passed its first resolution on air pollution.[8] This calls on countries, and

the WHO Secretariat, to scale up their response to this major health issue, strengthening the health sector's contribution to decision making across sectors at local and national levels to clean the air and maximise health benefits. It also underscores opportunities to achieve cobenefits from actions that reduce emissions of warming climate-altering pollutants and at the same time improve health. We will indeed address the challenge of air pollution, and help guide countries to, wherever possible, make choices that also help to achieve climate change goals.

Third, the Commission highlights the need for monitoring and assessment of progress, similar to the Countdown to 2015 initiative[9] that has helped to drive progress on reducing maternal and child mortality. This is critical: what gets measured gets done. Last year, at the first WHO global Conference on Health and Climate, the Executive-Secretary of the United Nations Framework Convention on Climate Change Secretariat and I committed to produce country-specific profiles on health and climate change in advance of the Paris climate change conference. These compile the best available evidence on climate risks to health, on the opportunities to improve health while reducing greenhouse gas emissions, and on the status of country policies. These can also serve as the baseline for monitoring future progress.

Finally, I draw attention to the Commission's message that the health community has a vital part to play in accelerating progress to tackle climate change. To quote UN Secretary-General Ban Ki-moon: "There is no plan B; there is no planet B". Health professionals have been at the forefront of social changes, such as those that have gradually made smoking increasingly unacceptable, driving down smoking rates—and saving many lives. I endorse the call for the health community to support the growing movement for a cleaner, more sustainable, and healthier future.

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I am Director-General of WHO. I declare that I have no competing interests.

1 Costello A, Abbas M, Allen A, et al. Managing the health effects of climate change: *Lancet* and University College London Institute for Global Health Commission. *Lancet* 2009; 373: 1693–733.
2 Watts N, Adger WN, Agnolucci P, et al. Health and climate change: policy responses to protect public health. *Lancet* 2015; published online June 23. http://dx.doi.org/10.1016/S0140-6736(15)60854-6.
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9 Countdown to 2015: Maternal, Newborn, and Child Survival. http://www.countdown2015mnch.org/ (accessed June 8, 2015).

Reduce short-lived climate pollutants for multiple benefits

Published Online
June 23, 2015
http://dx.doi.org/10.1016/S0140-6736(15)61043-1

See Online/The Lancet Commissions
http://dx.doi.org/10.1016/S0140-6736(15)60854-6

Deep cuts in carbon dioxide emissions are urgently needed to prevent dangerous climate change, but they must be complemented by reductions in short-lived climate pollutants (SLCPs), which produce a strong global warming effect but have relatively brief atmospheric lifetimes (figure). SLCPs generally cause more radiative forcing per kg than carbon dioxide, and their mitigation could have a greater effect on climate change in the near term (in some cases almost immediately)—eg, by reducing the melting of snow and ice.

Some SLCPs, namely black carbon (a component of combustion-derived particulate matter) and tropospheric ozone, are also strongly associated with adverse health outcomes, whereas others (eg, methane) are ozone precursors.[2–4] Black carbon is often coemitted with other particulates and ozone precursors, and its removal often clears these particulates as a by-product, therefore enhancing the health benefits of emission reductions. Reduction of these pollutants therefore provides a unique opportunity to simultaneously mitigate climate change and improve population health in the near term, with benefits realised on a temporal and spatial scale relevant to policy makers.

Mitigation of SLCPs can provide health benefits in three ways. First, a decrease in black carbon and its coemissions, or emissions of ozone precursors, will reduce the substantial health burden attributable to air pollution. This reduction is a direct route to climate and health cobenefits and is most often the focus of policy discussion. Air quality improvements, from implementation of nine proposed mitigation actions targeting black carbon assessed by the UN Environment Programme and World Meteorological Organization, are estimated to prevent about 2·4 million deaths annually.[5] Reduction in ozone exposure can also benefit health because it is responsible for roughly 150 000 deaths annually worldwide.[6]

Second, the indirect effects of emission reductions can yield cobenefits. For instance, ozone and black carbon cause warming and decrease agricultural yields, thus threatening food security for poor individuals; ozone is toxic to many plants, whereas black carbon diminishes the amount and quality of sunlight available for photosynthesis.[5]

Third, health benefits directly related to some SLCP mitigation actions can accrue independently of reduced air pollution. For example, in affluent populations, improved diets with reduced consumption of red and processed meat, together with increased consumption of plant-based foods, especially fruit and vegetables, can improve health, lessen demand for land, and reduce emissions of SLCPs.[6–8]

Some mitigation actions take advantage of all three mechanisms (table). Encouragement of active travel instead of mechanised transport, for instance with construction of safe walking and cycling networks, can reduce population exposure to various risk factors, such as air and noise pollution, physical inactivity, and, with proper planning, road traffic injuries.[9] Interventions promoting clean household energy solutions also offer

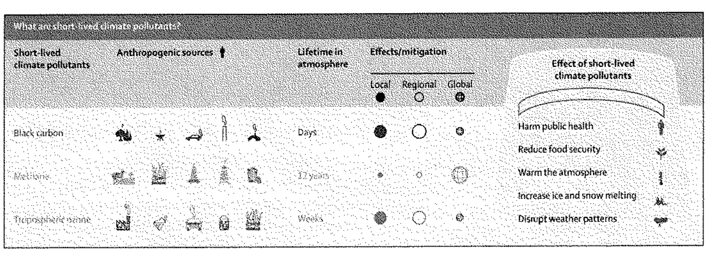

Figure: **Properties of common short-lived climate pollutants**
Adapted from UN Environment Programme,[3] by permission of the Climate and Clean Air Coalition.

	Certainty of major SLCP-related climate benefit*	Aggregate level of potential health benefit†	Main health benefit(s)	Potential level of CO_2 reduction cobenefit
Agriculture				
Promotion of healthy plant-based diets	Medium to high	High	Reduced diet-sensitive chronic diseases‡	Medium to high§
Reduced food waste	Medium to high	Low to medium	Reduced food insecurity and undernutrition	Medium to high§
Transport				
Support active (and mass) transport	High	High	Increased physical activity, improved air quality, reduced noise, fewer road traffic injuries¶	High
Diesel particle filters	Medium to high	Medium	Improved air quality	None
Tight vehicle emissions and efficiency standards	High	Medium to high	Improved air quality	High‖
Household air pollution and building design				
Improved cook stoves and fuel switching to reduce solid fuel use	Medium to high	High	Improved air quality, lower injury risk from carrying fuel, lower violence risk during fuel collection, fewer burns	Medium§
Improved lighting to replace kerosene lamps	Medium	Medium	Improved air quality, fewer burns	Low to medium
Passive design principles**	Low to medium	Medium	Thermal regulation, improved air quality	Medium
Electricity				
Switch from fossil fuels to renewables††	Low	High (coal and oil) or low to medium (gas)	Improved air quality, fewer occupational injuries	High
Control of fugitive emissions from fossil fuel industry	High	Low	Improved air quality	Low to medium‡‡
Small Industry				
Improved brick kilns	Low to medium	Medium	Improved air quality	Low to medium§
Improved coke ovens	Low to medium	Medium	Improved air quality	Low to medium§
Waste management				
Landfill gas recovery	Medium	Low	Improved air quality	Low to medium‡‡
Improved wastewater treatment (including sanitation provision)	Medium	Medium to high	Reduced risk of infectious disease, improved air quality	Low to medium‡‡

See Online for appendix

Data are based on our own estimations (appendix). SLCP=short-lived climate pollutants. CO_2=carbon dioxide. *Incorporates the potential for major reductions in emissions and the certainty that those reductions will have the desired climate effect—eg, a reduction in emissions of black carbon from black carbon-rich sources (eg, diesel) will have less uncertainty than a reduction in black carbon from sources higher in coemitted cooling agents (eg, open burning). †Assessed at the population level. ‡Avoid when the risk of nutrient inadequacy is high. §Includes potential of CO_2 uptake by reforested land or use for bioenergy crops. ¶Assumes provision of safe infrastructure. ‖Increased efficiency might induce increased travel (a rebound) so should be combined with complementary interventions (eg, fuel taxes). **For example enhancing energy efficiency through improved insulation and natural ventilation. ††Does not include fugitive emissions (eg, leakage of methane from natural gas supplies) which are considered separately. ‡‡Includes potential displacement of fossil fuels by use of captured gas.

Table: **Potential magnitude of climate and health effects of select mitigation actions**

a range of ancillary benefits such as reduced exposure to household air pollution, fewer injuries and burns, and reduced time and energy spent on collection of solid fuel, such as wood and dung.

Policies related to SLCPs are particularly appealing if they also reduce carbon dioxide, which will largely determine long-term climate change. In some cases, mitigation of SLCPs (eg, increased use of diesel particle filters) might have little effect on carbon dioxide. For some mitigation measures, however, carbon dioxide coreductions can be large, including measures that have great potential to improve health (table). Such examples include support for active travel and promotion of low emission vehicles.

Despite the benefits of mitigation, emissions of SLCPs have been rising in many areas.[10] This might be partly attributable to low awareness of the adverse effects of these pollutants, but practical impediments also exist. Some uncertainties arise from scientific questions, particularly regarding the net climate effect of black carbon and coemitted carbon species. However, new analyses have identified the sources that present particularly good opportunities for climate mitigation, including emissions from diesel and kerosene combustion, some industries (eg, traditional brick and coke production), and residential use of solid fuels.[5,11]

The key to the facilitation of policy action is therefore to promote more inclusive accounts of the benefits

www.thelancet.com Published online June 23, 2015 http://dx.doi.org/10.1016/S0140-6736(15)61043-1

versus costs of SLCP mitigation. Three strategies for action are of primary importance. The first relates to the use by the UN Framework Convention on Climate Change of the 100-year time horizon (known as Global Warming Potential 100) as the metric for climate change. The use of this metric has encouraged incentives necessary for long-term projects, but gives insufficient attention to actions (such as mitigation of SLCPs) that might reduce near-term climate change and create healthy and resilient populations. Policy makers should therefore consider various effects by using many or broader metrics.[12]

Second, the cobenefits approach implicitly assumes that governments use various metrics to assess policies and prioritise those fulfilling several objectives in parallel. However, governments are often organised into defined departments and some interventions, such as the promotion of active travel, are potentially controlled by more than one department (eg, transport, health, and environment). Although any single policy alone might prove cost effective to one department, the appeal is likely to be far greater when multiple outcomes of relevance to different departments are considered. Similarly, integrated development between departments can enhance synergies. Cities designed to be compact and pedestrian friendly, with complementary services located in close proximity, can reduce traffic (and pollution) and facilitate walking and cycling.[13] Improved planning also allows for efficient energy supply and enables more cost-effective delivery of essential services such as waste collection.[13] Hence, systems to foster cross-sectoral collaboration should be enhanced to identify and adopt mitigation actions with diverse benefits.

The final issue is to reject the belief that the environmental challenges that the population faces are the inevitable result of exercising personal choice. Lifestyle choices do not arise in a vacuum and are legitimate subjects for democratic debate and government action. What we eat, how we travel, and the energy sources we use are a function of policy decisions, institutions, and infrastructure, none of which are immutable.

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This Comment draws on an analysis of potential health cobenefits of short-lived climate pollutant mitigation measures, commissioned and supervised by WHO and partly supported by the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC). We thank Maria Neira and Helena Molin Valdés, who guided this analysis. DS and AH are members of the Scientific Advisory Panel of the CCAC. We declare no competing interests.

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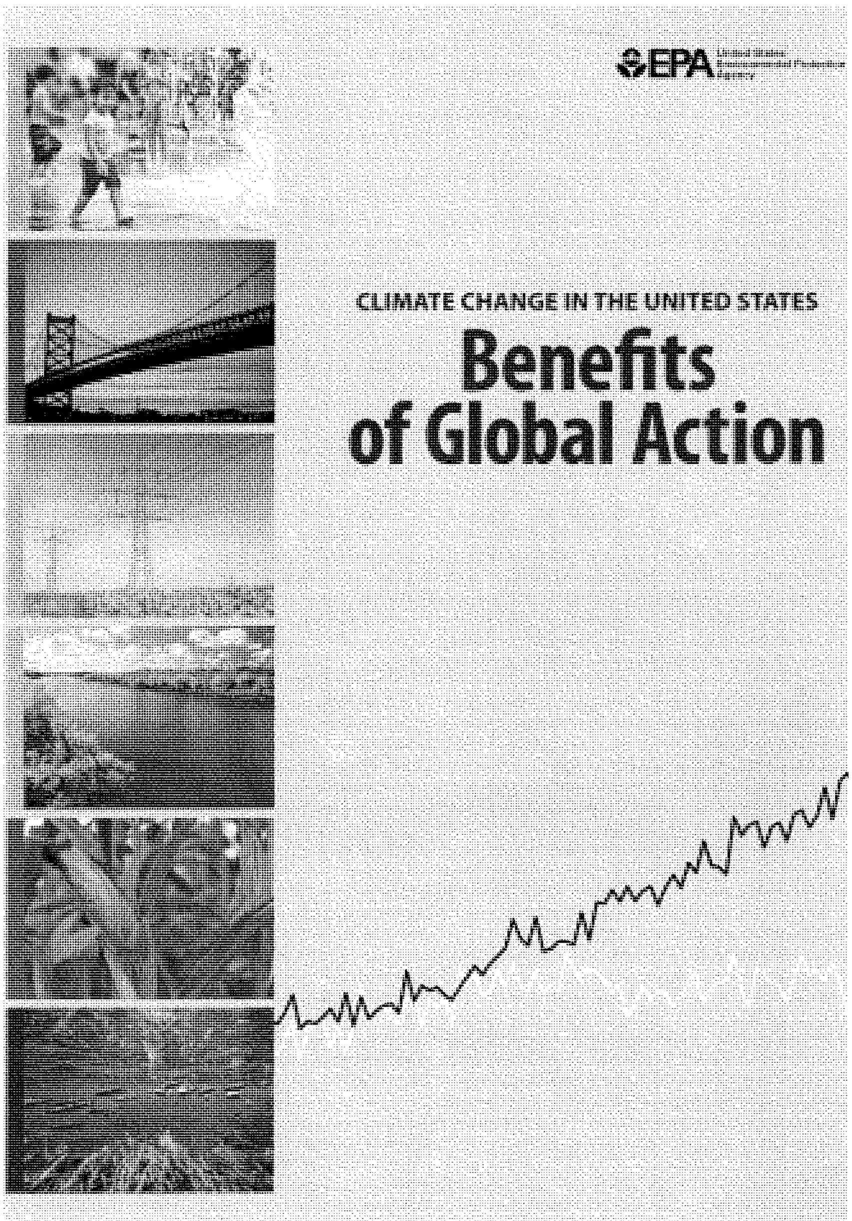
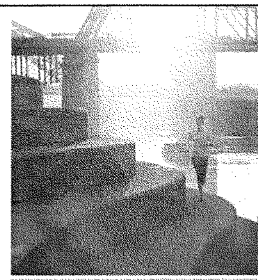
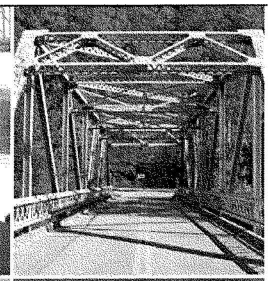

EPA

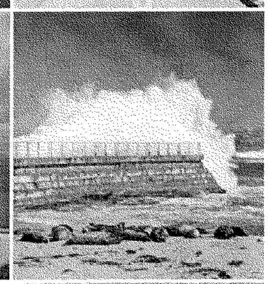
CLIMATE CHANGE IN THE UNITED STATES

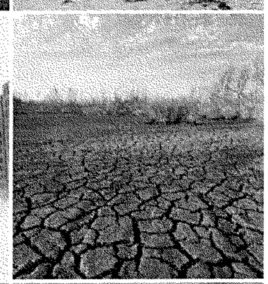
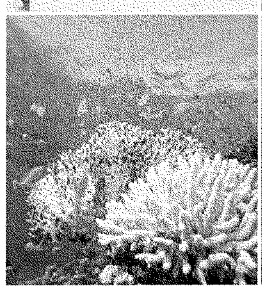
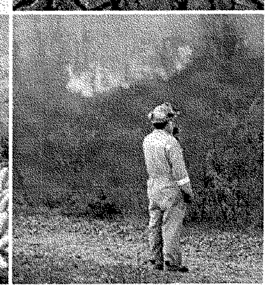
Benefits of Global Action


FIND US ONLINE
EPA's climate change website features a user-friendly interface for this report with downloadable graphics. To view information about EPA's Climate Change Impacts and Risk Analysis (CIRA) project, share your thoughts on this effort, and access the corresponding Technical Appendix for this report, please visit EPA's website at:

Contents



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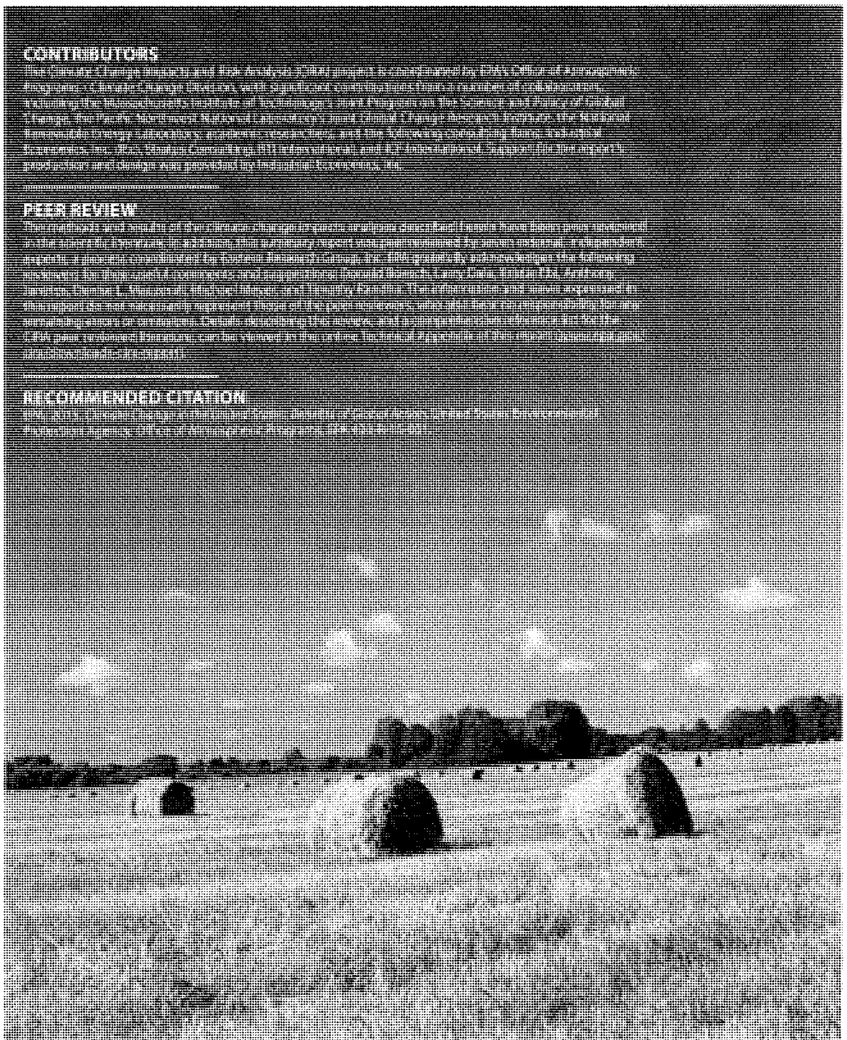
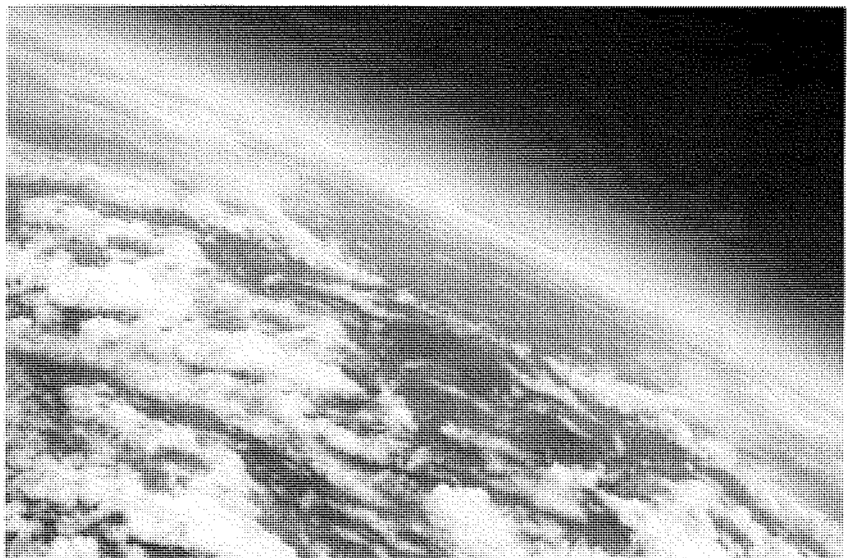


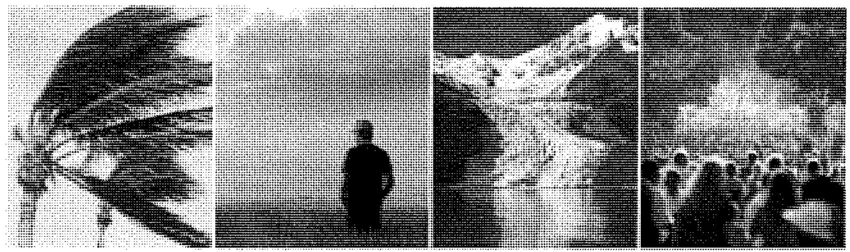
Introduction



The Earth's changing climate is affecting human health and the environment in many ways. Across the United States (U.S.), temperatures are rising, snow and rainfall patterns are shifting, and extreme climate events are becoming more common. Scientists are confident that many of the observed changes in the climate are caused by the increase in greenhouse gases (GHGs) in the atmosphere. As GHG emissions from human activities increase, many climate change impacts are expected to increase in both magnitude and frequency over the coming decades, with risks to human health, the economy, and the environment.

Actions can be taken now to reduce GHG emissions and avoid many of the adverse impacts of climate change. Quantifying the benefits of reducing GHG emissions (i.e., how GHG mitigation reduces or avoids impacts) requires comparing projections of climate change impacts and damages in a future with policy actions and a future without policy actions. Looking across a large number of sectors, this report communicates estimates of these benefits to the U.S. associated with global action on climate change.

Introduction



About this Report

This report summarizes and communicates the results of EPA's ongoing Climate Change Impacts and Risk Analysis (CIRA) project. The goal of this work is to estimate to what degree climate change impacts and damages to multiple U.S. sectors (e.g., human health, infrastructure, and water resources) may be avoided or reduced in a future with significant global action to reduce GHG emissions, compared to a future in which current emissions continue to grow. Importantly, only a small portion of the impacts of climate change are estimated, and therefore this report captures just some of the total benefits of reducing GHGs.

To achieve this, a multi-model framework was developed to estimate the impacts and damages to the human health and welfare of people in the U.S. The CIRA framework uses consistent inputs (e.g., socioeconomic and climate scenarios) to enable consistent comparison of sectoral impacts across time and space. In addition, the role of adaptation is modeled for some of the sectors to explore the potential for risk reduction and, where applicable, to quantify the costs associated with adaptive actions.

The methods and results of the CIRA project have been peer reviewed in the scientific literature, including a special issue of *Climatic Change* entitled, "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States."[1] The research papers underlying the modeling and results presented herein are cited throughout this report and are listed in Section B of the Technical Appendix.

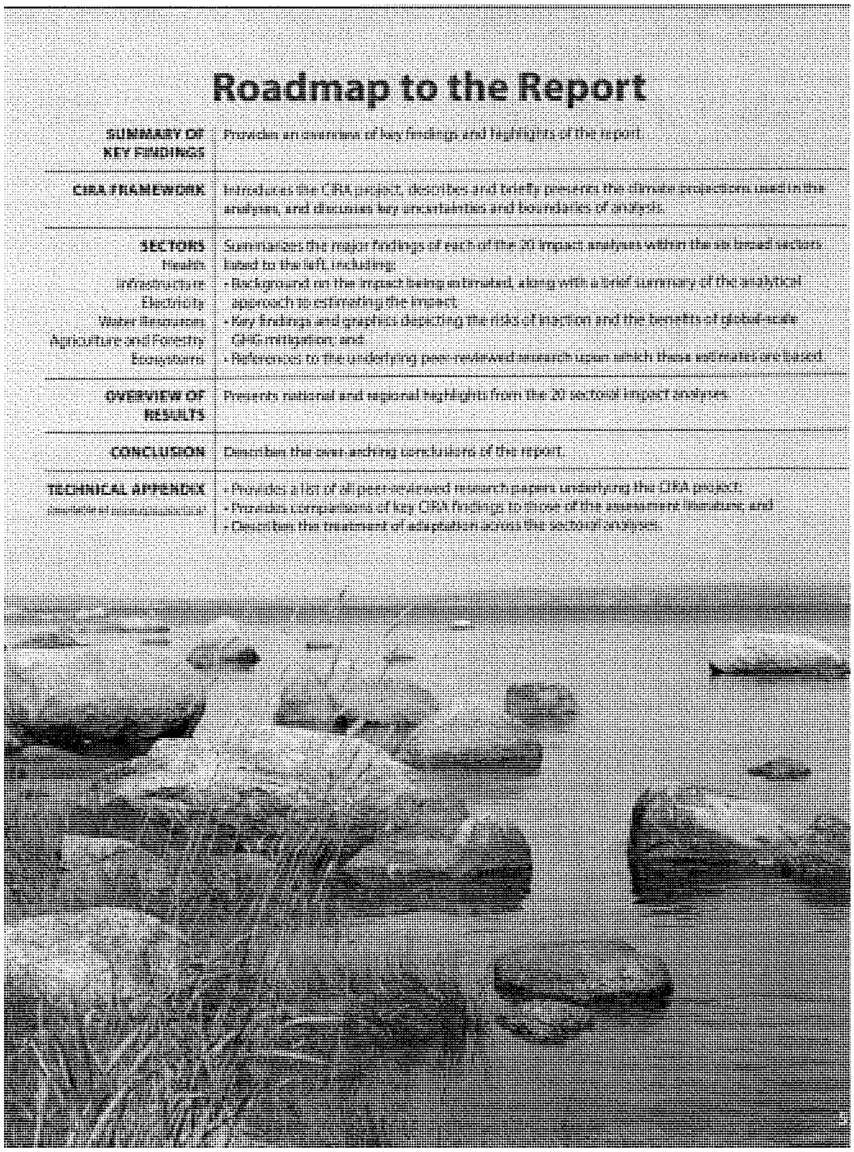
Interpreting the Results

This report presents results from a large set of sectoral impact models that quantify and monetize climate change impacts in the U.S., with a primary focus on the contiguous U.S., in futures with and without global GHG mitigation. The CIRA analyses are intended to provide insights about the potential direction and magnitude of climate change impacts and the benefits (avoided impacts) to the U.S. of global emissions reductions. However, none of the estimates presented in this report should be interpreted as definitive predictions of future impacts at a particular place or time.

The CIRA analyses do not evaluate or assume specific GHG mitigation or adaptation policies in the U.S. or in other world regions. Instead, they consider plausible scenarios to illustrate potential benefits of significant GHG emission reductions compared to a business-as-usual future. The results should not be interpreted as supporting any particular domestic or global mitigation policy or target. A wide range of global mitigation scenarios could be modeled in the CIRA framework,[2] and results would vary accordingly. For ease of communicating results, however, this report focuses on a future where the increase in average global temperature is limited to approximately 2°C (3.6°F) above preindustrial levels—a goal relevant to international discussions on GHG emission reductions.[3]

This report includes as many climate change impacts as feasible at present, but is not all-inclusive. It is not intended to be as comprehensive as major assessments, such as those conducted by the U.S. Global Change Research Program (USGCRP), which capture a wider range of impacts from the published literature.[4] By using a consistent set of socioeconomic and climate scenarios, CIRA produces apples-to-apples comparisons of impacts across sectors and regions—something that is not always achieved, or even sought, in the major assessments. Also, the assessments typically do not monetize damages, nor do they focus on quantifying mitigation benefits. CIRA's ability to estimate how global GHG mitigation may benefit the U.S. by reducing or avoiding climate change impacts helps to fill an important literature and knowledge gap.

The CIRA analyses do not serve the same analytical purpose nor use the same methodology as the Social Cost of Carbon (SCC), an economic metric quantifying the marginal global benefit of reducing one ton of carbon dioxide (CO_2).[5] In addition, the costs of reducing GHG emissions,[6] and the health benefits associated with co-reductions in other air pollutants, are well-examined elsewhere in the literature[7] and are beyond the scope of this report.



Roadmap to the Report

SUMMARY OF KEY FINDINGS	Provides an overview of key findings and highlights of the report.
CIRA FRAMEWORK	Introduces the CIRA project, describes and briefly presents the climate projections used in the analyses, and discusses key uncertainties and boundaries of analysis.
SECTORS Health Infrastructure Electricity Water Resources Agriculture and Forestry Ecosystems	Summarizes the major findings of each of the 20 impact analyses within the six broad sectors listed to the left, including: - Background on the impact being estimated, along with a brief summary of the analytical approach to estimating the impact; - Key findings and graphics depicting the risks of inaction and the benefits of global-scale GHG mitigation; and - References to the underlying peer-reviewed research upon which these estimates are based.
OVERVIEW OF RESULTS	Presents national and regional highlights from the 20 sectoral impact analyses.
CONCLUSION	Describes the over-arching conclusions of the report.
TECHNICAL APPENDIX	- Provides a list of all peer-reviewed research papers underlying the CIRA project; - Provides comparisons of key CIRA findings to those of the assessment literature; and - Describes the treatment of adaptation across the sectoral analyses.

3

Summary of Key Findings

Climate change poses significant risks to humans and the environment. The CIRA project quantifies and monetizes the risks of inaction and benefits to the U.S. of global GHG mitigation within six broad sectors (water resources, electricity, infrastructure, health, agriculture and forestry, and ecosystems). Looking across the impact estimates presented in this report, several common themes emerge.[1]

Global GHG Mitigation Reduces the Frequency of Extreme Weather Events and Associated Impacts

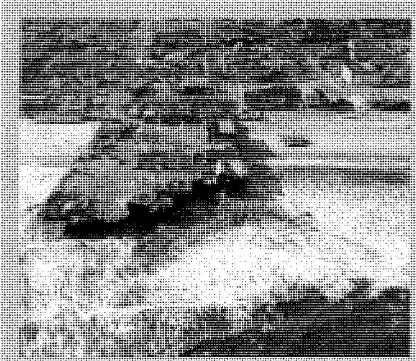
Global GHG mitigation is projected to have a substantial effect on reducing the incidence of extreme temperature and precipitation events by the end of the century, as well as the impacts to humans and the environment associated with these extreme events.[2] For example, by 2100 mitigation is projected to avoid 12,000 deaths annually associated with extreme temperatures in 49 U.S. cities, compared to a future with no emission reductions. Inclusion of the entire U.S. population would greatly increase the number of avoided deaths, while accounting for adaptation could reduce this number.

Global GHG Mitigation Avoids Costly Damages in the U.S.

For nearly all sectors analyzed, global GHG mitigation is projected to prevent or substantially reduce adverse impacts in the U.S. this century compared to a future without emission reductions. For many sectors, the projected benefits of mitigation are substantial; for example, in 2100 mitigation is projected to result in cost savings of $4.2-$7.4 billion associated with avoided road maintenance. Global GHG mitigation is also projected to avoid the loss of 230,000-360,000 acres of coldwater fish habitat across the country compared to a future without emissions reductions.

The Benefits of GHG Mitigation Increase over Time

For a large majority of sectors analyzed, the benefits of GHG mitigation are projected to be greater in 2100 than in 2050. In addition, the benefits of GHG mitigation are often not apparent until mid-century. This delay in benefits is consistent with many studies,[3] and is attributable to inertia in the climate system. Therefore, decisions we make today can have long-term effects, and delaying action will likely increase the risks of significant and costly impacts in the future.



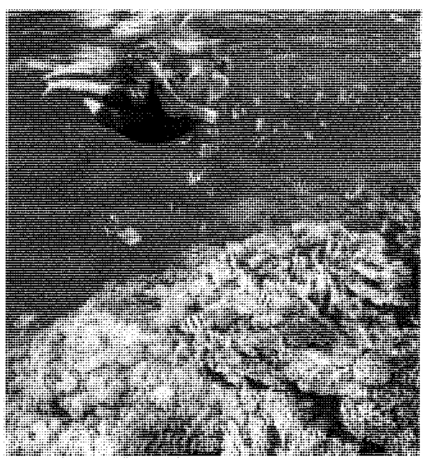
Adaptation Can Reduce Overall Damages in Certain Sectors

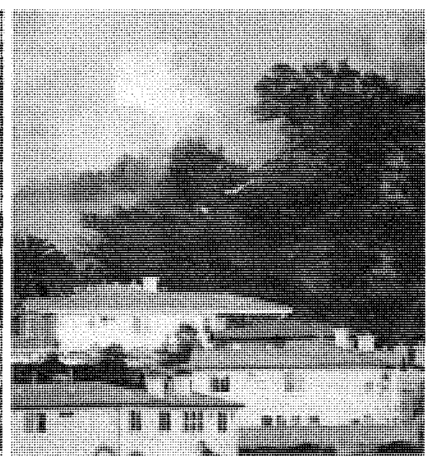
Adaptation can substantially reduce certain impacts of climate change regardless of whether future GHG levels are low or high. For example, the estimated damages to coastal property from sea level rise and storm surge in the contiguous U.S. are $5.0 trillion through 2100 (discounted at 3%) in a future without emission reductions. When cost-effective adaptation along the coast is included, the estimated damages are reduced to $810 billion.

Impacts Vary across Time and Space

Important regional changes may be masked when results are presented at the national level. For example, the wildfire analysis reveals that the projected changes in the Southwest and Rocky Mountain regions are the primary drivers of national trends of increasing wildfire activity over time.

The temporal scale of climate change impacts is also important. While some impacts are likely to occur gradually over time, others may exhibit threshold (tipping point) responses to climate change, as large changes manifest over a short period of time. For example, high-temperature bleaching events projected to occur by 2025 are estimated to severely affect coral reefs in the Caribbean. Therefore, simply analyzing an impact in one time period (e.g., 2100) may mask important temporal dynamics that are relevant to decision makers.





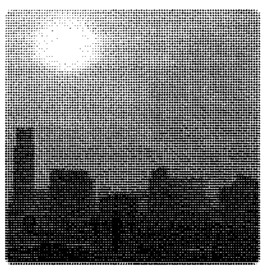
SUMMARY OF KEY FINDINGS

Estimated Benefits to the U.S. in 2100

This graphic presents a selection of the estimated benefits of global GHG mitigation in 2100 for major U.S. sectors. Unless otherwise noted, the results presented below are estimates of annual benefits (or disbenefits) of mitigation in the year 2100.* Importantly, only a small portion of the impacts of climate change are estimated, and therefore this report captures just some of the total benefits of reducing GHGs.

HEALTH

AIR QUALITY
An estimated 57,000 fewer deaths from poor air quality in 2100

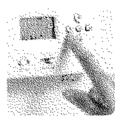


EXTREME TEMPERATURE
In 49 major U.S. cities, an estimated 12,000 fewer deaths from extreme temperature in 2100

LABOR
Approximately $110 billion in avoided damages from lost labor due to extreme temperatures in 2100

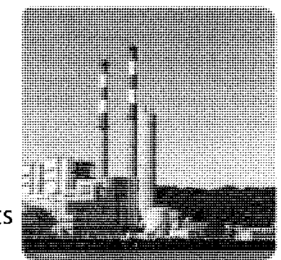
WATER QUALITY
An estimated $2.6-$3.0 billion in avoided damages from poor water quality in 2100†

ELECTRICITY

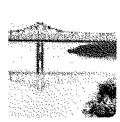


ELECTRICITY DEMAND
An avoided increase in electricity demand of 1.1%-4.0% in 2050‡

ELECTRICITY SUPPLY
An estimated $10-$34 billion in savings on power system costs in 2050‡

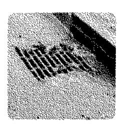


INFRASTRUCTURE

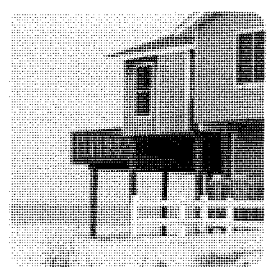


BRIDGES
An estimated 720-2,200 fewer bridges made structurally vulnerable in 2100†

ROADS
An estimated $4.2-$7.4 billion in avoided adaptation costs in 2100†



URBAN DRAINAGE
In 50 U.S. cities, an estimated $50 million-$6.4 billion in avoided adaptation costs in 2100†



COASTAL PROPERTY
Approximately $3.1 billion in avoided damages and adaptation costs from sea level rise and storm surge in 2100

* Monetary estimates for this summary are presented for either 2050 or 2100 only, and are undiscounted (2014$). See the Sectors section for the use of discounting throughout this report.

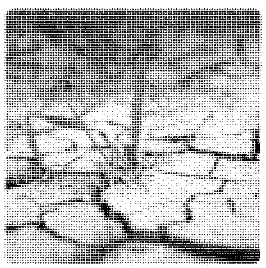
† Estimated range of results relies upon climate projections from two climate models showing different patterns of precipitation in the U.S. The IGSM-CAM projects a relatively "wetter" future for most of the U.S. compared to the drier MIROC model (see the CIRA Framework section of this report for more information).

# of Reducing Global GHG Emissions

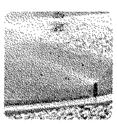
For detailed information on the results, please refer to the Sectors section of this report.

WATER RESOURCES

INLAND FLOODING
Estimates range from approximately $2.8 billion in avoided damages to $38 million in increased damages in 2100†

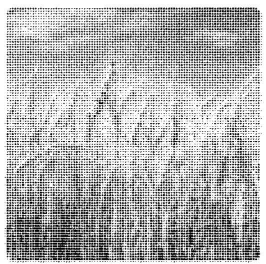


DROUGHT
An estimated 40%-59% fewer severe and extreme droughts in 2100†

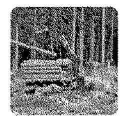


SUPPLY & DEMAND
An estimated $11-$180 billion in avoided damages from water shortages in key economic sectors in 2100†

AGRICULTURE AND FORESTRY

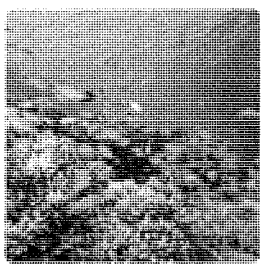


AGRICULTURE
An estimated $6.6-$11 billion in avoided damages to agriculture in 2100



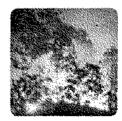
FORESTRY
An estimated $520 million to $1.5 billion in avoided damages to forestry in 2100

ECOSYSTEMS

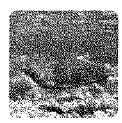


CORAL REEFS
An avoided loss of approximately 35% of current Hawaiian coral in 2100, with a recreational value of $1.1 billion

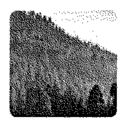
SHELLFISH
An avoided loss of approximately 34% of the U.S. oyster supply, 37% of scallops, and 29% of clams in 2100



WILDFIRE
An estimated 6.0-7.9 million fewer acres burned by wildfires in 2100†



FRESHWATER FISH
An estimated 230,000-360,000 acres of cold-water fish habitat preserved in 2100†



CARBON STORAGE
An estimated 1.0-26 million fewer tons of carbon stored in vegetation in 2100†§

† Results reflect the estimated range of benefits from the reduction in demand and system costs resulting from lower temperatures associated with GHG mitigation. The Electricity section in this report presents an analysis that includes the costs to the electric power sector of reducing GHG emissions.

§ See the Carbon Storage section of this report for cumulative results from 2000-2100, which show benefits of GHG mitigation for parts, and in some cases all, of the century.

CIRA Framework

The primary goal of the CIRA project is to estimate the degree to which climate change impacts in the U.S. are avoided or reduced in the 21st century under significant global GHG mitigation. The CIRA framework is designed to assess the physical impacts and economic damages of climate change to the U.S. In this report, the benefits (or disbenefits) of global GHG mitigation are assessed as the difference between the impacts in futures with and without mitigation policy using multiple models driven by →

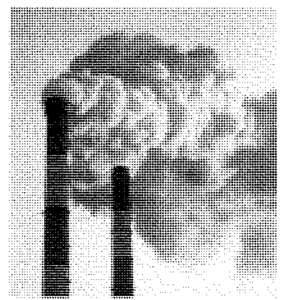
1| Design GHG Emissions Scenarios

GHG emissions from human activities, and the resulting climate change impacts and damages, depend on future socioeconomic development (e.g., population growth, economic development, energy sources, and technological change). Emissions scenarios provide scientifically credible starting points for examining questions about an uncertain future and help us visualize alternative futures.[2] They are neither forecasts nor predictions, and the report does not assume that any scenario is more or less likely than another. GHG emissions scenarios are illustrations of how the release of different amounts of climate-altering gases and particles into the atmosphere will produce different climate conditions in the U.S. and around the globe.

To allow for a better understanding of the potential benefits of global-scale GHG mitigation, the CIRA results presented in this report consider two emissions scenarios (see Table 1): a business-as-usual future in which GHG emissions continue to increase unchecked (referred to as the Reference scenario), and a mitigation scenario in which global GHG emissions are substantially reduced (referred to as the Mitigation scenario).[3,4] These scenarios were developed using the Massachusetts Institute of Technology's Emissions Predictions and Policy Analysis (EPPA) model,[5] the human systems component within the Integrated Global System Model (IGSM). EPPA provides projections of world economic development and emissions, including analysis of proposed emissions control measures. These measures include, for example, limiting GHGs from major emitting sectors, such as electricity production and transportation. EPPA-IGSM, along with a linked climate model, provide a consistent framework to develop GHG emission and climate scenarios for impacts assessment.

Table 1 provides information on the characteristics of each emissions scenario in 2100. Similar to the Representative Concentration Pathways (RCPs) used by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report,[6] the CIRA scenarios are based on different trajectories of GHG emissions and radiative forcing—a metric of the additional heat added to the Earth's climate system caused by anthropogenic and natural emissions.

Figure 1 compares the two primary CIRA scenarios used throughout this report to the RCPs, showing that these scenarios fall within the range of IPCC's latest projections. The



CIRA emissions scenarios provide illustrations for analytical comparison and do not represent specific policies. For more information about the design of these scenarios, please refer to Paltsev et al. (2013).[7]

Table 1. Characteristics of the Reference and Mitigation Scenarios in 2100

BUSINESS AS USUAL "REFERENCE"	GLOBAL EMISSIONS REDUCTIONS "MITIGATION"
GHG RADIATIVE FORCING (IPCC/RCP METHOD)	
9.8 W/m^2 (8.6 W/m^2)	3.6 W/m^2 (3.2 W/m^2)
GLOBAL GHG EMISSIONS	
~2.5 x 2005 levels	~0.28 x 2005 levels
ATMOSPHERIC CO_2 CONCENTRATION	
826 ppm	462 ppm
ATMOSPHERIC GHG CONCENTRATION (CO_2 EQUIVALENT)	
1750 ppm	500 ppm

STEP 1 | DESIGN GHG EMISSIONS SCENARIOS

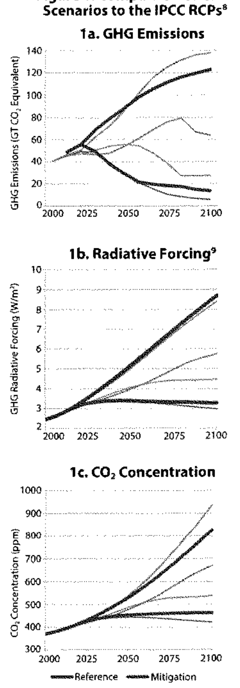
Two scenarios are used throughout this report:
- Business as usual or the "**Reference**" scenario
- Global emissions reductions or the "**Mitigation**" scenario

STEP 2 | PROJECT FUTURE CLIMATE

- Temperature
- Precipitation
- Sea level rise
- CO_2 concentration
- Sea surface temperature
- Cloud cover
- Wind speed
- Relative humidity
- Solar radiation

a consistent set of climatic, socioeconomic, and technological scenarios. A three-step approach for assessing benefits includes developing GHG emissions scenarios; simulating future climate under these scenarios; and applying these projections in a series of coordinated impacts analyses encompassing six sectors (health, infrastructure, electricity, water resources, agriculture and forestry, and ecosystems). For more information on the objectives and design of the CIRA framework, please refer to Martinich et al. (2015).[1]

Figure 1. Comparison of CIRA Scenarios to the IPCC RCPs[8]



2 | Project Future Climate

To simulate future climate in the U.S., CIRA primarily uses the IGSM-CAM framework, which links the IGSM to the National Center for Atmospheric Research's Community Atmosphere Model (CAM). The IGSM-CAM simulates changes in a large number of climate variables, such as temperature and precipitation, at various temporal scales. Other outputs include: sea level rise, atmospheric CO_2 concentration, cloud cover, wind speed, relative humidity, and solar radiation.[10] The CIRA climate projections are briefly described in the following pages of this report. As described in the Levels of Certainty section, results using other climate models with different patterns of projected precipitation are compared to the IGSM-CAM results for sectoral analyses that are sensitive to changes in precipitation (e.g., drought and flooding). Specifically, results under the IGSM-CAM projections, which estimate a wetter future for most of the contiguous U.S., are complemented with drier projections to investigate the influence on impact estimates. Additional information on the development and characteristics of the CIRA climate projections can be found in Monier et al. (2014).[11]

3 | Analyze Sectoral Impacts

This report analyzes 20 specific climate change impacts in the U.S., which are categorized into six broad sectors (health, infrastructure, electricity, water resources, agriculture and forestry, and ecosystems). The impacts were selected based on the following criteria: sufficient understanding of how climate change affects the sector; the existence of data to support the methodologies; availability of modeling applications that could be applied in the CIRA framework; and the economic, iconic, or cultural significance of impacts and damages in the sector to the U.S. It is anticipated that the coverage of sectoral impacts in the CIRA project will expand in future work.

To quantify climate change impacts in each sector, process-based or statistical models were applied using the socioeconomic and climate scenarios described above. This approach, which ensures that each model is driven by the same inputs, enables consistent comparison of impacts across sectors and in-depth analysis across regions and time. Many of the analyses explore the potential for adaptation to reduce risks and quantify the costs associated with adaptive actions (see the Sectors section of this report and Section D of the Technical Appendix for more information).[12] Lastly, the CIRA analyses investigate key sources of variability in projecting future climate, as further discussed in the Levels of Certainty section.

STEP 3 | ANALYZE SECTORAL IMPACTS

HEALTH	INFRASTRUCTURE	ELECTRICITY	WATER RESOURCES	AGRICULTURE AND FORESTRY	ECOSYSTEMS
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CIRA FRAMEWORK

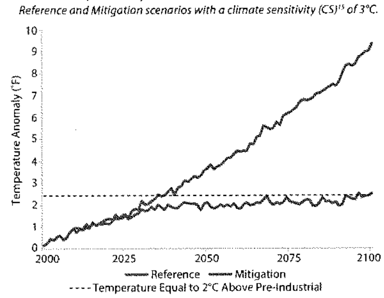
Temperature Projections

Global Temperature Change

Global mean temperature under the CIRA Reference scenario is projected to increase by over 9°F by 2100 (Figure 1). This estimated increase is consistent with the USGCRP Third National Climate Assessment, which projects a range of 5-11°F by 2100.[13,14] To help illustrate the magnitude of such a change in global mean temperature, the last ice age, which covered the northern contiguous U.S. with ice sheets, was approximately 9°F cooler than today. While some areas will experience greater increases than others, Figure 1 presents the average change that is projected to occur across the globe under the Reference and Mitigation scenarios. As shown, temperatures in the Mitigation scenario eventually stabilize, though due to the inertia of the climate system, stabilization is not reached until several decades after the peak in radiative forcing. The Reference scenario continues to warm, reaching a temperature increase of almost five times that of the Mitigation scenario by the end of the century. This demonstrates that significant GHG mitigation efforts can stabilize temperatures and avoid an additional 7°F of warming this century, but due to climate system inertia, benefits may not be apparent for several decades.

Figure 1. Change in Global Mean Temperature with and without Global GHG Mitigation

Time series of global annual mean surface air temperature relative to present-day (1980-2009 mean) for IGSM-CAM under the Reference and Mitigation scenarios with a climate sensitivity (CS)[15] of 3°C.



Limiting Future Warming to 2°C

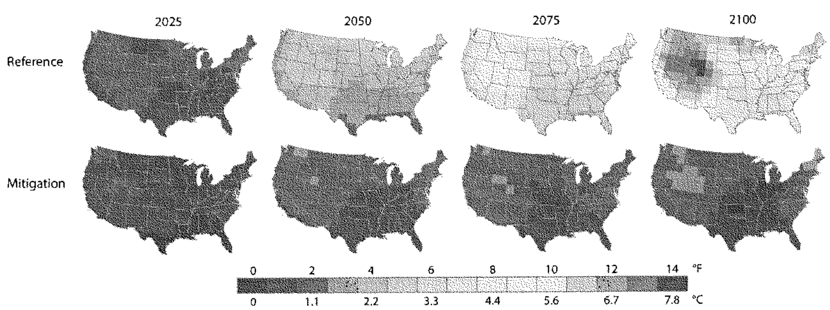
Limiting the future increase in global average surface temperature to below 2°C (3.6°F) above preindustrial levels is a commonly regarded goal for avoiding dangerous climate change impacts.[16] Global temperatures, however, have already warmed 0.85°C (1.5°F) from preindustrial times.[17,18] The level of global GHG mitigation achieved under the CIRA Mitigation scenario is consistent with the amount required to meet the 2°C target (Figure 1),[19] and therefore the estimates presented in this report describing the potential benefits to the U.S. of global GHG mitigation are a reasonable approximation of the benefits that would result from meeting this goal.

Temperature Change in the U.S.

Under the Reference scenario, the largest increases in average temperature across the contiguous U.S. by 2100 are projected to occur in the Mountain West—up to a 14°F increase from present-day average temperature (Figure 2). The northern regions are also likely to see larger temperature increases than the global average (up to 12°F, compared to a global average of 9.3°F), while the Southeast is projected to experience a relatively lower level of overall warming (but comparable to the global average increase). Under the Mitigation scenario, temperature increases across the country are far lower compared to the Reference, with no regions experiencing increases of more than 4°F.

Figure 2. Distribution of Temperature Change with and without Global GHG Mitigation

Change in annual mean surface air temperature relative to present-day (1980-2009 average) for IGSM-CAM under the Reference and Mitigation scenarios (CS 3°C).



Seasonal and Extreme Temperatures

Just as presenting global average temperature changes masks geographic patterns of variability, presenting annual average temperature changes conceals seasonal patterns of change. Some seasons are expected to warm faster than others, and the impacts of warming will also vary by season. For example, in some regions, greater levels of warming may occur in the winter, but warming in summer will matter most for changes in the frequency and intensity of heat waves. Figure 3 provides an illustrative example of the changes in average summertime temperature that select states may experience over time with and without global GHG mitigation. Under the Reference scenario, summertime temperatures in some northern states are projected to feel more like the present-day summertime conditions in southern states. However, under the Mitigation scenario, states are projected to experience substantially smaller changes.

In addition to increasing average summertime temperatures, climate change is projected to result in an increase in extreme temperatures across most of the contiguous U.S. In the Mountain West, for example, the hottest days of the year are estimated to be over 14°F hotter than today under the Reference scenario by the end of the century (Figure 4). Many parts of the Midwest and Northeast are projected to experience increases in extreme temperatures ranging from 7-10°F, an amount similar to the increase in average summertime temperatures. These changes are projected to be far less severe under the Mitigation scenario, however, with no regions experiencing increases of more than 4°F.

Figure 3. Change in Summertime Temperatures for Select States with and without Global GHG Mitigation

The map compares mean summertime (June, July, and August) temperature in South Dakota, Illinois, and Maryland in 2050 and 2100 under the Reference and Mitigation scenarios to states with similar present-day temperatures. For example, the projected mean summertime temperature in Illinois in 2100 under the Reference scenario (83°F) is projected to be analogous to the mean summertime temperature in Louisiana from 1980-2009 (81°F). In other words, without global GHG mitigation, Illinois summers by 2100 are projected to "feel like" present-day Louisiana summers. The maps are not perfect representations of projected climate, as other factors such as humidity are not included, but they do provide a way of visualizing the magnitude of possible changes in the summertime conditions of the future.

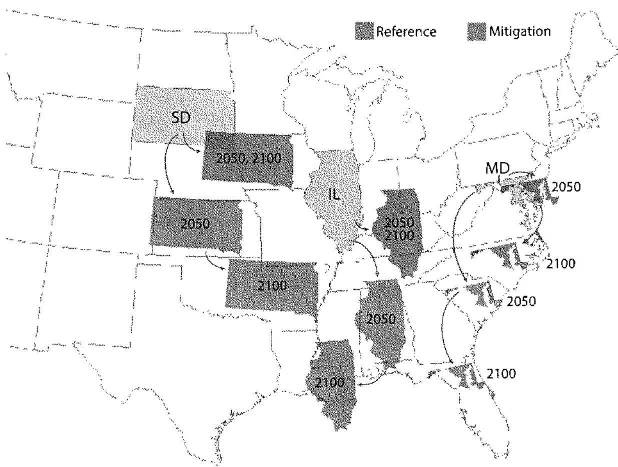
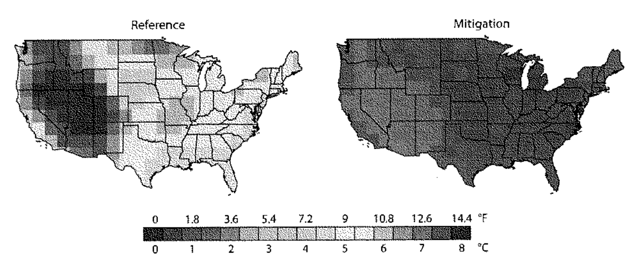


Figure 4. Change in Magnitude of Extreme Heat Events with and without Global GHG Mitigation

Change in the extreme heat index (T99)—the temperature of the hottest four days, or 99th percentile, of the year—simulated by the IGSM-CAM for 2100 (average 2085-2115) relative to the baseline (average 1981-2010) (CS 3°C).[20]



CIRA FRAMEWORK

Precipitation Projections

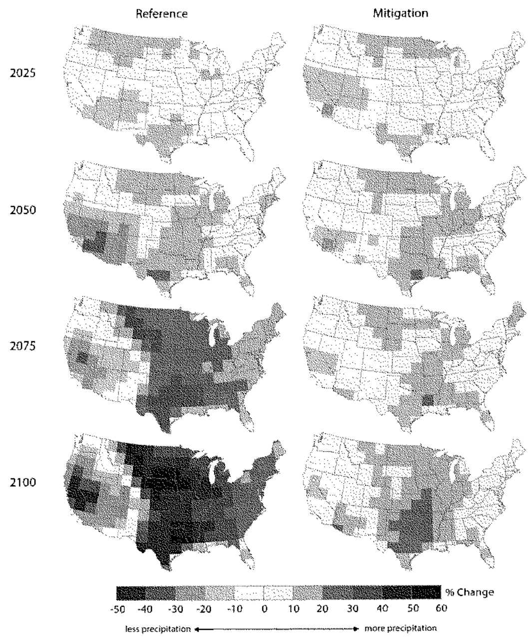
Precipitation in the U.S.

The IGSM-CAM projects future changes in annual mean precipitation over the course of the 21st century under the Reference and Mitigation scenarios (Figure 1). Under the CIRA Reference scenario, the model estimates increasing precipitation over much of the U.S., especially over the Great Plains. However, the western U.S. is estimated to experience a decrease in precipitation compared to present day. Under the Mitigation scenario, a similar but less intense pattern of increasing precipitation is projected over much of the country, particularly in the central states.

As projections of future precipitation vary across individual climate models, the CIRA analyses use outputs from additional climate models (see the Levels of Certainty section of this report). Compared to multi-model ensemble projections presented in the IPCC and USGCRP, the CIRA projections exhibit some regional differences in the pattern of projected precipitation. A comparison between the CIRA climate projections and those presented in these assessment reports can be found in Section E of the Technical Appendix.

Figure 1. Percentage Change in Annual Mean Precipitation with and without Global GHG Mitigation

Percentage change in annual mean precipitation from the historical period (1980-2009) for IGSM-CAM under the Reference and Mitigation scenarios (CS 3°C).

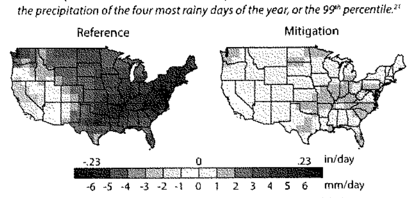


Extreme Precipitation

Figure 2 shows the change in the intensity of extreme precipitation events from present day to 2100. Blue areas on this map indicate that the future's heaviest precipitation events will be more intense compared to today. Under the Reference, the IGSM-CAM shows a general increase in the intensity of extreme precipitation events, except over California. The increase is particularly strong over the Northeast, Midwest, and Southeast. Global GHG mitigation is likely to greatly reduce the increase in intensity of extreme precipitation events, as shown in the right panel of Figure 2.

Figure 2. Change in the Intensity of Extreme Precipitation with and without Global GHG Mitigation

Change in the extreme precipitation index (P99) simulated by IGSM-CAM for the 2085-2115 period relative to the 1981-2010 period (CS 3°C). The P99 index reflects the precipitation of the four most rainy days of the year, or the 99th percentile.[21]



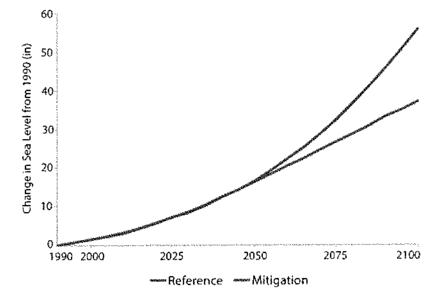
Sea Level Rise Projections

Global Sea Level Rise

Figure 1 shows the change in global mean sea level from present day to 2100 under the Reference and Mitigation scenarios. Global mean sea levels are projected to rise about 56 inches by 2100 under the Reference and about 37 inches under the Mitigation scenario. These results fall within the range for risk planning presented in the Third National Climate Assessment of 8-79 inches by 2100, with the Reference scenario's rate being slightly larger than the Assessment's likely range of 12-48 inches.[22,23] As shown in Figure 1, global sea level rise is similar across the CIRA scenarios through mid-century, primarily due to inertia in the global climate system and lasting effects from past GHG emissions. As a result, it is not until the second half of the century that global GHG mitigation results in a reduction in sea level rise compared to the Reference.

The projections for global sea level rise account for dynamic ice-sheet melting by estimating the rapid response of sea levels to atmospheric temperature change.[24] These adjustments incorporate estimates of ice-sheet melt from the empirical model of Vermeer and Rahmstorf (2009),[25,26] using the decadal trajectory of global mean surface air temperature results from the IGSM as inputs.[27]

Figure 1. Change in Global Mean Sea Level with and without Global GHG Mitigation

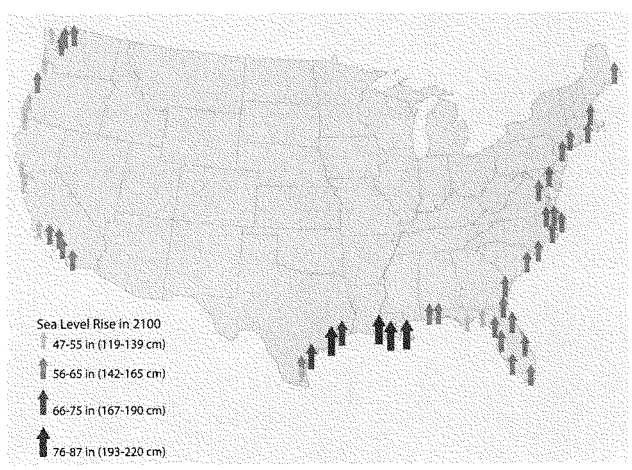


Sea Level Rise in the U.S.

Figure 2 shows projected relative sea level rise under the Reference scenario for select areas along the U.S. coast in 2100. For each coastal area, global rates of sea level change under the two scenarios were adjusted to account for vertical land movement (e.g., subsidence or uplift) using tide gauge data.[28] Areas located along the Gulf of Mexico and Atlantic Coast are projected to experience greater sea level rise, due to compounding effects of land subsidence, while areas along the West Coast are estimated to experience relatively lower levels of rise.

Figure 2. Projected Sea Level Rise along the Contiguous U.S. Coastline in 2100

Map shows projected relative (to land) sea level rise under the Reference scenario for select coastal counties in the contiguous U.S. Projections are based on global mean sea level rise in 2100 (56 inches), adjusted for local subsidence and uplift.[29]



CIRA FRAMEWORK

Levels of Certainty

The CIRA modeling project was designed to investigate the relative importance of four key sources of uncertainty inherent to projecting future climate:

Future GHG emissions: Future emissions will be driven by population growth, economic growth, technology advancements, and decisions regarding climate and energy policy. Sensitivity analyses explore the uncertainty associated with varying levels of future GHG emissions under different policy scenarios.

Climate sensitivity: Future climate change depends on the response of the global climate system to rising GHG concentrations (i.e., how much temperatures will rise in response to a given increase in atmospheric CO_2). This response is complicated by a series of feedbacks within Earth's climate system that act to amplify or diminish an initial change.[33] Climate sensitivity is typically reported as the change in global mean temperature resulting from a doubling in atmospheric CO_2 concentration.

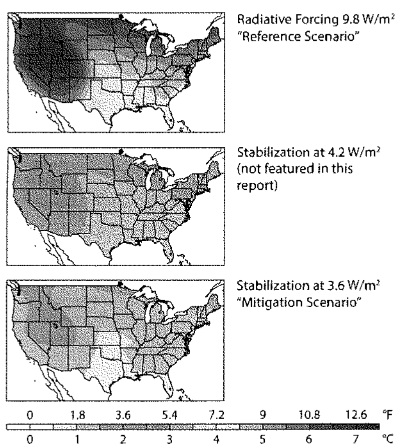
Natural variability: Natural, small- to medium-scale variations within Earth's climate system, such as El Niño events and other recurring patterns of ocean-atmosphere interactions, can drive increases or ⟶

Emissions Scenarios

The CIRA framework includes scenarios with different levels of GHG emissions: a business-as-usual scenario with unconstrained emissions ("Reference") and a total radiative forcing of 9.8 W/m^2 by 2100 (8.6 W/m^2 using the IPCC method for calculating radiative forcing); a stabilization scenario reflecting global-scale reductions in GHG emissions, with a total radiative forcing of 4.2 W/m^2 by 2100 (3.8 W/m^2 using IPCC method; this scenario is not featured in this report); and a more stringent stabilization scenario with greater emissions reductions ("Mitigation") and a total radiative forcing of 3.6 W/m^2 by 2100 (3.2 W/m^2 using IPCC method).[34] Results using the Reference and Mitigation scenarios are the focus of this report.

Figure 1. Temperature Change in 2100 Relative to Present Day for the CIRA Emissions Scenarios

Changes in surface air temperature in 2100 (2091-2110 mean) relative to present-day (1991-2010 mean).[35]



Climate Sensitivity

The four climate sensitivity values considered are 2, 3, 4.5, and 6°C, which represent, respectively, the lower bound (CS 2°C), best estimate (CS 3°C), and upper bound (CS 4.5°C) of likely climate sensitivity based on the IPCC Fourth Assessment Report (AR4),[36] and a low-probability/high-risk climate sensitivity (CS 6°C).[37] Results using a climate sensitivity of 3°C are the focus of this report.

Figure 2. Influence of Climate Sensitivity on Global Temperature Change Relative to Present Day

Temperature change relative to the historic baseline (mean 1980-2009) under the Reference and Mitigation scenarios. The bold lines represent the results using a climate sensitivity of 3°C, and the shaded areas represent the range of temperature anomaly outcomes when using climate sensitivities of 2°C and 6°C.

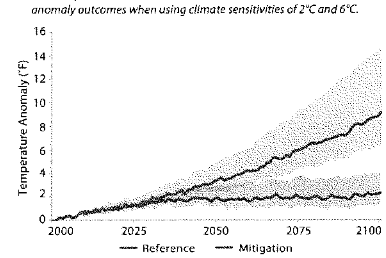
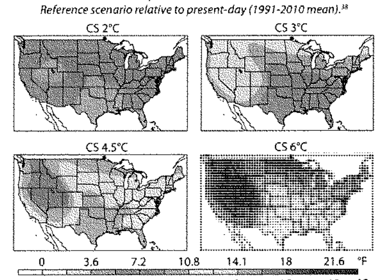


Figure 3. Future Temperature Change under Different Climate Sensitivities

Increases in surface air temperature in 2100 (2091-2110 mean) under the Reference scenario relative to present-day (1991-2010 mean).[38]

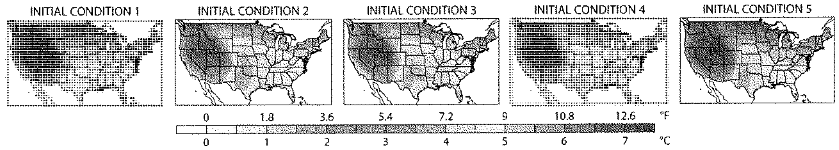


Natural Variability

For each emissions scenario and climate sensitivity combination, the IGSM-CAM was simulated five times with slightly different initial conditions ("initializations") to account for uncertainty due to natural variability. Some sectors in the report use the average result of the five initializations.

Figure 4. The Effect of Natural Variability on Future Climate Projections

Increases in surface air temperature in 2100 (2091-2110 mean) relative to present-day (1991-2010 mean) for each of the IGSM-CAM initializations.[39]



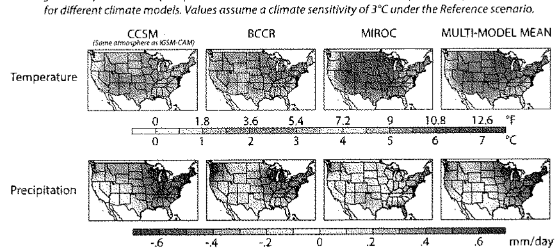
Climate Model

The results presented in this report rely primarily upon climate projections from the IGSM-CAM. To analyze the implications of a broader set of climate model outputs, the CIRA framework uses a pattern scaling method in the IGSM[40] for three additional climate models, plus a multi-model ensemble mean from the IPCC AR4 archive. As shown in Figure 5, there is better agreement across climate models with regard to temperature projections, and higher variability with regard to precipitation projections.[41]

- The NCAR Community Climate System Model version 3 (CCSM3.0) was chosen to compare with the IGSM- CAM model. Both have the same atmospheric and land components and similar biases over land.
- Bjerknes Centre for Climate Research Bergen Climate Model version 2.0 (BBCR_BCM2.0) was chosen because this model projects the largest increases in precipitation over the contiguous U.S.
- Model for Interdisciplinary Research on Climate version 3.2 medium resolution (MIROC3.2_medres) was chosen because this model projects decreases in precipitation over much of the contiguous U.S. Results using this "drier" pattern are shown in several sections of this report to provide comparison to the "wetter" IGSM-CAM simulations, which generally show increases in precipitation for much of the country (excluding the West). This comparison helps to bound uncertainty in future changes in precipitation for the contiguous U.S.

Figure 5. Climate Model Uncertainty for Future Projections

Changes in temperature and precipitation in 2100 (2091-2110 mean) relative to present-day (1991-2010 mean) for different climate models. Values assume a climate sensitivity of 3°C under the Reference scenario.



Future Climate Change Across Uncertainty Sources

Investigation of the relative contribution of the four sources of uncertainty described in this section reveals that temperature change is most influenced by decisions regarding whether to reduce GHG emissions and the value of climate sensitivity used (GHG emissions scenario being the dominant contributor). The contributions from different climate models and natural variability for temperature change are small in comparison. It is worth noting that the GHG emissions scenario is the only source of uncertainty that society has control over. Conversely, these same four sources of uncertainty contribute in roughly equal measure to projected changes in precipitation over the U.S., with large spatial differences.[42]

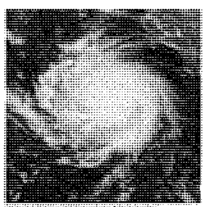
Boundaries of Analysis

The design of the CIRA project allows the results to be interpreted as the potential benefits (avoided impacts) to many economically important sectors of the U.S. due to global-scale actions to mitigate GHG emissions. The analytical approach offers a number of advantages, including consistency in the use of socio-economic and climate change scenarios across a wide range of sectoral impact and damage models, and exploration of the changes in impacts and damages across key sources of uncertainty.

As with any study, there are some analytical boundaries of the CIRA project and its underlying analyses that are important to consider, several of which are described below.[43] Future work to address these limitations will strengthen the estimates presented in this report, including the broader use of ranges and confidence intervals. Limitations specific to the individual sectoral analyses are described in the Sectors section of this report, as well as in the scientific literature underlying the analyses.

Emission and Climate Scenarios

With the goal of presenting a consistent and straightforward set of climate change impact analyses across sectors, this report primarily presents results for the Reference and Mitigation scenarios under a single simulation (initialization) of the IGSM-CAM climate model and assumes a climate sensitivity of 3°C. As described in the Levels of Certainty section, a large number of emissions and climate scenarios were developed under the CIRA project, reflecting various combinations of emissions scenarios, climate models, climate sensitivity, and climate model initializations. However, only some of these emissions and climate scenarios have been simulated across all sectoral analyses, primarily due to the level of effort necessary to run each scenario through the large number of sectoral models of the CIRA project. Analyzing results under the full set of scenarios would further characterize the range and potential likelihood of future risks.



Coverage of Sectors and Impacts

The analyses presented in this report cover a broad range of potential climate change impacts in the U.S., but there are many important impacts that have not yet been modeled in CIRA. Examples of these impacts include changes in vector-borne disease, morbidity from poor air quality, impacts on specialty crops and livestock, and a large number of effects on ecosystems and species. Without information on these impacts, this report provides only partial insight into the potential risks of climate change, and therefore does not account for all potential benefits of mitigation.

In addition, it is important to note that impacts are only partially valued economically in some sectors. For example, the Wildfire section presents estimated response and fuel management costs, but not other damages (e.g., health effects from decreased air quality, and property damages). A more complete valuation approach would likely increase the damages described in this report.

Finally, this report does not present results on the possibility of large-scale, abrupt changes that have wide-ranging and possibly catastrophic consequences, such as the intensification of tropical storms, or the rapid melting of the Greenland or West Antarctic ice sheets.[44] In general, there are many uncertainties regarding the timing, likelihood, and magnitude of the impacts resulting from these abrupt changes, and data limitations have precluded their inclusion in the analyses presented in this report. Their inclusion would assist in better understanding the totality of risks posed by climate change and the potential for GHG mitigation to reduce or avoid these changes.

Variability Across Climate Models

The choice of climate model in an impact analysis can influence patterns of future climate change. Within a number of the CIRA analyses, this uncertainty was evaluated through the use of "pattern scaling," a method by which the average change produced by running a climate model is combined with the specific geographic pattern of change calculated from a different model in order to approximate the result that would be produced by the second model. In this report, analyses that are sensitive to changes in precipitation are presented using both the IGSM-CAM (relatively wetter for the contiguous U.S.) and MIROC (relatively drier) climate models. However, not all sectoral impact models used pattern scaling in addition to the IGSM-CAM simulations, particularly for those impacts primarily driven by temperature, where there is generally more agreement across climate models. Finally, we note the limitation that pattern scaling is not a perfect representation of alternate models.[45]

Sectoral Impacts Modeling

With the exception of the electricity demand and supply sections of this report, the impact estimates presented were developed using a single sectoral impact model. While these models are complex analytical tools, the structure of the model, and how it may compare to the design of similar applications, can create important uncertainties that affect the estimation of impacts.[46] The use of additional models for each sector would help improve the understanding of potential impacts in the future. The results presented in this report were developed with little or no interactions among the impact sectors. As a result, the estimated impacts may omit important and potentially unforeseen effects. For example, the wildfire projections presented in this report will likely generate meaningful increases in air pollution, a potentially important linkage for the air quality analysis. Similarly, there are numerous connections among the agriculture, water, and electricity sectors that affect the impacts estimates in each.[47] Although some of these interactions are captured within integrated assessment models, it is difficult for these broader frameworks to capture all of the detail provided in the CIRA sectoral analyses. Improved connectivity between CIRA sectoral models will aid in gaining a more complete understanding of climate change impacts across sectors in the U.S.

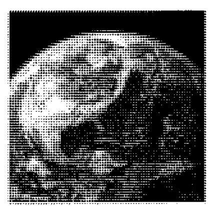
Variability in Societal Characteristics

The impacts of climate change will not affect Americans equally. In addition to regional differences in impacts, socioeconomic factors (e.g., income, education) affect adaptive capacity and can make some communities more vulnerable to impacts. These issues are explored in the Coastal Property section, but the rest of the sectors do not analyze impacts across different levels of social vulnerability.

Feedbacks

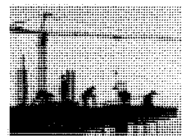
The CIRA project uses a linear path from changes in socioeconomics and the climate system to impacts (with consistent inputs across multiple models). The socioeconomic scenarios that drive the CIRA modeling analyses do not incorporate potential feedbacks from climate change impacts to the climate system (e.g., GHG emissions from forest fires) and from sectoral damages to the economy (e.g., significant expenditures on "climate defensive" adaptation would likely reduce available financial capital to the economy for productive uses, or increase the cost of financing capital expenditures).

Geographic Coverage



The report does not examine impacts and damages occurring outside of U.S. borders. Aside from their own relevance for policy-making, these impacts could affect the U.S. through, for example, changes in world food production, migration, and concerns for national security.

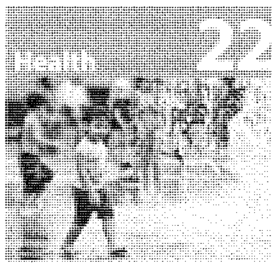
In addition, the primary geographic focus of this report is on the contiguous U.S., with most of the sectoral analyses excluding Hawaii, Alaska, and the U.S. territories. This omission is particularly important given the unique climate change vulnerabilities of these high-latitude and/or island locales. Finally, several sectoral analyses assess impacts in a limited set of major U.S. cities, and incorporation of additional locales would gain a more comprehensive understanding of likely impacts.

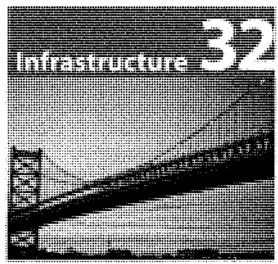


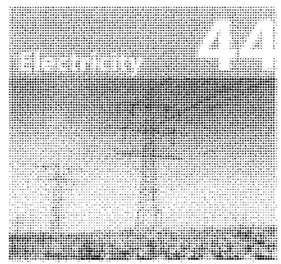
Use of Point Estimates

Results in this report are primarily presented as point estimates. For some sectors, ranges are provided based on the design of the underlying modeling analysis (i.e., the approach yields confidence intervals) or because of the scenarios used in that sector. Regarding the latter, the use of wetter and drier climate projections for sectors sensitive to changes in precipitation provides ranges of estimates bounding this uncertainty source. The uncertainties and limitations described in this section, along with others detailed throughout this report and in the underlying CIRA literature, signify that the estimates described in this report should not be interpreted as definitive predictions of future impacts at a particular place and time. The further exploration of these uncertainties, including the development of ranges for all impact projections, will further strengthen the CIRA results.

Sectors







ABOUT THE RESULTS

Unless otherwise noted, results presented in this section were developed using the following:

Emissions scenarios: The results are presented for the CIRA Reference and Mitigation scenarios.

Climate models: The results primarily rely upon climate projections from the IGSM-CAM. For sectors sensitive to changes in precipitation, results are also presented for the drier MIROC climate model.

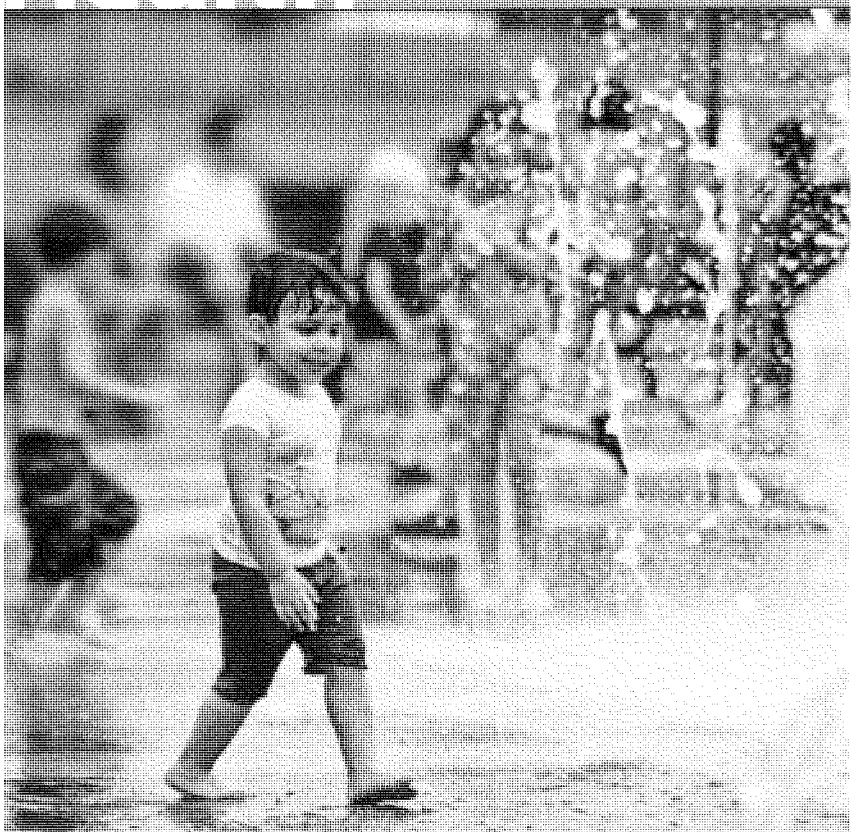
Climate sensitivity: The results assume a climate sensitivity of 3.0°C.

Accounting for inflation: The results are presented in constant 2014 dollars.[1]

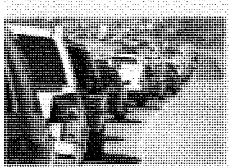
Discounting: To estimate present value, annual time series of costs are discounted at a 3% annual rate, with a base year of 2015.[2] Annual estimates (i.e., costs in a given year) are not discounted.

Reporting of estimates: For consistency, results are reported with two significant figures.

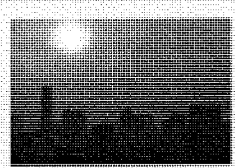
Health



SUBSECTORS



Air Quality



Extreme Temperature

Weather and climate play a significant role in our health and well-being. As a society, we have structured our day-to-day behaviors and activities around historical and current climate conditions. Increasing GHGs in the atmosphere are changing the climate faster than any time in recent history.[3] As a result, the conditions we are accustomed to and the environment in which we live will change in ways that affect human health. In addition to creating new problems, changes in the climate can exacerbate existing human health stressors, such as air pollution and disease. Many of the adverse effects brought on by climate change may be compounded by how our society is changing, including population growth, an aging population, and migration patterns that are concentrating development in urban and coastal areas.

HOW ARE PEOPLE VULNERABLE TO CLIMATE CHANGE?

Climate change is projected to harm human health in a variety of ways through increases in extreme temperature, increases in extreme weather events, decreases in air quality, and other factors.[4] Extreme heat events can cause illnesses and death due to heat stroke, cardiovascular disease, respiratory disease, and other conditions. Increased ground-level ozone is associated with a variety of health problems, including reduced lung function, increased frequency of asthma attacks, and even premature mortality.[5] Higher temperatures and changes in the timing, intensity, and duration of precipitation affect water quality, with impacts on the surface water we use. There are a variety of other impacts driven by climate change that are expected to pose significant health hazards, including increases in wildfire activity (see the Wildfire section of this report).[6]

WHAT DOES CIRA COVER?

CIRA analyzes the potential impacts of climate change on human health by focusing on air quality, extreme temperature mortality, labor, and water quality. Analyses of many other important health effects are not included in CIRA; these include, for example, impacts from increased extreme weather events (e.g., injury or death from changes in tropical storms), air pollution from wildfires, and vector-borne disease (e.g., Lyme disease and West Nile virus).

Labor

Water Quality

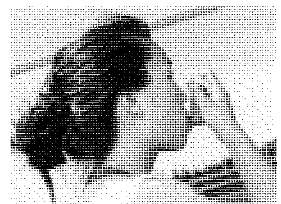
Air Quality

KEY FINDINGS

1. Unmitigated climate change is projected to worsen air quality across large regions of the U.S., especially in eastern, mid-western, and southern states. Impacts on ozone and fine particulate matter pollution are projected to be especially significant for densely-populated areas. The analysis holds emissions of traditional air pollutants constant at current levels to isolate the climate change related impact on air quality.

2. Global GHG mitigation is projected to reduce the impact of climate change on air quality and the corresponding adverse health effects related to air pollution. Mitigation is estimated to result in significant public health benefits in the U.S., such as avoiding 13,000 premature deaths in 2050 and 57,000 premature deaths in 2100. Economic benefits to the U.S. of avoided premature deaths are estimated at $160 billion in 2050, and $930 billion in 2100.

Climate Change and Air Quality Health Effects



Changes in climate are projected to affect air quality across the U.S. In already polluted areas, warmer temperatures are anticipated to increase ground-level ozone (O_3), a component of smog, and increase the number of days with poor air quality.[7] Changes in weather patterns may also affect concentrations of fine particulate matter ($PM_{2.5}$), a mixture of particles smaller than 2.5 micrograms per cubic meter ($\mu g\ m^{-3}$), emitted from power plants, vehicles, and wildfires. Inhaling ozone and fine particulate matter can lead to a broad range of adverse health effects, including premature mortality and aggravation of cardiovascular and respiratory disease.[8,9]

Risks of Inaction

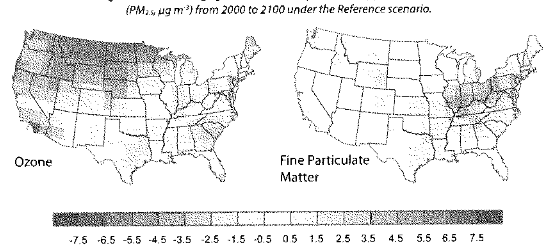
Without global GHG mitigation, climate change is projected to have a substantial effect on air quality across the contiguous U.S., with important regional differences (Figure 1). Ozone concentrations are projected to increase in the Reference scenario in more densely-populated regions, such as the East, Midwest, and South, while some less densely-populated areas experience decreases in ozone concentrations.[10] Although the national annual average ozone concentration is projected to decrease slightly (1.3 ppb +/- 0.2) by 2100, human exposure to ozone is projected to increase, driven by increasing concentrations in densely-populated areas. Climate-driven ozone increases are especially substantial during summer months. By 2100, the U.S.-average 8-hour-maximum ozone concentration in June-August is projected to increase 4.7 ppb (95% confidence interval ± 0.5).[11]

Unmitigated climate change is projected to exacerbate fine particulate matter pollution, especially in the Midwest and East. The annual U.S.-average $PM_{2.5}$ concentrations are projected to increase by 0.3 $\mu g\ m^{-3}$ (± 0.1) in 2050 and 0.7 $\mu g\ m^{-3}$ (± 0.1) in 2100 in the Reference scenario.[12]

Projections that climate change will lead to increased ozone in polluted regions are consistent with the assessment literature. There is less agreement regarding the magnitude of climate change effects on particulate matter, with the exception of increasing wildfire activity on particulates.[13] The results presented in this report add to this emerging area of research.

Figure 1. Projected Impacts of Unmitigated Climate Change on Air Pollution in the U.S.

Estimated change in annual-average ground-level hourly ozone (O_3, ppb) and fine particulate matter ($PM_{2.5}$, $\mu g\ m^{-3}$) from 2000 to 2100 under the Reference scenario.



Reducing Impacts through GHG Mitigation

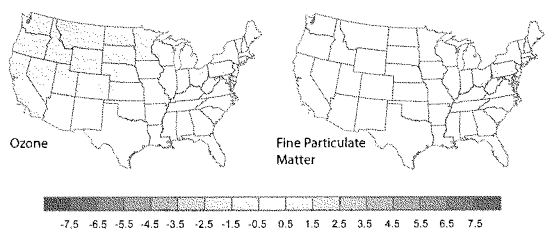
Global GHG mitigation is projected to avoid significant adverse impacts to air quality that would occur under the Reference scenario in densely-populated areas. Figure 2 shows air quality changes in the Mitigation scenario, which are much smaller than those under the Reference (Figure 1). Despite smaller reductions in ozone in some less densely-populated areas, global GHG mitigation is projected to reduce the increase in the annual-average, 8-hour-maximum, population-weighted ozone concentration by approximately 2.6 ppb (95% confidence interval ± 0.3) that would occur in the Reference in the U.S.

Global GHG mitigation is also projected to lessen the adverse effects of climate change on fine particulate matter pollution in the U.S. In 2100, the increase in the annual-average population-weighted $PM_{2.5}$ concentration under the Reference is reduced by approximately 1.2 $\mu g\ m^{-3}$ (± 0.1) under the Mitigation scenario.

Reducing the impacts of climate change on air quality through global GHG mitigation is projected to result in significant health benefits across the U.S. For example, the Mitigation scenario is estimated to prevent an estimated 13,000 premature deaths in 2050 (95% confidence interval of 4,800-22,000) and 57,000 premature deaths in 2100 (95% confidence interval of 21,000-95,000) compared to the Reference.[14] Economic benefits to the U.S. of these avoided deaths are estimated at $160 billion and $930 billion in 2050 and 2100, respectively. In addition to reducing premature mortality, global GHG mitigation would result in other health benefits not presented here, including reduced respiratory- and cardiovascular-related hospital admissions.[15,16]

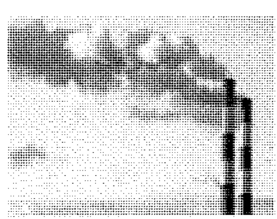
Figure 2. Projected Impacts on Air Pollution in the U.S. with Global GHG Mitigation

Estimated change in annual-average ground-level hourly ozone (O_3, ppb) and fine particulate matter ($PM_{2.5}$, $\mu g\ m^{-3}$) from 2000 to 2100 under the Mitigation scenario.



Treatment of Co-Benefits

This analysis does not quantify the additional benefits to air quality and health that would stem from simultaneous reductions in traditional air pollutants along with GHG emissions (both are emitted from many of the same sources). Incorporating these "co-benefits," which recent analyses[17] and assessments[18] indicate could provide large, near-term benefits to human health, would result in a more comprehensive understanding of air quality and climate interactions.



APPROACH

The CIRA analysis assesses the impact of climate change on air quality across the contiguous U.S. through changes in ground-level ozone and fine particulate matter ($PM_{2.5}$) concentrations.[19] Future concentrations of these pollutants are simulated in an atmospheric chemistry model, driven by weather patterns from the CIRA climate projections. The analysis projects future concentrations for five initializations of the IGSM-CAM climate model under the Reference and Mitigation scenarios in 30-year periods centered on 2050 and 2100 (with 95% confidence intervals based on the difference in mean across the initializations). Despite assumptions about growth in GHG emissions in the Reference and Mitigation scenarios, emissions of the traditional air pollutants are kept fixed at present-day levels to isolate the climate change-related impact on air quality. Changes in pollution due to projected increases in wildfires and changes in sea salt and dust are not considered. Pollutant concentrations are used to estimate changes in air pollution exposure in people. The Environmental Benefits Mapping and Analysis Program (BenMAP) is applied to estimate health effects (with 95% confidence interval based on concentration response functions in BenMAP).[20] To monetize the effects of changing mortality, a value of statistical life (VSL) of $9.45 million for 2010 (2014$) is used, adjusted to future years by assuming an elasticity of VSL to gross domestic product (GDP) per capita of 0.4.[21]

For more information on the approach, models used, and results for the air quality sector, please refer to Garcia-Menendez et al. (2015).[22]

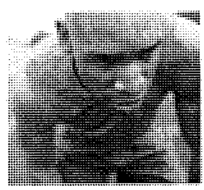
Extreme Temperature

KEY FINDINGS

1. Without global GHG mitigation, the average number of extremely hot days in the U.S. is projected to more than triple from 2050 to 2100. The projected reduction in deaths from extremely cold days is more than offset by the projected increase in deaths from extremely hot days. This result holds for all reported future years, indicating that unmitigated climate change clearly poses an increasing health risk from extreme temperatures.

2. Global GHG mitigation is projected to result in approximately 12,000 fewer deaths from extreme temperature in the 49 modeled cities in 2100. Inclusion of the entire U.S. population would greatly increase the number of avoided deaths, but accounting for adaptation could decrease the number.

Climate Change and Extreme Temperature Mortality



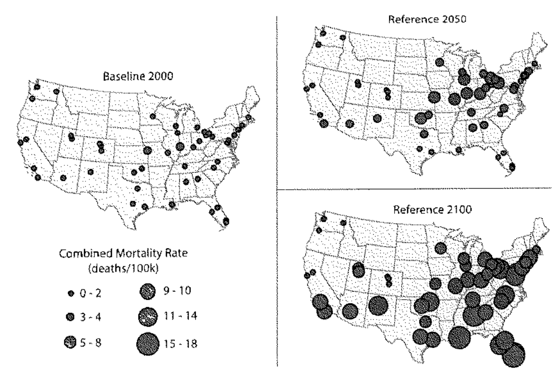
Climate change will alter the weather conditions that we are accustomed to. Extreme temperatures are projected to rise in many areas across the U.S., bringing more frequent and intense heat waves and increasing the number of heat-related illnesses and deaths.[23] Exposure to extreme heat can overwhelm the body's ability to regulate its internal temperatures, resulting in heat exhaustion and/or heat stroke, and can also exacerbate existing medical problems, such as heart and lung diseases.[24] During a 1995 heat wave in Chicago, an estimated 700 individuals died as a result of the extreme heat.[25] Warmer temperatures are also expected to result in fewer extremely cold days, which may also reduce deaths associated with extreme cold.[26]

Risks of Inaction

Climate change poses a significant risk to human health as more days with extreme heat are projected to cause more deaths over time. Without global GHG mitigation, the average number of extremely hot days is projected to more than triple from 2050 to 2100, while the number of extremely cold days is projected to decrease. The projected increase in deaths due to more frequent extremely hot days is much larger than the projected decrease in deaths due to fewer extremely cold days, a finding that is consistent with the conclusions of the assessment literature.[27] Under the Reference, the net increase in projected deaths from more extremely hot days and fewer extremely cold days in 49 cities is approximately 2,600 deaths in 2050, and 13,000 deaths in 2100, but accounting for adaptation could decrease these numbers. Figure 1 shows the net mortality rate from extreme hot and cold temperatures by city in the Reference scenario.

Figure 1. Projected Extreme Temperature Mortality in Select Cities Due to Unmitigated Climate Change

Estimated net mortality rate from extremely hot and cold days (number of deaths per 100,000 residents) under the Reference scenario for 49 cities in 2050 and 2100. Red circles indicate cities included in the analysis; cities without circles should not be interpreted as having no extreme temperature impact.

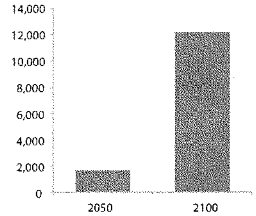


Reducing Impacts through GHG Mitigation

As shown in Figure 2, the projected mortality rates under the Mitigation scenario show small changes through 2100, unlike in the Reference where rates increase substantially. As a result, the net benefits associated with GHG mitigation increase over time. As shown in Figure 3, global GHG mitigation is estimated to result in significant public health benefits across the U.S. by substantially reducing the risk of extreme temperature-related deaths that would occur under the Reference. Under the Mitigation scenario, extreme temperature mortality is reduced by 64% in 2050 and by 93% in 2100[28] compared to the Reference. For the 49 cities analyzed, global GHG mitigation is projected to save approximately 1,700 U.S. lives in 2050, and approximately 12,000 U.S. lives in 2100 (Figure 3).

In 2050, the economic benefits of GHG mitigation are estimated at $21 billion, increasing to $200 billion in 2100 (see the Approach section for more information). It is important to note that these projections reflect only the results for the 49 cities included in this study; corresponding national benefits would be much larger.

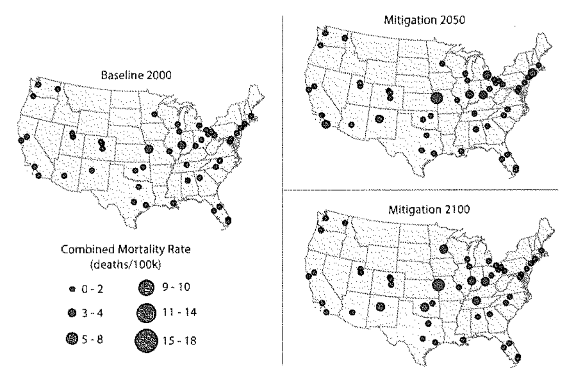
Figure 3. Avoided Extreme Temperature Mortality in 49 U.S. Cities Due to Global GHG Mitigation



The analysis also examines the implications of adjusting temperature thresholds to account for potential adaptation of the human body to warmer temperatures. Specifically, the analysis assumes that the human health response to extreme temperatures in all 49 cities was equal to that of Dallas. Using this approach, results show that mitigation would still save a projected 5,500 lives in 2100 compared to the Reference.

Figure 2. Projected Extreme Temperature Mortality in Select Cities with Global GHG Mitigation

Estimated net mortality rate from extremely hot and cold days (number of deaths per 100,000 residents) under the Mitigation scenario for 49 cities in 2050 and 2100. Red circles indicate cities included in the analysis; cities without circles should not be interpreted as having no extreme temperature impact.



APPROACH

The CIRA analysis estimates the number of deaths over the course of the 21st century attributable to extreme temperatures in 49 cities in the contiguous U.S., which account for approximately one third of the national population. City-specific relationships between daily deaths (of all causes) and extreme temperatures are combined with the IGSM-CAM projections of extremely hot and cold days using city-specific extreme temperature thresholds to estimate future deaths from heat and cold in the Reference and Mitigation scenarios. Extremely hot days are defined as those with a daily minimum temperature warmer than 99 percent of the days in the period 1989-2000. Extremely cold days are defined as those with a daily maximum temperature colder than 99 percent of the days in the period 1989-2000. As a result, the study explicitly addresses the question of the net mortality impact of climate change on future extreme temperature days. The potential impact of future population change is accounted for using an EPA demographic model (ICLUS).[29] To monetize the effects of changing mortality, a baseline value of statistical life (VSL) of $9.45 million for 2010 (2014$) is used, adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4.[30] The results presented in this section have been updated since Mills et al. (2014) to include additional cities and more recent mortality rate data.[31] Finally, this analysis did not estimate impacts across ages or socioeconomic status. As these demographics change, they could impact the results presented here.

For more information on the CIRA approach and results for the extreme temperature mortality sector, please refer to Mills et al. (2014).[32]

Labor

KEY FINDINGS

1. Without global GHG mitigation, labor hours in the U.S. are projected to decrease due to increases in extreme temperatures. Over 1.8 billion labor hours are projected to be lost in 2100, costing an estimated $170 billion in lost wages.

2. Global GHG mitigation is estimated to save 1.2 billion labor hours and $110 billion in wages in 2100 in the contiguous U.S. that would otherwise be lost due to unmitigated climate change.

Climate Change and Labor

Climate change may affect labor in a number of ways, but projections of hotter summer temperatures raise a particular concern. Extreme summer heat is increasing in the U.S. and will be more frequent and intense in the future.[33] Heat exposure can affect workers' health, safety and productivity.[34] When exposed to high temperatures, workers are at risk for heat-related illnesses and therefore may take more frequent breaks, or have to stop work entirely, resulting in lower overall labor capacity. This is especially true for high-risk industries where workers are doing physical labor and have a direct exposure to outdoor temperatures (e.g., agriculture, construction, utilities, and manufacturing).[35]

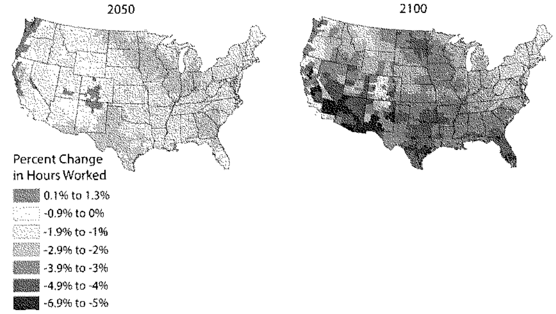
Risks of Inaction

Without global GHG mitigation, an increase in extreme heat is projected to have a large negative impact on U.S. labor hours, especially for outdoor labor industries. In 2100, over 1.8 billion labor hours across the workforce are projected to be lost due to unsuitable working conditions (95% confidence interval of 1.2-2.4 billion). These lost hours would be very costly, totaling over $170 billion in lost wages in 2100 (95% confidence interval of $110-$220 billion).

As shown in Figure 1, the majority of the country is projected to experience decreases in labor hours due to extreme temperature effects. In 2100, parts of the Southwest and Florida are estimated to experience a decrease in hours worked for high-risk industries ranging from -5% to -7%. Although the impacts vary by region, only a limited number of counties are projected to experience increases in labor hours.

Figure 1. Impacts of Unmitigated Climate Change on Labor in the U.S.

Estimated percent change in hours worked from 2005 to 2050 and 2100 under the Reference scenario. Estimates represent change in hours worked at the county level for high-risk industries only, and are normalized by the high-risk working population in each county.



Reducing Impacts through GHG Mitigation

At the national level, impacts to labor under the Mitigation scenario (Figure 2) are substantially smaller compared to the Reference (Figure 1). Counties in the Southwest, Texas, and Florida that are estimated to lose up to 7% of high-risk labor hours under the Reference in 2100 do not experience such losses under the Mitigation scenario.

When comparing the two scenarios (Figure 3), global GHG mitigation is projected to prevent the loss of approximately 360 million labor hours across the workforce in 2050, saving nearly $18 billion in wages. In 2100, the avoided loss of labor hours more than triples, and losses are substantially reduced over a majority of the contiguous U.S. Specifically, mitigation is estimated to prevent the loss of nearly 1.2 billion labor hours and $110 billion in wages in 2100 compared to the Reference.

Figure 2. Labor Impacts in the U.S. with Global GHG Mitigation

Estimated percent change in hours worked from 2005 to 2050 and 2100 under the Mitigation scenario. Estimates represent change in hours worked at the county level for high-risk industries only, and are normalized by the high-risk working population in each county.

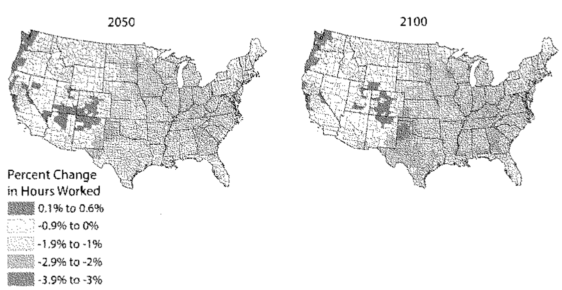
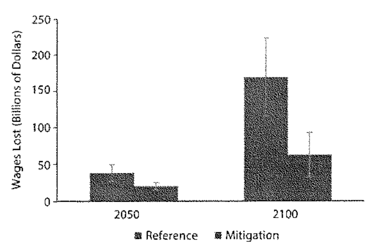


Figure 3. Economic Impacts to Labor with and without Global GHG Mitigation

Estimated wages lost under the Reference and Mitigation scenarios for all labor categories in the contiguous U.S. (billions 2014$). Error bars represent lower- and upper-95% confidence intervals of the dose-response function (see the Approach section for more information).

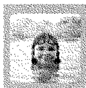


APPROACH

The CIRA analysis focuses on the impact of changes in extreme temperatures on labor supply[36] across the contiguous U.S. Specifically, the analysis estimates the number of labor hours lost due to changes in extreme temperatures using dose-response functions for the relationship between temperature and labor from Graff Zivin and Neidell (2014).[37] Mean maximum temperatures from the IGSM-CAM are projected for two future periods (2050 and 2100, 5-year averages centered on those years) at the county level in the CIRA Reference and Mitigation scenarios. The analysis estimates the total labor hours lost in all categories of the labor force and also for workers in high-risk industries (most likely to be strongly exposed to extreme temperature), taking into account the CIRA county-level population projections from the ICLUS model.[38] The fraction of workers in high-risk industries is calculated using Bureau of Labor Statistics data from 2003-2007 and is assumed to remain fixed over time for each county.[39] A range of estimates for the dose-response function are assessed and used to calculate confidence intervals to show the sensitivity of the results. The dose-response functions are estimates of short-run responses to changes in weather, and as such do not account for longer-term possibilities, such as acclimation of workers, relocation of industries, or technological advancements to reduce exposure.

The analysis estimates the cost of the projected losses in labor hours based on the Bureau of Labor Statistics' estimated average wage in 2005 ($23.02 per hour in a 35 hour work week),[40] adjusted to 2100 based on the projected change in GDP per capita.

For more information on the CIRA approach for the labor sector, please refer to Graff Zivin and Neidell (2014)[41] and Section G of the Technical Appendix for this report.



Water Quality

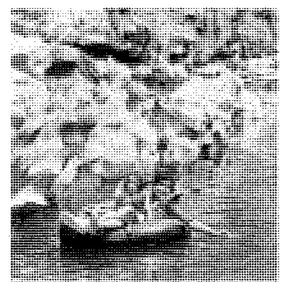
KEY FINDINGS

1. Unmitigated climate change is projected to have negative impacts on water quality in the U.S., particularly in the Southwest and parts of Texas.

2. Global GHG mitigation is projected to prevent many of the water quality damages estimated under the Reference scenario, primarily by reducing the warming of water bodies across the country.

3. Under the Mitigation scenario, costs associated with decreased water quality are reduced approximately 82% in 2100 compared to the Reference, corresponding to cost savings of approximately $2.6-$3.0 billion.

Climate Change and Water Quality



Climate change is likely to have far-reaching effects on water quality in the U.S. due to increases in river and lake temperatures and changes in the magnitude and seasonality of river flows, both of which will affect the concentration of water pollutants. These physical impacts on water quality will also have potentially substantial economic impacts, since water quality is valued for drinking water and recreational and commercial activities such as boating, swimming, and fishing.[42,43] The analysis presented in this section estimates changes in water quality, but does not quantify the resulting health effects.

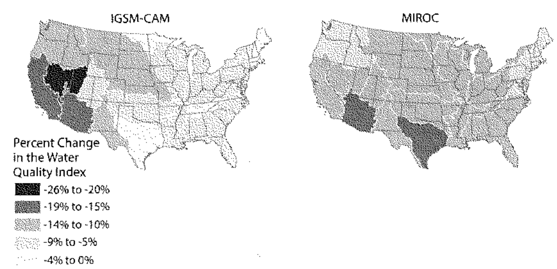
Risks of Inaction

Unmitigated climate change is projected to decrease water quality in the U.S. compared to a future with no climate change. The Water Quality Index (WQI) calculated in the CIRA analysis includes several key water quality constituents, including temperature, dissolved oxygen, total nitrogen, and total phosphorus.[44] The WQI serves as a measure of water quality; the higher the WQI, the higher the water quality.

As shown in Figure 1, the WQI across the U.S. is projected to decline in the Reference scenario in 2100 using both the IGSM-CAM and MIROC climate models. Parts of Texas and the Southwest, in particular, are estimated to experience substantial WQI declines of 15-26% in 2100. Projections that climate change will decrease river and lake water quality are consistent with the findings of the assessment literature.[45]

Figure 1. Effects of Unmitigated Climate Change on U.S. Water Quality in 2100

Percent change in the Water Quality Index in 2100 under the Reference scenario compared to the Control (to isolate the effects of climate change). The WQI is calculated for the 2,119 8-digit hydrologic unit codes (HUCs) of the contiguous U.S., and aggregated to the 18 Water Resource Regions (2-digit HUCs).



Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to reduce the increase in water temperature that is estimated to occur under the Reference, with corresponding water quality benefits (i.e., avoided degradation) primarily due to better oxygenation. The effects of mitigation on total nitrogen and total phosphorus concentrations vary by region, but the increase in total nitrogen is reduced by up to 80% in some areas of the western U.S. compared to the Reference scenario.

Figure 2 presents the projected change in water quality damages in 2050 and 2100 under the Reference and Mitigation scenarios for the IGSM-CAM and MIROC climate models. As shown in the figure, increases in damages are projected in both scenarios, but most notably in the Reference, where damages are estimated to increase by approximately $3.2-$3.7 billion in 2100. Under the Mitigation scenario, damages are reduced by approximately 82% compared to the Reference in 2100, corresponding to approximately $2.6-$3.0 billion in avoided costs.

Figure 3 presents the avoided water quality damages in 2100 under the Mitigation scenario compared to the Reference using the IGSM-CAM and MIROC climate models. As shown in the figure, global GHG mitigation is projected to result in economic benefits relative to the Reference across the entire contiguous U.S. California is projected to experience the greatest benefits of mitigation in 2100, ranging from approximately $750 million to $1.0 billion.

Figure 2. Change in U.S. Water Quality Damages with and without Global GHG Mitigation

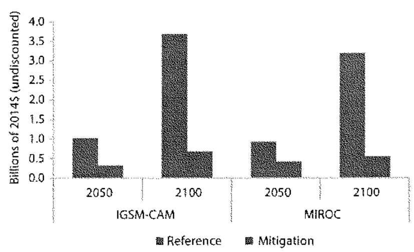
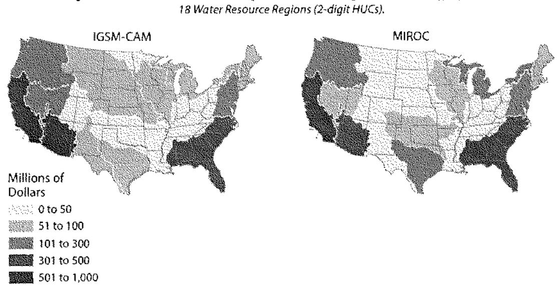


Figure 3. Benefits of Global GHG Mitigation for U.S. Water Quality in 2100

Avoided damages under the Mitigation scenario compared to the Reference in 2100 (millions 2014$). Damages are calculated for the 2,119 8-digit HUCs of the contiguous U.S., and aggregated to the 18 Water Resource Regions (2-digit HUCs).

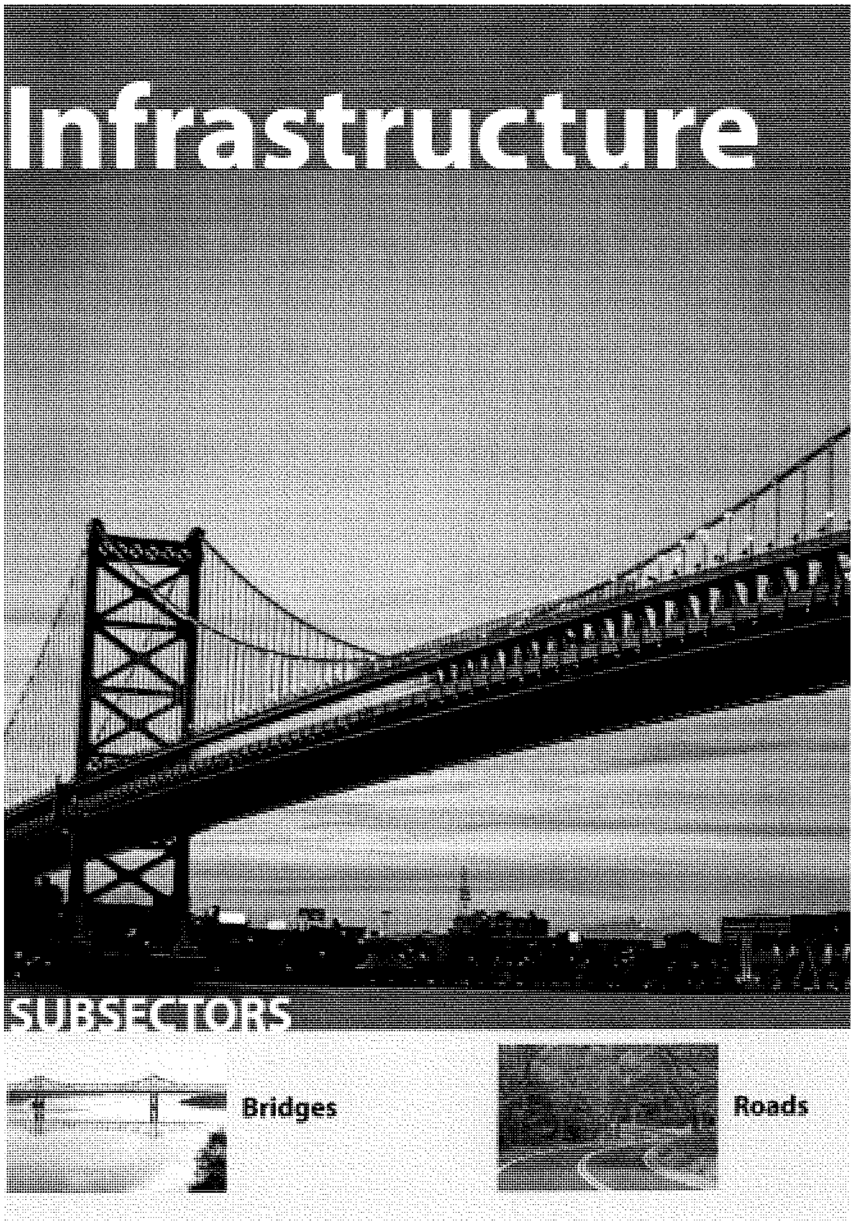


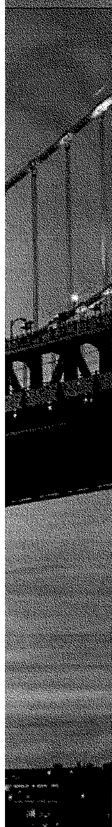
APPROACH

The CIRA analysis uses a series of linked models to evaluate the impacts of climate change on water quality in futures with and without global GHG mitigation. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. The CIRA temperature and precipitation projections inform a rainfall-runoff model (CLIRUN-II) that estimates river flow.[46] A water demand model projects water requirements of the municipal and industrial (M&I), agriculture, and other sectors. The runoff and demand projections inform a water supply and demand model that estimates reservoir storage and release, and in turn produces a time series of water allocations for the various demands. After this allocation step, the analysis relies on the QUALIDAD water quality model to simulate a number of water quality constituents in rivers and reservoirs.[47] Changes in overall water quality are estimated using changes in the Water Quality Index (WQI), a commonly used metric that combines multiple pollutant and water quality measures. Finally, a relationship between changes in the WQI and changes in the willingness to pay for improving water quality is used to estimate the economic implications of projected water quality changes.

Results for the CIRA scenarios are compared to a Control to isolate the effect of climate change. See the Water Resources section of this report for information on projected changes in the Inland Flooding, Drought, and Water Supply and Demand sectors. Decreases in water quality due to climate change will likely have an adverse effect on human health due to, for example, the increased risk of harmful aquatic blooms and impacts on sources of drinking water. Human health effects due to decreased water quality are not estimated, but are important considerations to fully understand climate change impacts in this sector. Inclusion of these effects would likely increase the benefits of GHG mitigation.

For more information on the CIRA approach and results for the water quality sector, please refer to Boehlert et al.[48]


Infrastructure
SUBSECTORS
Bridges
Roads



Infrastructure makes up the basic physical and organizational structure of our society and is by design interdependent and interconnected. Built infrastructure includes urban buildings; systems for energy, transportation, water, wastewater, drainage, and communication; industrial structures; and other products of human design and construction.[1] U.S. infrastructure has enormous value, both directly as a capital asset and indirectly to support human well-being and a productive economy.

Total public spending on transportation and water infrastructure exceeds $300 billion annually; roughly 25 percent of that total is spent at the federal level and accounts for three percent of total federal spending.[2] Recent analyses point to large gaps between existing capital and maintenance spending and the level of expenditure necessary to maintain current levels of services.[3]

HOW IS INFRASTRUCTURE VULNERABLE TO CLIMATE CHANGE?

Experience over the past decade provides compelling evidence of how vulnerable infrastructure can be to climate change effects, including sea level rise, storm surge, and extreme weather events.[4] Climate change will put added stress on the nation's aging infrastructure to varying degrees over time. Sea level rise and storm surge, in combination with the pattern of heavy development in coastal areas, are already resulting in damage to infrastructure such as roads, buildings, ports, and energy facilities. Floods along the nation's rivers, inside cities, and on lakes following heavy downpours, prolonged rains, and rapid melting of snowpack are damaging infrastructure in towns and cities, on farmlands, and in a variety of other places across the nation. In addition, extreme heat is damaging transportation infrastructure such as roads, rails, and airport runways.

WHAT DOES CIRA COVER?

CIRA analyzes potential climate change impacts and damages to four types of infrastructure in the U.S.: roads, bridges, urban drainage, and coastal property. Analyses of several important types of infrastructure are not included in CIRA, particularly telecommunications and energy transmission networks, and the Urban Drainage analysis only analyzes impacts in 50 cities of the contiguous U.S. Further, some analyses in this sector assume that adaptation measures will be well-timed. This likely results in conservative estimates of future damages, as history has shown that infrastructure investment and maintenance are often not implemented in optimal, well-timed ways.

Urban Drainage

Coastal Property

Bridges

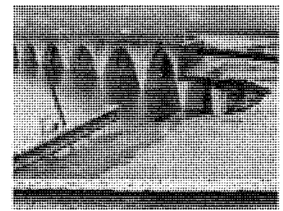
KEY FINDINGS

1. Without reductions in global GHG emissions, an estimated 190,000 inland bridges across the nation will be structurally vulnerable because of climate change by the end of the century. In some areas, more than 50% of bridges are projected to be vulnerable as a result of unmitigated climate change. This analysis estimates the damages of climate change in terms of increased costs to maintain current levels of service (i.e. adaptation costs). Without adaptation, climate change could render many bridges unusable, leading to large economic damages.

2. Global GHG mitigation is estimated to substantially reduce the number of bridges across the U.S. that become vulnerable in the 21st century by reducing the projected increase in peak river flows under the Reference scenario.

3. Global GHG mitigation is projected to reduce adaptation costs that would be incurred under the Reference scenario. The benefits of global GHG mitigation are estimated at \$3.4-\$42 billion from 2010-2050 and \$10-\$15 billion from 2051-2100 (discounted at 3%).

Climate Change and Bridges



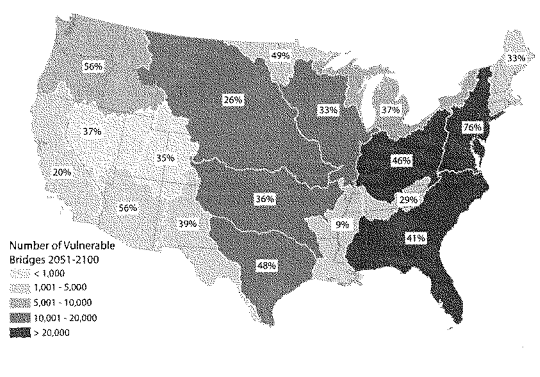
Road bridges are a central component of the U.S. transportation system. With the average U.S. bridge now over 40 years old, however, more than 250 million vehicles cross structurally deficient bridges on a daily basis.[5] Similar to other transportation infrastructure, bridges are vulnerable to a range of threats from climate change.[6] Currently, most bridge failures are caused by scour, where swiftly moving water removes sediment from around bridge structural supports, weakening or destroying their foundations. Increased flooding and long-term river flow changes caused by climate change are expected to increase the frequency of bridge scour, further stressing the aging U.S. transportation system.

Risks of Inaction

Increased inland flooding caused by climate change threatens bridges across the U.S. and risks a net increase in maintenance costs. Figure 1 shows the number and percent of bridges in each hydrologic region of the contiguous U.S. identified as vulnerable to climate change in the late 21st century under the Reference scenario using the IGSM-CAM climate model. In total, approximately 190,000 bridges are identified as vulnerable. In addition, the costs of adapting bridges to climate change under the Reference scenario are estimated at \$170 billion for the period from 2010 to 2050, and \$24 billion for the period from 2051 to 2100 (discounted at 3%). The higher costs during the first half of the century are primarily due to the large number of vulnerable bridges that require strengthening in the near term in the face of increasing peak river flows due to climate change. These findings regarding near-term bridge vulnerability and adaptation costs due to unmitigated climate change are consistent with the findings of the assessment literature.[7]

Figure 1. Bridges Identified as Vulnerable in the Second Half of the 21st Century Due to Unmitigated Climate Change

Estimated number of vulnerable bridges in each of the 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. in the period from 2051-2100 under the Reference scenario using the IGSM-CAM climate model. The map also shows the percentage of inland bridges in each HUC that are vulnerable due to climate change.



Reducing Impacts through GHG Mitigation

As shown in Figure 2, global GHG mitigation is projected to substantially reduce the number of vulnerable bridges in many areas of the contiguous U.S. compared to the Reference scenario (Figure 1). For example, the percentage of vulnerable bridges in the Northwest region, which includes Washington and parts of Oregon and Idaho, is reduced from 56% under the Reference to 25% under the Mitigation scenario. At the national scale, the total number of vulnerable bridges is reduced by roughly 40,000 through 2050 compared to the Reference scenario, and by over 110,000 in the second half of the century.

In addition, the analysis estimates that global GHG mitigation reduces the costs of adaptation substantially relative to the Reference scenario. In the period from 2010 to 2050, costs under the Mitigation scenario are approximately $42 billion lower than under the Reference (discounted at 3%). Although adaptation costs are lower in the second half of the century, costs under the Mitigation scenario are nearly 60% lower than they are under the Reference scenario, with savings estimated at $15 billion (discounted at 3%). These results rely upon climate projections using the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). The projected benefits of global GHG mitigation are lower with the drier MIROC model (not shown) for the 2010-2050 period, at approximately $3.4 billion, but are higher in the 2051-2100 period, at approximately $10 billion (discounted at 3%).

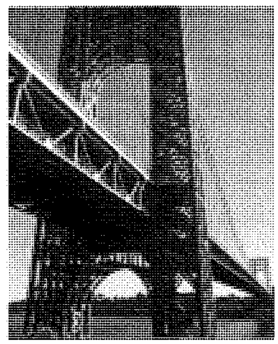


Figure 2. Bridges Identified as Vulnerable in the Second Half of the 21st Century with Global GHG Mitigation

Estimated number of vulnerable bridges in each of the 2-digit HUCs of the contiguous U.S. in the period from 2051-2100 under the Mitigation scenario using the IGSM-CAM climate model. The map also shows the percentage of inland bridges in each HUC that are vulnerable due to climate change.

APPROACH

The CIRA analysis identifies inland bridges in the contiguous U.S. that may be vulnerable to increased peak river flows due to climate change and estimates the costs to adapt the at-risk infrastructure.[8] The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. Bridge performance and vulnerability are determined using the National Bridge Inventory database and are based on the following four elements:

- substructure condition;
- channel and channel protection condition;
- waterway adequacy; and
- vulnerability to scour.

The analysis estimates the timing of bridge vulnerability (based on the 100-year, 24-hour storm event), and the adaptation costs of maintaining the current condition and level of service of the at-risk bridges. Two types of bridge fortification and the costs of their implementation are analyzed: the use of riprap (large rocks and rubble) to stabilize bridge foundations and the use of additional concrete to strengthen bridge piers and abutments. Although there will likely be significant changes to the nation's bridges over the course of the century—some bridges will be strengthened, some will deteriorate, some will be removed, and new bridges will be built—this analysis estimates the costs of adapting the nation's existing bridge infrastructure to different future climates based on its current state (i.e., the additional costs due to climate change are isolated).[9,10]

For more information on the CIRA approach and results for the bridges sector, please refer to Neumann et al. (2014)[11] and Wright et al. (2012).[12]

Roads

KEY FINDINGS

1. Climate change is projected to increase the cost of maintaining road infrastructure. This analysis estimates the damages of climate change in terms of increased costs to maintain current levels of service (i.e. adaptation costs). Without adaptation, climate change could render many roadways unusable, leading to large economic damages.

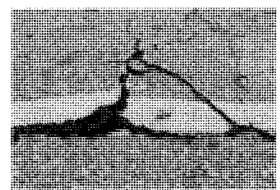
2. In all regions, adaptation costs associated with the effects of higher temperatures on paved roadways are estimated to increase over time. In the central regions of the country, in particular, changes in precipitation patterns are projected to increase costs associated with re-grading unpaved roadways.

3. Without global GHG mitigation, adaptation costs in 2100 in the U.S. roads sector are estimated to range from $5.8-$10 billion.

4. Global GHG mitigation is projected to avoid an estimated $4.2-$7.4 billion of the damages under the Reference scenario in 2100.

Climate Change and Roads

The U.S. road network is one of the nation's most important capital assets. Climate stress on roads will likely change in the future, with various potential impacts and adaptation costs.[13] For example, roads may experience more frequent buckling due to increased temperatures, more frequent washouts of unpaved surfaces from increases in intense precipitation, and changes in freeze-thaw cycles that cause cracking.[14]

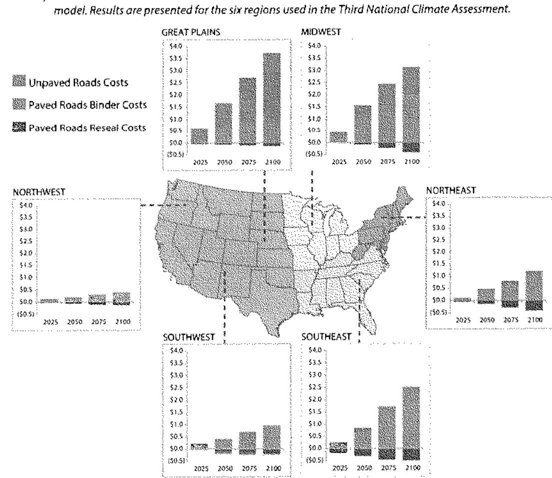


Risks of Inaction

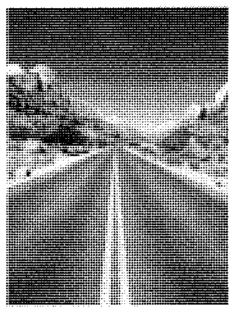
Without reductions in global GHG emissions, the costs of maintaining, repairing, and replacing pavement are projected to increase, which is consistent with the findings of the assessment literature regarding adaptation costs for road infrastructure.[15] Figure 1 presents the estimated regional damages (in the form of adaptation costs) to the U.S. road network under the Reference scenario using the IGSM-CAM climate model. The greatest impacts are projected to occur in the Great Plains region, where costs are mainly due to erosion of unpaved roads associated with increased precipitation. Costs associated with the use of different pavement binders to avoid cracking of paved roads are also high, particularly in the Midwest and Southeast regions, and they increase over time in all regions due to the projected rise in temperature. Costs of resealing roads after freeze-thaw events decrease over time as the climate changes, but the magnitude of the decrease does not offset the projected increase in other costs.

Figure 1. Projected Impacts of Unmitigated Climate Change on U.S. Road Infrastructure

Adaptation costs (billions 2014$, undiscounted) under the Reference scenario using the IGSM-CAM climate model. Results are presented for the six regions used in the Third National Climate Assessment.



Reducing Impacts through GHG Mitigation

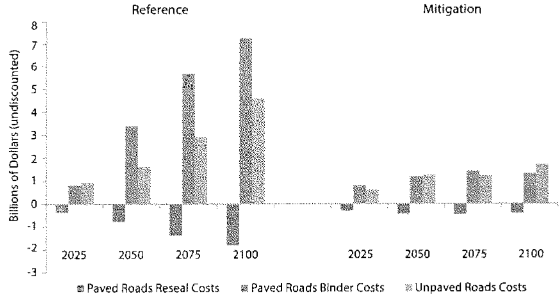


Adaptation costs for the U.S. road network are substantially reduced with global GHG mitigation compared to the Reference scenario (Figure 2). These reductions are due in large part to the effect of lower temperatures under the Mitigation scenario on maintenance needs for paved roads. Specifically, costs associated with asphalt binders account for a large share of the adaptation costs nationally under the Reference, and these costs are significantly lower with mitigation. Costs associated with adaptation for unpaved roads are also substantially lower under the Mitigation scenario, as heavy precipitation events are projected to be less severe compared to the Reference. Costs of resealing roads after freeze-thaw cycles are projected to decrease under both scenarios, but the magnitude of the decrease does not offset the projected increase in other costs.

By 2050, the adaptation costs under the Reference scenario are substantially higher, illustrating the benefits that accrue over time with GHG mitigation. In addition, although the costs of adaptation increase over the course of the century under both scenarios, they do so at a much faster rate under the Reference. Under the Reference, adaptation costs are estimated at approximately $10 billion in 2100, whereas under the Mitigation scenario costs are estimated at $2.6 billion. As a result, global GHG mitigation is projected to avoid over $7 billion in damages in 2100. These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). The projected benefits of global GHG mitigation are lower with the drier MIROC model (not shown), at $4.2 billion in 2100, reflecting the reduced impact of precipitation on unpaved roads under both scenarios.[16]

Figure 2. Projected Impacts on U.S. Road Infrastructure with and without Global GHG Mitigation

Costs of adaptation for the Reference and Mitigation scenarios using the IGSM-CAM climate model (billions 2014$). The reduction in adaptation costs under the Mitigation scenario relative to the Reference reflects the benefits of global GHG mitigation.



APPROACH

The CIRA approach assesses four risks to road infrastructure associated with climate change:

- rutting of paved roads from precipitation;
- rutting of paved roads caused by freeze-thaw cycles;
- cracking of paved roads due to high temperatures; and
- erosion of unpaved roads from precipitation.

The CIRA analysis examines the implications of changes in climate over time for the U.S. road network based on stressor-response functions for each of the above effects. The analysis considers the effects of temperature and precipitation, but does not include impacts due to sea level rise and storm surge, which would likely increase damages to roads. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model.

The costs of adaptation to effectively counteract the climate change impacts and maintain roads at their current levels of service are estimated for each of the CIRA scenarios. As there will be continued maintenance needs over time, this analysis focuses on the additional costs due to climate change. The response measures include more frequent resealing to avoid rutting; use of different pavement binders during resurfacing to avoid cracking of asphalt-paved roads; and more frequent re-grading of unpaved roads to minimize erosion impacts. This analysis assumes well-timed adaptation to maintain service levels, a potentially overly optimistic assumption given that infrastructure investments are oftentimes delayed.

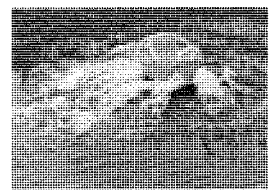
For more information on the CIRA approach and results for the roads sector, please refer to Neumann et al. (2014)[17] and Chinowsky et al. (2013).[18]

Urban Drainage

KEY FINDINGS

1. Climate change is projected to result in increased adaptation costs for urban drainage systems in cities across the U.S., particularly in the Great Plains region.
2. Without global GHG mitigation, adaptation costs in 2100 associated with the 50-year, 24-hour storm in 50 major U.S. cities are projected to range from $1.1-$12 billion.
3. Global GHG mitigation is projected to result in cost savings for urban drainage systems in these cities ranging from $50 million to $6.4 billion in 2100 for the 50-year, 24-hour storm, depending on the climate model used. Inclusion of all U.S. cities would likely increase the cost savings by a substantial amount.

Climate Change and Drainage



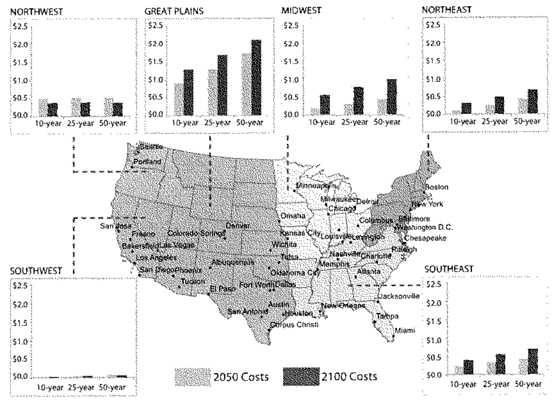
Urban drainage systems capture and treat stormwater runoff and prevent urban flooding. During storm events, the volume of runoff flowing into drainage systems and the ability of these systems to manage runoff depend on a variety of site-specific factors, such as the imperviousness of the land area in the drainage basin. Changes in storm intensity associated with climate change have the potential to overburden drainage systems, which may lead to flood damage, disruptions to local transportation systems, discharges of untreated sewage to waterways, and increased human health risks.[19] In areas where precipitation intensity increases significantly, adaptation investments may be necessary to prevent runoff volumes from exceeding system capacity.

Risks of Inaction

Without global GHG mitigation, climate change is projected to result in increased adaptation costs for urban drainage infrastructure, a finding that is consistent with the conclusions of the assessment literature.[20] Figure 1 presents the projected costs for the 50 modeled cities in 2050 and 2100 under the Reference scenario using the IGSM-CAM climate model for the three categories of storm events modeled (24-hour events with precipitation intensities occurring every 10, 25, and 50 years).[21] The average per-square-mile costs are projected to be highest in the Great Plains region in both 2050 and 2100 due to the projected increase in heavy precipitation in that region. Adaptation costs are estimated to be relatively low in the Southwest due to the projected reduction in precipitation in that region.

Figure 1. Projected Impacts of Unmitigated Climate Change on U.S. Urban Drainage Systems

Weighted average per-square-mile adaptation costs (millions 2014$, undiscounted) in 2050 and 2100 for the 10-, 25-, and 50-year storms under the Reference scenario using the IGSM-CAM climate model. Costs for each of the 50 modeled cities (shown) are aggregated to the six regions used in the Third National Climate Assessment.

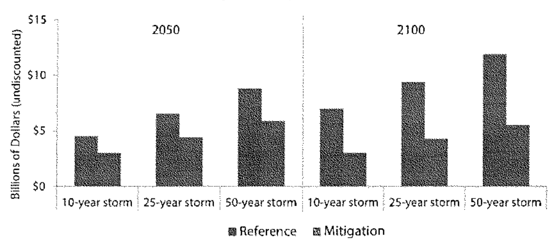


Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to result in substantial adaptation cost savings for urban drainage systems in the 50 modeled cities (Figure 2). Overall, cost savings are projected to be higher in 2100 than in 2050, and increase according to the intensity of the storm modeled, with the greatest savings occurring for the 50-year, 24-hour storm. For this particular storm event, total adaptation costs for the modeled cities are projected to be $12 billion in 2100 under the Reference. Under the Mitigation scenario, these costs are reduced to approximately $5.5 billion, which represents a cost savings of approximately $6.4 billion. Cost savings for the 10- and 25-year storms under the Mitigation scenario are approximately $3.9 billion and $5.1 billion, respectively, in 2100. Looking across the contiguous U.S., the Great Plains region is projected to experience the largest reductions in adaptation costs as a result of global GHG mitigation. These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). Using the drier MIROC model, projected benefits of GHG mitigation for the modeled cities associated with the 50-year, 24-hour storm event are estimated at $50 million.

Figure 2. Projected Impacts on Urban Drainage Systems in 50 U.S. Cities with and without Global GHG Mitigation

Projected adaptation costs in 2050 and 2100 for the Reference and Mitigation scenarios using the IGSM-CAM climate model (billions 2014$). The values of the red bars represent the sum of all adaptation costs shown in Figure 1 for the years 2050 and 2100.



APPROACH

The CIRA analysis estimates the costs of adapting urban drainage systems to meet future demands of increased runoff associated with more intense rainfall under climate change. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. Adaptive actions focus on the use of best management practices to limit the quantity of runoff entering stormwater systems. While many site-specific factors influence the effect of climate change on a given drainage system, the CIRA analysis uses a streamlined approach that allows for the assessment of potential impacts in multiple U.S. cities under the CIRA scenarios.[22] Specifically, the analysis uses a reduced-form approach for projecting changes in flood depth and the associated costs of flood prevention, based on an approach derived from EPA's Storm Water Management Model (SWMM).

The simplified approach yields impact estimates in units of average adaptation costs per square mile for a total of 50 cities across the contiguous U.S. (see Figure 1) for three categories of 24-hour storm events (those with precipitation intensities occurring every 10, 25, and 50 years—metrics commonly used in infrastructure planning) and four future time periods (2025, 2050, 2075, and 2100). The analysis assumes that the systems are able to manage runoff associated with historical climate conditions, and estimates the costs of implementing the adaptation measures necessary to manage increased runoff under climate change.

For more information on the CIRA approach and results for the urban drainage sector, please refer to Neumann et al. (2014)[23] and Price et al. (2014).[24,25]

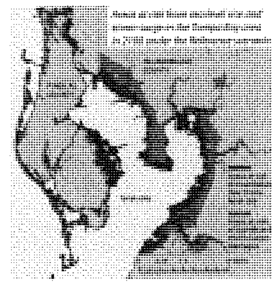
Coastal Property

KEY FINDINGS

1. A large area of U.S. coastal land and property is at risk of inundation from global sea level rise, and an even larger area is at risk of damage from storm surge, which will intensify as sea levels continue to rise.
2. Without adaptation, unmitigated climate change is projected to result in $5.0 trillion in damages for coastal property in the contiguous U.S. through 2100 (discounted at 3%). Protective coastal adaptation measures significantly reduce total costs to an estimated $810 billion.
3. Global GHG mitigation reduces adaptation costs for coastal areas, but the majority of benefits occur late in the century.
4. Areas of higher social vulnerability are more likely to be abandoned than protected in response to unmitigated sea level rise and storm surge. GHG mitigation decreases this risk.

Climate Change and Coastal Property

Coastal areas in the U.S. are some of the most densely populated, developed areas in the nation, and they contain a wealth of natural and economic resources. Rising temperatures are causing ice sheets and glaciers to melt and ocean waters to expand, contributing to global sea level rise at increasing rates. Sea level rise threatens to inundate many low-lying coastal areas and increase flooding, erosion, wetland habitat loss, and saltwater intrusion into estuaries and freshwater aquifers. The combined effects of sea level rise and other climate change factors, such as increased intensity of coastal storms, may cause rapid and irreversible change.[26]

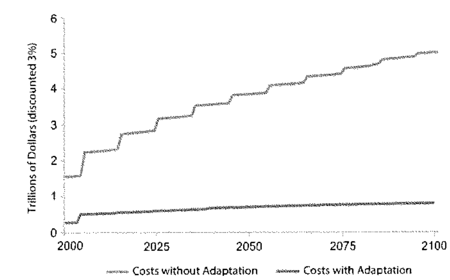


Risks of Inaction

Sea level rise and storm surge pose increasingly large risks to coastal property, including costs associated with property abandonment, residual storm damages, and protective adaptation measures (e.g., elevating properties and armoring shorelines). As shown in Figure 1, the analysis estimates that under the Reference scenario the cumulative damages to coastal property across the contiguous U.S. will be $5.0 trillion through 2100 (discounted at 3%) if no adaptation measures are implemented. If adaptation measures are taken, these damages are reduced to $810 billion. Projections of increasing risks of sea level rise and storm surge for coastal property, and of the potential for adaptation to reduce overall costs, are consistent with the findings of the assessment literature.[27] The graphic above illustrates the importance of these potential impacts at a local scale by identifying at-risk land in the Tampa Bay, FL area. In this locale, approximately 83,000 acres are projected to be at risk of inundation due to sea level rise by 2100, and an additional 51,000 acres are projected to be at risk of significant storm surge. The total area at risk (130,000 acres) is approximately one and a half times the size of the City of Tampa.

Figure 1. Costs of Sea Level Rise and Storm Surge to Coastal Property with and without Adaptation under the Reference Scenario

The step-wise nature of the graph is due to the fact that storm surge risks are evaluated every ten years, beginning in 2005. Costs with adaptation include the value of abandoned property, residual storm damages, and costs of protective adaptation measures (trillions 2014$).



Reducing Impacts through GHG Mitigation

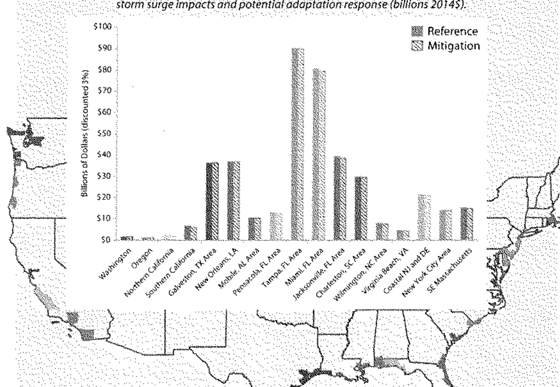
Under the Mitigation scenario, total costs (i.e., property damages and protective investments) across the contiguous U.S. are estimated at $790 billion through 2100 (discounted at 3%), about 3% less than the Reference scenario.[28] The effect of global GHG mitigation in reducing adaptation costs is modest and is likely underestimated in this analysis for several reasons. First, as described in the CIRA Framework section, global sea level rise is similar under the Reference and Mitigation scenarios through mid-century. It is not until the second half of the century when the benefits of reduced sea level rise under the Mitigation scenario become apparent. Further, the proportional effect of global GHG mitigation in reducing the rate of sea level rise is smaller under the CIRA scenarios compared to other scenarios in the literature.[29]

Second, when considering the present value total cost under the Reference and Mitigation scenarios, avoided adaptation costs accrued in later years are more heavily affected by discounting.[30] Third, the analysis assumes that coastal areas will implement cost-efficient and well-timed adaptation measures in response to the risks under both the Reference and Mitigation scenarios. Since many parts of the coastline are not sufficiently protected today, and because adaptation measures that are taken are oftentimes not well-timed, the CIRA estimates for this sector likely underestimate damages. For comparison purposes, the benefits of global GHG mitigation increase by a factor of ten if adaptation measures are not implemented.

Figure 2 shows the costs of adaptation for coastal properties (including the value of properties that are abandoned due to the severity of sea level rise or storm surge damages) for 17 key sites under the Reference and Mitigation scenarios. As shown, costs are only modestly lower under the Mitigation scenario. Costs vary across sites primarily due to the value of property at risk and the severity of the storm surge threats. For example, adaptation costs are comparatively higher in sites, such as Tampa and Miami, where there are many high-value properties in low-lying areas and high levels of storm surge are projected in the future.

Figure 2. Costs to Coastal Property of Sea Level Rise and Storm Surge through 2100

Costs are shown for 17 multi-county coastal areas that were modeled for sea level rise and storm surge impacts and potential adaptation response (billions 2014$).



APPROACH

The CIRA analysis identifies at-risk coastal property across the contiguous U.S. and estimates the costs that would be incurred due to climate change, with and without adaptation. Importantly, impacts to other coastal assets (e.g., roads and ecological resources) are not estimated in this analysis. The analysis relies upon sea level rise projections through 2100[31] that account for dynamic ice-sheet melting based on a semi-empirical model,[32] and are adjusted for regional land movement using local tide gauge data.[33] The analysis then uses a tropical cyclone simulator[34] and a storm surge model[35] to estimate the joint effects of sea level rise and storm surge for East and Gulf Coast sites, and an analysis of historic tide gauge data to project future flood levels for West Coast sites.[36]

Using EPA's National Coastal Property Model, the CIRA analysis estimates how areas along the coast may respond to sea level rise and storm surge and calculates the economic impacts of adaptation decisions (i.e., damages due to climate change). The approach uses four primary responses to protect coastal land and property: beach nourishment; property elevation; shoreline armoring; and property abandonment. The model projects an adaptation response for areas at risk based on sea level rise, storm surge height, property value, and costs of protective measures. Developed using a simple metric to estimate potential adaptation responses in a consistent manner for the entire coastline, the estimates presented here should not be construed as recommending any specific policy or adaptive action. Further, additional adaptation options not included in this analysis, such as marsh restoration, may be appropriate and potentially more cost-effective for some locales. The analysis also explores the potential impact of climate change on socially disadvantaged populations (see the Environmental Justice section of this report).

For more information on the CIRA approach and results for the coastal property sector, please refer to Neumann et al. (2014a)[37] and Neumann et al. (2014b).[38]

COASTAL PROPERTY

Environmental Justice

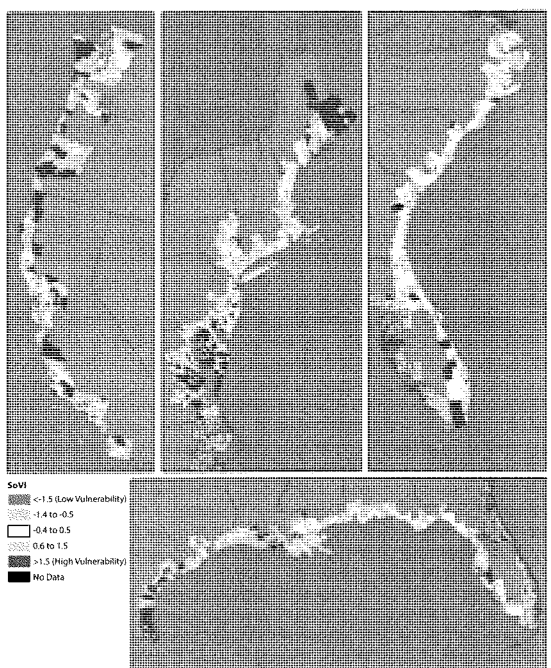
Building on the coastal property impacts described in the previous section, this analysis examines the environmental justice implications of projected sea level rise and storm surge in the contiguous U.S. Specifically, the approach quantifies how sea level rise and storm surge risks are distributed across different socioeconomic populations along the U.S. coastline; how these populations are likely to respond; and what adaptation costs (i.e., property damage and protection investments) will potentially be incurred.

The Social Vulnerability Index

The CIRA analysis uses the Social Vulnerability Index (SoVI) to identify socially vulnerable coastal communities in the U.S.[39] SoVI was developed to quantify social vulnerability using county-level (and later Census tract-level) socioeconomic and demographic data. The index is a well-vetted tool, and does not include any environmental risk factors, thereby eliminating the risk of double counting climate risk when socioeconomic and demographic data are combined with sea level rise and storm surge vulnerability.[40] The CIRA analysis uses Census tract-level SoVI values based on 2000 Census data for 26 demographic variables, capturing information on wealth, gender, age, race, and employment. Figure 1 shows the SoVI index values for the four coastal regions used in the analysis: Pacific (California through Washington), North Atlantic (Maine through Virginia), South Atlantic (North Carolina through Monroe County, Florida), and Gulf (Collier County, Florida through Texas).

Figure 1. Social Vulnerability Index for the Coastal U.S.

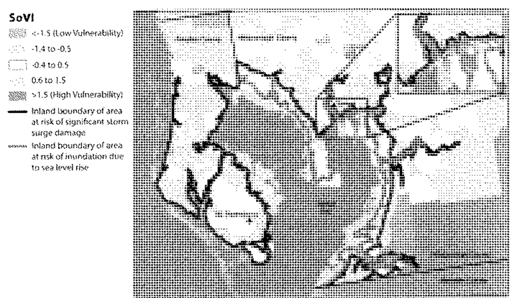
Census tract-level SoVI values are regionally normalized to allow for comparisons of the SoVI scores within each area. Areas with low SoVI scores (i.e., people with lower social vulnerability) are shaded in green and areas with higher SoVI scores (i.e., people with greater social vulnerability) are shaded in pink.



Case Study: Tampa Bay Area

EPA's National Coastal Property Model identifies areas along the contiguous U.S. coastline that are likely to be at risk from sea level rise and storm surge through 2100.[41, 42] By layering these projections on top of the SoVI results, following the approach described in Martinich et al. (2013),[43] the analysis assesses the potential impact of sea level rise and storm surge on socially disadvantaged populations in coastal areas. Figure 2 presents a case study of the Tampa Bay, Florida area (Pinellas and Hillsborough Counties). The area from the water to the gray lines represents the projected area at risk of inundation due to sea level rise, while the area from the water to the black lines represents projected areas at risk from significant storm surge damage in 2100.[44] As shown, there are areas with higher socially vulnerable populations (pink shading) near the city of Tampa, in particular, that are projected to be at risk of significant storm surge damages.

Figure 2. Social Vulnerability of Areas at Risk from Sea Level Rise and Storm Surge in the Tampa Bay Area by 2100 under the Reference Scenario



National Results

Figure 3 compares the number of people in the 17 multi-county coastal areas (see previous section for locations) identified as at risk due to climate change under the Reference and Mitigation scenarios, by SoVI category. As shown, the Mitigation scenario reduces the number of at-risk people compared to the Reference scenario for all SoVI categories. The benefits of global GHG mitigation are particularly high for the population identified by the SoVI as most socially vulnerable; for this population, the number of at-risk people is reduced by 23% under the Mitigation scenario compared to the Reference.

The CIRA analysis also projects adaptation responses based on sea level rise, storm surge height, property value, and costs of adaptation.[45] The model estimates whether people living in coastal areas are likely to respond to climate threats by: 1) protecting property through beach nourishment, property elevation, or shoreline armoring; 2) abandoning property, or 3) incurring storm surge damages without adapting. Figure 4 presents the adaptation results, by area, for the five SoVI categories in the Reference. More area is likely to be abandoned than protected across all social vulnerability categories. However, in the most vulnerable SoVI categories (0.6-1.5 and greater than 1.5), a relatively larger proportion of the area inhabited is likely to be abandoned (89% and 86%, respectively) rather than protected through adaptation measures (8% and 10%, respectively).

Figure 3. Social Vulnerability of Populations at Risk from Sea Level Rise and Storm Surge through 2100 with and without Global GHG Mitigation

Vulnerability estimated in 17 multi-county coastal areas in the contiguous U.S., along with the estimated percent changes from Reference to Mitigation.

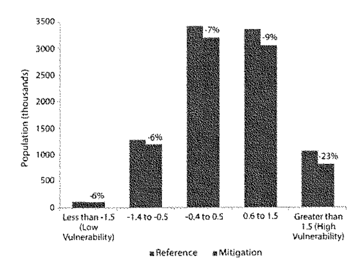
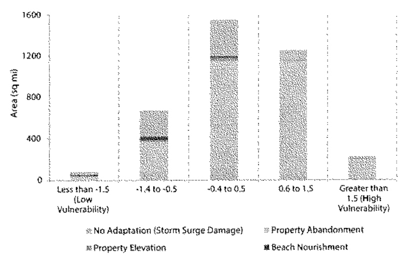
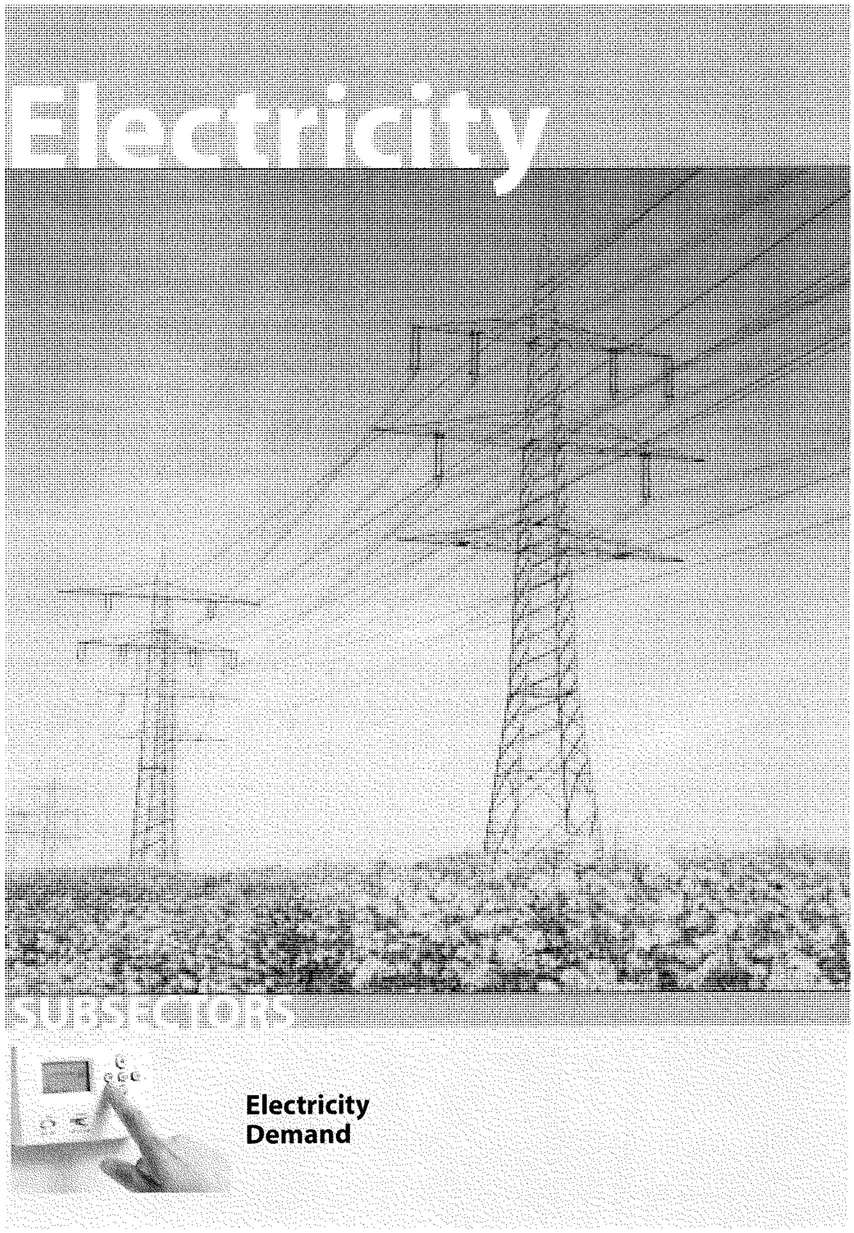
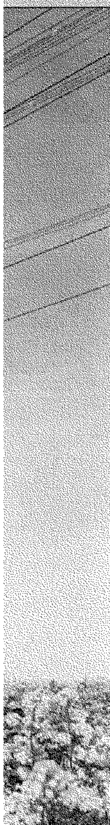


Figure 4. Adaptation Measures by SoVI Category under the Reference Scenario




Electricity
SUBSECTORS
Electricity
Demand



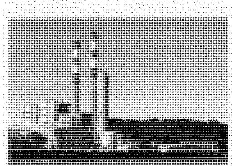
Electricity is an essential element of modern life. It lights and cools our homes, powers our computers, supports the production of goods and services, and enables critical infrastructure services such as water treatment and telecommunications. The generation of electricity in the U.S., most of which comes from fossil fuels, also contributes to climate change, accounting for approximately 30% of U.S. greenhouse gas emissions.[1]

HOW IS THE ELECTRICITY SECTOR VULNERABLE TO CLIMATE CHANGE?

Climate change has implications for electricity production, distribution, and use.[2] For example, coastal electricity infrastructure, such as power plants and substations, are vulnerable to storm surge and wind damage. Elevated temperatures diminish thermal power plant efficiency and capacity, and can reduce the capacity of transmission lines. In addition, effects on water supply alter the quantity and temperature of cooling water available for thermoelectric generation.[3] On the demand side, warmer winters decrease the demand for heating. However, this reduction is smaller than the increase in electricity demand for cooling due to higher summer temperatures. Across the U.S., higher minimum temperatures increase the number of days in a year when air conditioning is needed, and higher maximum temperatures increase the peak electricity demand, further stressing our aging power grid.

WHAT DOES CIRA COVER?

Numerous studies highlight the potential for emission reductions in the electricity sector, yet fewer studies have explored the physical, operational, and economic impacts of a changing climate on this sector. CIRA assesses the impacts of rising temperatures on electricity demand, system costs, and the generation mix needed to meet increasing demand across the contiguous U.S. through 2050.[4] Importantly, impacts to the demand and supply of other energy sources (e.g., fuel for transportation) are not estimated. Also, the electricity supply analysis does not include the effects of climate change on hydropower and water availability for thermoelectric power generation. Additional work is necessary to further evaluate climate change impacts on electricity supply, particularly the effects of extreme heat events and storm damage on capacity and reliability. Finally, future work to improve connectivity between the CIRA electricity, water, and agriculture analyses will aid in better understanding potential cross-sector impacts.



Electricity Supply

Electricity Demand

KEY FINDINGS

1. Without global GHG mitigation, rising temperatures will likely result in higher electricity demand across the country, as the increased need for air conditioning outweighs decreases in electric heating requirements. The estimated percent increase in electricity demand for air conditioning is highest in the Northeast and Northwest regions.

2. Global GHG mitigation, which lessens the rise in temperature, is projected to lead to lower electricity demand across all regions of the country relative to the Reference scenario.

Climate Change and Electricity Demand

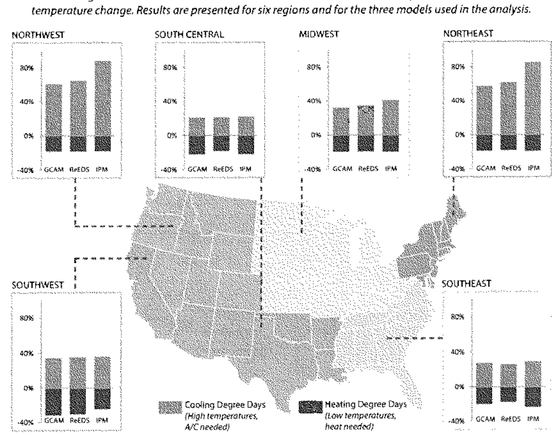
As air temperatures rise due to climate change, electricity demands for cooling are expected to increase in every U.S. region.[5] Higher summer temperatures, particularly during heat waves, will likely increase peak electricity demand, placing more stress on the electricity grid and increasing electricity costs. Although the majority of U.S. residential and commercial cooling demand is met with electricity, less than 9% of heating demand is met with electricity.[6,7] Therefore, although higher average temperatures are expected to reduce electricity demands for heating, net electricity use is projected to increase under climate change. This section presents estimated impacts on electricity demand, but does not consider impacts on demand for other fuel sources used in residential cooling or heating.

Risks of Inaction

Rising temperatures are projected to increase electricity demands for cooling. Figure 1 shows the percent change in regional heating and cooling degree days (HDDs/CDDs, see Approach for definitions) from 2005 to 2050 in the Reference scenario. Results are presented for the three models used in the analysis (GCAM, ReEDS, and IPM), which exhibit similar trends of falling HDDs (shown in purple) and rising CDDs (shown in orange). These trends are consistent with projections described in the assessment literature.[8] Across the U.S., HDDs decrease between 18%-29% on average, with greater decreases occurring in the South due in part to already-high temperatures. The increase in CDDs is highest in the Northeast and Northwest (68% and 71% on average, respectively). The projected changes in HDDs and CDDs have implications for regional electricity demand. Average U.S. electricity demand is projected to increase under the Reference by 1.5%-6.5% by 2050, compared to a Control with no temperature change. Across the regions and models shown in Figure 2, electricity demand is projected to increase by 0.5%-9.0%, with the exception of the ReEDS model in the Northwest, which projects a decrease of 0.5%.[9]

Figure 1. Projected Impact of Unmitigated Climate Change on Regional Heating and Cooling Degree Days from 2005 to 2050

Percent change in HDDs and CDDs from 2005 to 2050 under the Reference compared to a Control with no temperature change. Results are presented for six regions and for the three models used in the analysis.



Reducing Impacts through GHG Mitigation

Global GHG emissions reductions under the Mitigation scenario result in smaller increases in temperatures compared to the Reference, thereby reducing cooling demand across the country. Figure 2 illustrates this effect, presenting the change in regional energy demand in 2050 in the Reference and Mitigation scenarios relative to a Control with no temperature change. As shown, the change in demand in the Mitigation scenario is consistently lower than in the Reference across all of the models. This decrease in demand is due in large part to lower temperatures under the Mitigation scenario compared to the Reference, and in the GCAM and ReEDS models the lower demand is also due to an increase in electricity costs associated with reducing GHG emissions. The impact of GHG mitigation on electricity supply is discussed in greater detail in the Electricity Supply section of this report.

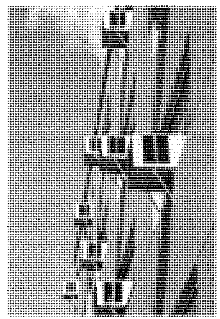
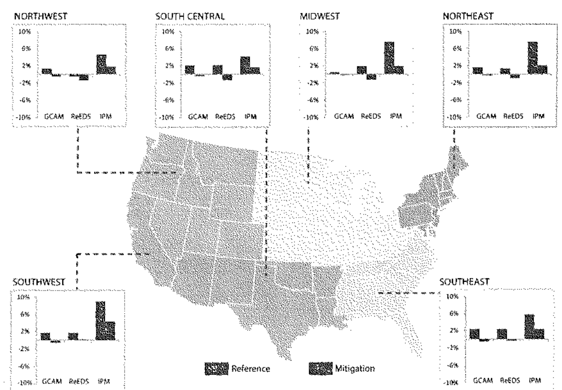


Figure 2. Change in Regional Electricity Demand in 2050 with and without Global GHG Mitigation

Change in regional electricity demand for the Reference and Mitigation scenarios relative to a Control (no temperature change). Results are presented for six regions and for each of the three models used in the analysis (GCAM, ReEDS, and IPM).



APPROACH

The CIRA analysis examines how rising temperatures under climate change will affect electricity demand. It applies a common set of temperature projections from IGSM-CAM to three models of the U.S. electric power sector:

- Global Change Assessment Model (GCAM-USA): a detailed, service-based building energy model for the 50 U.S. states;[10, 11]
- Regional Electricity Deployment System Model (ReEDS): a technology-rich model of the deployment of electric power generation technologies and transmission infrastructure for the contiguous U.S.;[12] and
- Integrated Planning Model (IPM®): a dispatch and capacity planning model used by the public and private sectors to inform business and policy decisions.[13]

The models project changes in electricity demand as functions of changes in heating and cooling degree-days (HDDs/CDDs). HDDs and CDDs are one way to measure the influence of temperature change on energy demand. They measure the difference between outdoor temperatures and a temperature that people generally find comfortable indoors. These measurements suggest how much energy people might need to use to heat and cool their homes and workplaces. The analysis compares the results across the CIRA scenarios, while also accounting for non-climate changes in electricity demand (e.g., population and economic growth). To assess the effect of rising temperatures in the Reference and Mitigation scenarios, changes in heating and cooling degree days and electricity demand are compared to a Control that assumes temperatures do not change over time.

For more information on the CIRA approach and results for the electricity demand sector, please refer to McFarland et al. (2015).[14]

Electricity Supply

KEY FINDINGS

1. Projected electricity supply is higher in all three electric power sector models under the Reference scenario, reflecting a higher demand for cooling, and lower under the Mitigation scenario as a result of lower temperatures and the demand response to GHG mitigation.

2. The relative magnitude of costs to the electric power system are similar under the Reference and Mitigation scenarios, highlighting that the costs associated with rising temperatures in the Reference are comparable to the costs associated with reducing GHG emissions in the Mitigation scenario. Specifically, the higher demands under the Reference scenario increase system costs by 1.7%-8.3% above the Control. Under the Mitigation scenario, system costs increase by 2.3%-10% above the Control, or 0.6%-5.5% above Reference scenario costs.

Climate Change and Electricity Supply

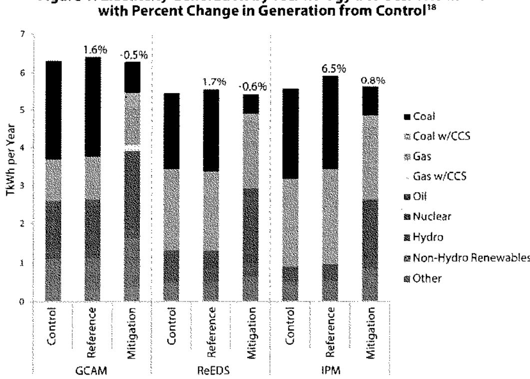
As described in the Electricity Demand section, warmer air temperatures under climate change are expected to result in higher demand for electricity, leading to the need for increased capacity in the power system to meet this demand. At the same time, higher temperatures reduce the capacity of both thermal power plants and transmission lines.

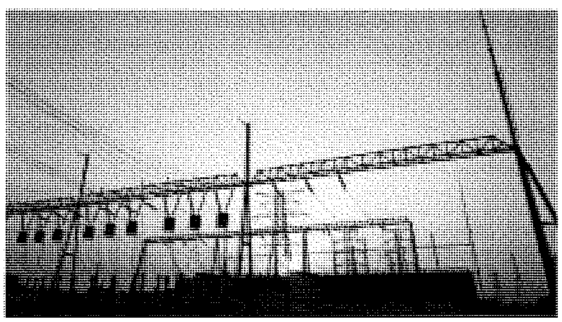
The power sector accounts for the largest share of GHG emissions in the U.S.,[15] and is also considered the most cost-effective source of emission reductions under mitigation policies.[16] A variety of impacts and changes are therefore expected to occur in this sector, including changes in sector emissions, system costs, and generation mix (i.e., the assortment of fuels used to generate electricity).

Effects on Electricity Generation

In the CIRA analyses, a large amount of CO_2 reductions in the U.S. under the Mitigation scenario occur in the electricity sector.[17] As a result, the generation capacity and mix of energy sources used to produce electricity is projected to change over time. Figure 1 shows the projected change in generation mix in 2050 from the three electric power sector models under the CIRA scenarios. Projected electricity supply is higher in all three models under the Reference, reflecting a higher demand for cooling, and lower under the Mitigation scenario as a result of lower temperatures and the costs of reducing GHG emissions. For any given model, the supply mix in the Reference does not differ substantially from the Control, which accounts for future population and economic growth, but no temperature change. However, all three models under the Mitigation scenario project substantial reductions in coal generation and expanded generation from nuclear and renewables.

Figure 1. Electricity Generation by Technology and Scenario in 2050 with Percent Change in Generation from Control[18]



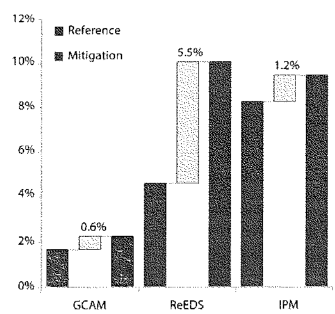


Change in System Costs

Rising temperatures under both scenarios, especially under the Reference, result in higher demands for electricity and increased power system costs to expand capacity. At the same time, altering the generation mix to reduce GHG emissions imposes costs on the power system. Figure 2 presents the percent change in cumulative system costs under the Reference and Mitigation scenarios compared to a Control with no temperature change (2015-2050, discounted at 3%). The costs increase by 1.7%-8.3% under the Reference and by 2.3%-10% under the Mitigation scenario. The incremental system costs of the Mitigation scenario above the Reference are 0.6%-5.5%, highlighting that the costs to the electric power sector associated with rising temperatures in the Reference are comparable to the costs associated with reducing GHG emissions in the Mitigation scenario. It is important to note, however, that this does not account for benefits of GHG mitigation outside of the electricity sector, nor does it examine other effects of climate change on electricity supply, such as changes in cooling water availability or extreme weather events.

Figure 2. Percent Change in Cumulative System Costs (2015-2050) in the Reference and Mitigation Scenarios Compared to the Control

Grey bars represent the difference between the Reference and Mitigation scenarios.

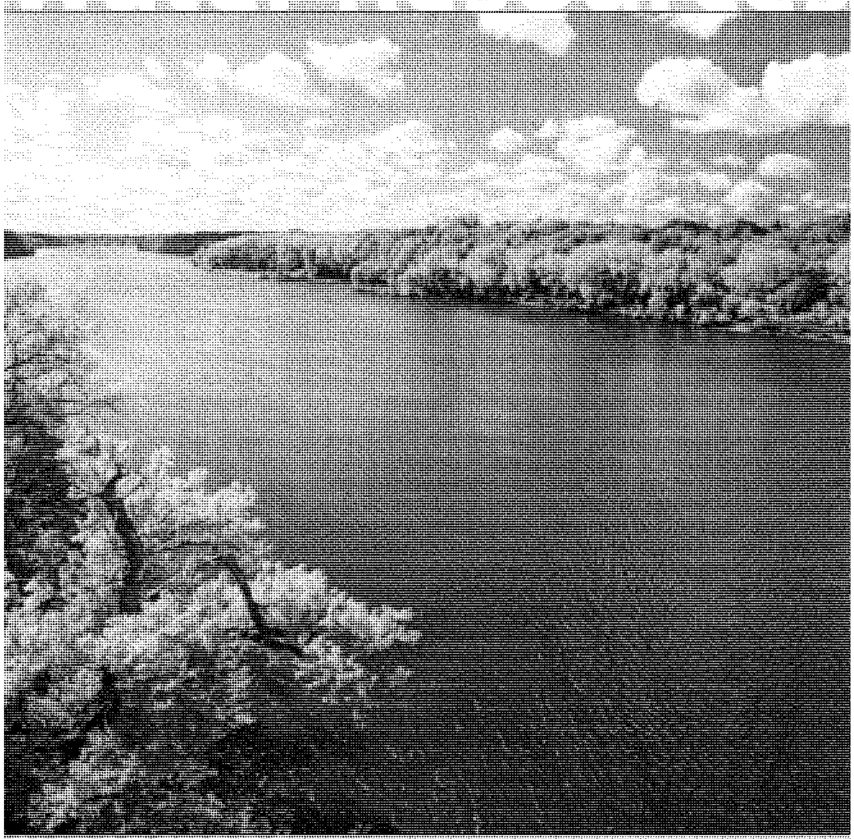


APPROACH

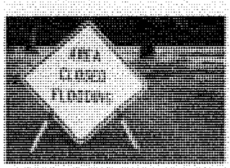
The CIRA analysis assesses impacts on the U.S. electricity sector's supply side using the same three models described in the Electricity Demand section. The models project changes in the generation mix needed to meet increasing demand due to future warming and socioeconomic changes (e.g., population and economic growth) under the CIRA scenarios. The three models also estimate the corresponding system costs—comprised of capital, operations and maintenance, and fuel costs—and the changes in CO_2 emissions over time. This analysis is unique compared to the other sectoral analyses of this report in that the costs of GHG mitigation in the electric power sector are estimated alongside the benefits. The three electric power sector models simulate these costs over time, and the rationale for presenting them here is to provide a comparison between the increase in power system costs due to mean temperature increases under the two scenarios and the costs associated with reducing GHG emissions from electric power generation. It is important to note that the effect of temperature change on generation accounts for only a small portion of the total effects of climate change on electricity supply. Other important effects, such as changes in hydropower generation or the availability of cooling water for thermoelectric combustion, are not included. Inclusion of these impacts on the electricity supply system would likely increase the benefits of mitigation to this sector.

For more information on the CIRA approach and results for the electricity supply sector, please refer to McFarland et al. (2015).[19]

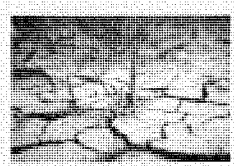
Water Resources



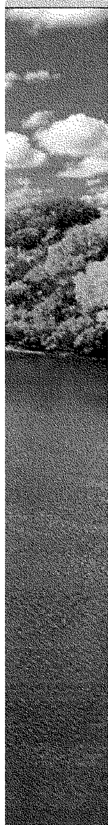
SUBSECTORS



Inland Flooding



Drought



Water, a resource that sustains life across the globe, is a vital component of a productive economy, providing a critical input to production in a number of key economic sectors.[1] In the U.S., water is used in many ways, including for human consumption, agricultural irrigation, power plant cooling, and hydropower generation. In addition, rivers, lakes, and oceans allow for navigation, fishing, and recreation activities. Water also plays an array of vital roles in ecosystems, which in turn provide crucial services that support human life. Analyzing the effects of climate change on water resources can be particularly challenging as climate variables affect both the supply and demand of water in different ways, and the impacts vary over space and time.

HOW IS WATER VULNERABLE TO CLIMATE CHANGE?

The water cycle is inextricably linked to climate, and climate change has a profound impact on water availability at global, regional, and local levels. As temperatures rise, the rate of evaporation increases, which makes more water available in the air for precipitation but also contributes to drying over some areas.[2] Further, climate change will result in increased intensity of precipitation events, leading to heavier downpours. Therefore, as climate change progresses, many areas are likely to see increased precipitation and flooding, while others will experience less precipitation and increased risk of drought. Some areas may experience both increased flooding and drought. Many of these meteorological changes, along with their associated impacts, are already being observed across the U.S. These changes, combined with demographic, socioeconomic, land use, and other changes, affect the availability, quality, and management of water resources in the U.S.[3]

WHAT DOES CIRA COVER?

The CIRA analyses estimate impacts and damages from three water resource-related models addressing flooding, drought, and water supply and demand (see the Health section of this report for water quality impacts). The models differ in the component of the water sector assessed and geographic scale, but together provide a quantitative characterization of water sector effects that no single model can capture. As the water cycle is sensitive to changes in precipitation, the analyses use a range of projections for future precipitation (see the CIRA Framework section for more information). Finally, future work to improve connectivity between the CIRA electricity, water, and agriculture analyses will aid in better understanding potential impacts to these sectors.

Water Supply and Demand

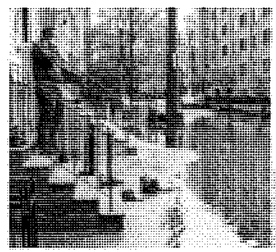
Inland Flooding

KEY FINDINGS

1. Warmer temperatures under climate change are projected to increase precipitation intensity in some regions of the contiguous U.S., raising the risk of damaging floods.

2. The effect of global GHG mitigation on flooding damages is sensitive to projected changes in precipitation. The flooding analysis using the IGSM-CAM climate model, which projects relatively wet conditions for most of the U.S., estimates that mitigation will result in a reduction in flood damages of approximately $2.9 billion in 2100 compared to the Reference. Using the drier MIROC model, the analysis projects that mitigation will result in disbenefits of approximately $38 million in 2100.

Climate Change and Inland Flooding



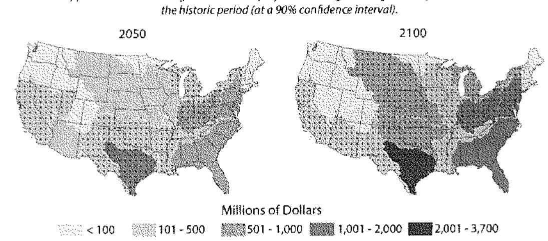
Extreme precipitation events have intensified in recent decades across most of the U.S., and this trend is projected to continue.[4] Heavier downpours can result in more extreme flooding and increase the risk of costly damages.[5] Flooding affects human safety and health, property, infrastructure, and natural resources.[6] In the U.S., non-coastal floods caused over 4,500 deaths from 1959 to 2005 and flood-related property and crop damages averaged nearly $8 billion per year[7] from 1981 to 2011.[8] The potential for increased damages is large, given that climate change is projected to continue to increase the frequency of extreme precipitation events and amplify risks from non-climate factors such as expanded development in floodplains, urbanization, and land-use changes.[9]

Risks of Inaction

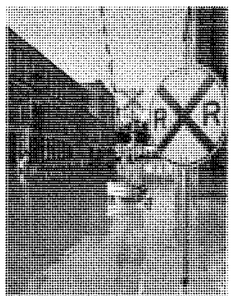
Without GHG mitigation, climate change under the IGSM-CAM projections is estimated to increase monetary damages associated with inland flooding across most of the contiguous U.S. Figure 1 presents the projected flood damages in 2050 and 2100 under the Reference scenario. As shown, substantial damages are projected to occur in more regions over time. By 2100, damages are projected to be significantly different from the historic period (at a 90% confidence interval) in 11 of the 18 large watersheds (2-digit hydrologic unit codes). The greatest damages are projected to occur in the eastern U.S. and Texas, with damages in these regions ranging from $1.0-$3.7 billion in 2100.[10] Projections of increased flood damages across most of the U.S. are consistent with the findings of the assessment literature.[11]

Figure 1. Estimated Flood Damages Due to Unmitigated Climate Change

Estimated flood damages under the Reference scenario in 2050 and 2100 for the IGSM-CAM climate model (millions 2014$). Results are presented for the 18 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. Stippled areas indicate regions where the projected damages are significantly different from the historic period (at a 90% confidence interval).



Reducing Impacts through GHG Mitigation

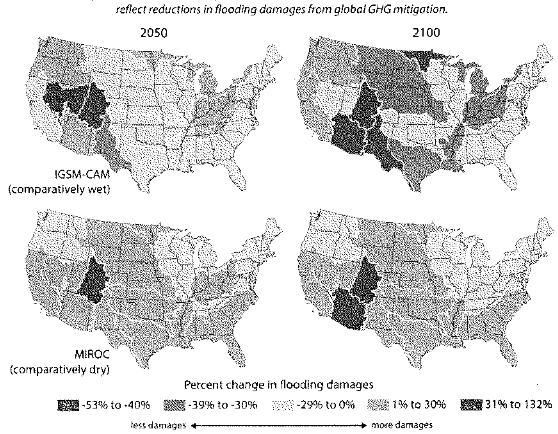


Under the relatively wetter IGSM-CAM climate projections, global GHG mitigation is projected to result in increased flooding damages compared to today, but decreased damages compared to the Reference scenario in most regions of the contiguous U.S. As shown in Figure 2, damages are reduced in 10 out of 18 regions in 2050 and in 14 out of 18 regions in 2100, with particularly pronounced differences between the scenarios in 2100. In 2100, the modeled reduction in damages is approximately $2.9 billion. By the end of the century, substantial benefits are projected over much of the Great Plains and Midwest regions, where damages are estimated to be reduced between 30% and 40% in many states. The four regions not showing benefits of GHG mitigation under the IGSM-CAM projections are located in the western part of the U.S., which also faces the highest risk of drought, as described in the Drought section of this report.

Figure 2 also presents results using the MIROC climate model, which projects a drier future compared to the IGSM-CAM model. Under the MIROC projections, flooding damages are generally reduced under both the Reference and Mitigation scenarios and, as a result, there are modest disbenefits of mitigation across most of the contiguous U.S. in 2050 and 2100. In 2100, damages are projected to increase nationally by $38 million under the Mitigation scenario compared to the Reference.

Figure 2. Change in Flooding Damages Due to Global GHG Mitigation

Percent change in flooding damages for the Mitigation scenario compared to the Reference. Results are presented for the 18 2-digit HUCs of the contiguous U.S. Negative values, shown in green, reflect reductions in flooding damages from global GHG mitigation.



APPROACH

The CIRA analysis quantifies how climate change could affect inland flooding damages in the contiguous U.S. Given the complexities inherent in projecting national flood damages, including the need for small watershed-scale hydrologic modeling, the results presented in this section should be considered first-order estimates. The analysis estimates changes in inland (non-coastal) flood damages following the approach described in Wobus et al. (2013).[12] Specifically, the analysis applies statistical relationships between historical precipitation and observed flood damages in each region of the U.S. to estimate the probability of damaging events occurring in a given year for the baseline period (1983-2008). Flood probabilities are then updated based on precipitation projections for specific events (i.e., 1-, 3-, 5-, and 7-day precipitation totals) under the Reference and Mitigation scenarios to estimate future flood damages. The analysis relies upon climate projections from two climate models: IGSM-CAM, which projects a relatively wetter future for most of the U.S., and the drier MIROC model. Damages are aggregated to the 18 U.S. Geological Survey National Water Resource Regions (WRRs) for two future periods (2050 and 2100), and are then statistically compared to modeled damages for the historic period. Importantly, the estimated damages do not include impacts on human health or economic disruption. The approach assumes that the distribution of monetary damages from flooding, including the effects of non-climate risk factors, will not change in the future.[13] Finally, the value of damages occurring in the future is scaled to account for changes in wealth using projected increases in per capita income in the two CIRA scenarios.

For more information on the CIRA approach and results for flooding damages, please refer to Strzepek et al. (2014)[14] and Wobus et al. (2013).[15]

Drought

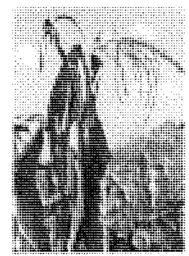
KEY FINDINGS

1. In the absence of global GHG mitigation, climate change is projected to result in a pronounced increase in the number of droughts in the southwestern U.S.

2. Global GHG mitigation leads to a substantial reduction in the number of drought months in the southwestern U.S. in both climate models analyzed. The effect of GHG mitigation in other regions is highly sensitive to projected changes in precipitation.

3. The reduction in drought associated with GHG mitigation provides economic benefits to the crop-based agriculture sector ranging from \$9.3-\$34 billion through 2100 (discounted at 3%).

Climate Change and Drought Risk



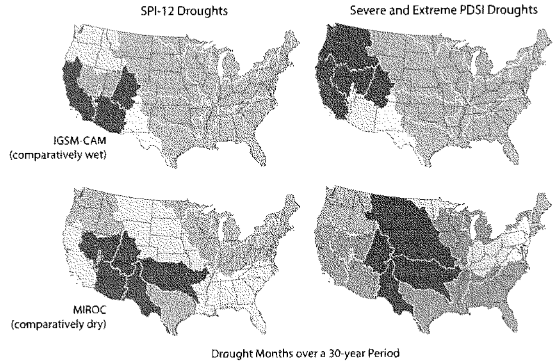
Climate change-related impacts on temperature and precipitation are expected to alter the location, frequency, and intensity of droughts in the U.S., with potentially devastating socioeconomic and ecological consequences.[16] Already, many U.S. regions face increasing water management challenges associated with drought, such as disruptions in navigation and water shortages for irrigation. In recent decades, recurring droughts across the West and Southeast have had significant socioeconomic and ecological impacts.[17]

Risks of Inaction

Without global GHG mitigation, climate change threatens to increase the number of droughts in certain regions of the U.S. The CIRA analysis uses multiple climate projections, each with unique patterns of regional change, to estimate the change in the number of SPI and PDSI droughts (see Approach for descriptions).[18] As discussed in the CIRA Framework section of this report, the IGSM-CAM projects a relatively wetter future for most of the contiguous U.S., while the MIROC model projects a drier future. Figure 1 shows that, although the climate models estimate different outcomes with respect to drought risk for the central and eastern U.S., they both project that the Southwest will experience pronounced increases in both SPI and PDSI drought months. Some areas of the country that are projected to experience increases in drought by 2100 are also projected to experience higher flooding damages (see the Inland Flooding section). This finding should not be interpreted as a conflicting result, and is consistent with the conclusions of the assessment literature,[19] which describe the drivers of these changes as more intense yet less frequent precipitation, and increases in evaporation due to higher temperatures.[20]

Figure 1. Effects of Unmitigated Climate Change on Drought Risk by 2100

Projected change in number of SPI and PSDI drought months under the Reference scenario over a 30-year period centered on 2100. Results are presented for the 18 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. Changes occurring in the grey-shaded areas should be interpreted as having no substantial change between the historic and future periods.



Reducing Impacts through GHG Mitigation

Global GHG mitigation leads to a substantial reduction in drought risk for many parts of the country (Figures 2 and 3). Under the IGSM-CAM climate projections, GHG mitigation substantially reduces drought occurrence across the western U.S., while under the MIROC model, drought is reduced over a majority of the country. Both climate models project reductions in drought in the Southwest, where the risks of increased droughts were highest under the Reference.

The overall decrease in the number of droughts under the Mitigation scenario, particularly in the West, results in substantial benefits to the crop-based agriculture sector. Through 2100, the present value benefits of GHG mitigation in the agricultural sector reach $9.3 billion (discounted at 3%) using the IGSM-CAM climate projections, compared to the Reference. Using the drier MIROC climate model, the Mitigation scenario provides benefits to the agriculture sector of approximately $34 billion (discounted at 3%). Projections from both climate models estimate higher economic benefits of GHG mitigation in the southwestern U.S., where drought frequency is projected to increase most dramatically in the absence of GHG mitigation.

Figure 2. Percentage Change in Number of Severe and Extreme Drought Months with and without GHG Mitigation

Change in number of PDSI drought months under the Reference and Mitigation scenarios over a 30-year period centered on 2100 in the contiguous U.S. Under both climate models, GHG mitigation results in fewer drought months compared to the Reference.

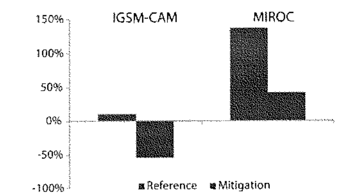
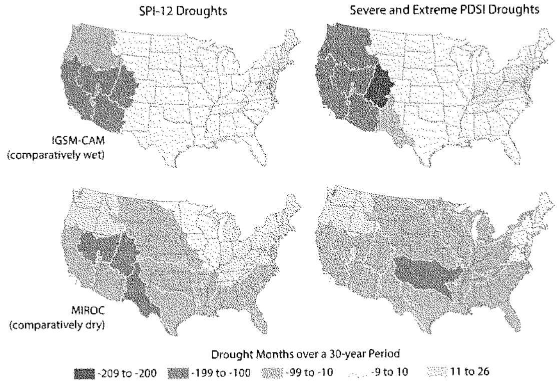


Figure 3. Effect of Global GHG Mitigation on Drought Risk by 2100

Estimated change in number of SPI and PDSI drought months under the Mitigation scenario compared to the Reference over a 30-year period centered on 2100. Results are presented for the 18 2-digit HUCs of the contiguous U.S. Shades of green represent reductions in the number of drought months due to GHG mitigation. Changes occurring in the grey-shaded areas should be interpreted as having no substantial change between the historic and future periods.

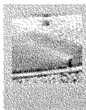


APPROACH

The CIRA analysis estimates the effect of climate change on the frequency and intensity of droughts across the contiguous U.S. The approach is based on the methodology from Strzepek et al. (2010).[21] It relies on two drought indices for both the historical and two 21st century time periods. The drought indices account for changes in key climate variables: the Standardized Precipitation Indices (SPI-5 and SPI-12) measure meteorological drought based on change in precipitation from the historical median, and the Palmer Drought Severity Index (PDSI) uses precipitation and temperature data to estimate the relative changes in a particular region's soil moisture. Drought risk is calculated for 99 sub-basins or watersheds in the contiguous U.S. and aggregated to 18 2-digit HUC regions.

The analysis then estimates the effect on crop-based agriculture of the change in frequency and intensity of droughts under the CIRA climate projections. This approach projects impacts using a sectoral model that relates historical drought occurrence with impacts on crop outputs.[22] The resulting relationships are then applied to climate projections under the CIRA Reference and Mitigation scenarios using the IGSM-CAM and MIROC climate models to estimate the economic impacts of climate change and effects of GHG mitigation.[23] This analysis only monetizes the impacts of drought on crop-based agriculture, and does not include other damages (e.g., decreased water availability, ecosystem disruption). Therefore the results estimated here likely underestimate the benefits of GHG mitigation for this sector.

For more information on the CIRA approach and results for the drought sector, please refer to Strzepek et al. (2014)[24] and Boehlert et al. (2015).[25]



Water Supply & Demand

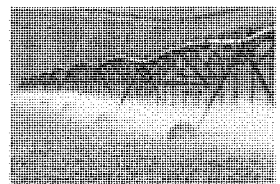
KEY FINDINGS

1 Unmitigated climate change is projected to have profound impacts on both water availability and demand in the U.S., compounding challenges from changes in demographics, land use, energy generation, and socioeconomic factors.

2 Without global GHG mitigation, damages associated with the supply and demand of water across the U.S. are estimated to range from approximately $7.7-$190 billion in 2100. The spread of this range indicates that the effect of climate change on water supply and demand is highly sensitive to projected changes in runoff and evaporation, both of which vary greatly across future climate projections and by U.S. region.

3 Global GHG mitigation is estimated to substantially decrease damages compared to the Reference. Projected benefits under the Mitigation scenario range from $11-$180 billion in 2100, depending on projected future climate. Importantly, global GHG mitigation is projected to preserve water supply and demand conditions more similar to those experienced today.

Climate Change and Water Supply and Demand



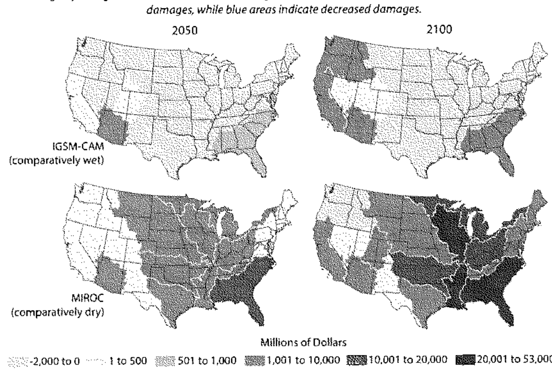
Water management in the U.S. is characterized by the struggle to balance growing demand from multiple sectors of the economy with increasingly limited supplies in many areas. Unmitigated climate change is projected to have profound impacts on both water availability and demand in the U.S., compounding challenges from changes in demographics, land use, energy generation, and socioeconomic factors. As temperatures rise and precipitation patterns become more variable, changes in regional water demand and surface and groundwater supplies are expected to increase the likelihood of water shortage for many areas and uses.[26]

Risks of Inaction

The effect of climate change on water supply and demand is highly sensitive to projected changes in runoff and evaporation, both of which vary across future climate projections and by U.S. region (Figure 1). Despite these variations, increased damages of unmitigated climate change are projected in the Southwest and Southeast regions under both climate models, and these damages increase over time. These projections are consistent with the findings of the assessment literature.[27] Using climate projections from the IGSM-CAM model, the analysis estimates damages at $7.7 billion in 2100. Despite the majority of U.S. regions showing modest increases in welfare (economic well-being) in 2100, the damages in the Southwest and Southeast are much larger in magnitude, and therefore drive the national total. Highlighting the sensitivity of this sector to the climate model used, the drier MIROC model estimates that net damages could be substantially larger, at approximately $190 billion in 2100.

Figure 1. Projected Impacts of Unmitigated Climate Change on Water Supply and Demand

Estimated change in economic damages under the Reference scenario in 2050 and 2100 compared to the historic baseline for the IGSM-CAM and MIROC climate models (millions 2014$). Results are presented for the 18 2-digit hydrologic unit codes (HUCs) of the contiguous U.S. Yellow, orange, and red areas indicate increased damages, while blue areas indicate decreased damages.



Reducing Impacts through GHG Mitigation

Global GHG mitigation is projected to substantially reduce damages compared to the Reference (Figures 2 and 3), and importantly, preserve water supply and demand conditions more similar to those experienced today. The IGSM-CAM model estimates that damages are $7.7 billion under the Reference scenario in 2100, while the Mitigation scenario results in an increase in welfare (collective economic well-being of the population) of $3.4 billion. Therefore, mitigation is estimated to result in a total increase in welfare of $11 billion in 2100 compared to the Reference. Using the drier MIROC model, the Mitigation scenario yields damages of approximately $19 billion in 2100; however, this represents avoided damages of approximately $180 billion compared to the Reference scenario (numbers do not sum due to rounding).

Figure 2. Economic Damages Associated with Impacts on Water Supply and Demand with and without Global GHG Mitigation

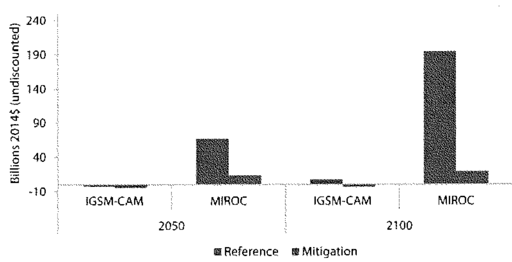
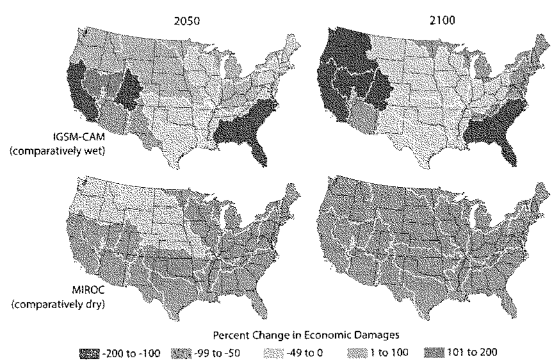


Figure 3. Projected Impacts of GHG Mitigation on Water Supply and Demand
Estimated percent change in economic damages under the Mitigation scenario in 2050 and 2100 relative to the Reference. Results are presented for the 18 2-digit HUCs of the contiguous U.S. Negative values (shown in green) indicate decreases in damages, or positive economic benefits, due to global GHG mitigation.



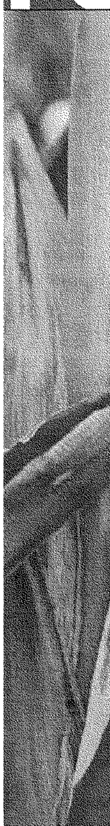
APPROACH

The CIRA analysis estimates the economic impacts associated with changes in the supply and demand of water, based on a national-scale optimization model developed by Henderson et al. (2013).[28] The model simulates changes in supply and demand in 99 sub-regions or watersheds of the contiguous U.S. based on changes in runoff and evaporation, population, irrigation demand, and other inputs that vary over time. Economic impact functions are applied for a range of water uses including irrigated agriculture, municipal and domestic water use, commercial and industrial water use, hydroelectric power generation, and in-stream flows.[29] The benefits from water use are maximized according to a wide range of constraints, such as storage and conveyance capacities, historic irrigated acreage, and renewable recharge capacity for groundwater. Economic damages are incurred in the model when any one of the water uses specified above does not receive sufficient volume to sustain the baseline activity level. Impacts are summed across all uses in each sub-region and reported as changes in economic welfare. Finally, the optimization model is driven by climate projections from the IGSM-CAM, as well as the MIROC climate model, which projects a relatively drier future for the contiguous U.S. compared to other climate models.[30]

For more information on the CIRA approach and results for the water supply and demand analysis, please refer to Strzepek et al. (2014)[31] and Henderson et al. (2013).[32]


Agriculture and
SUBSECTORS
Crop and
Forest Yields

Forestry



The U.S. has a robust agriculture sector that produces nearly $330 billion per year in agricultural commodities.[1] The sector ensures a reliable food supply and supports job growth and economic development.[2] In addition, as the U.S. is currently the world's leading exporter of agricultural products, the sector plays a critical role in the global economy.[3]

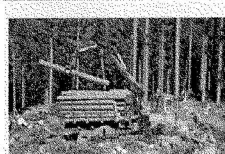
U.S. forests provide a number of important goods and services, including timber and other forest products, recreational opportunities, cultural resources, and habitat for wildlife. Forests also provide opportunities to reduce future climate change by capturing and storing carbon, and by providing resources for bioenergy production.[4]

HOW ARE AGRICULTURE AND FORESTRY VULNERABLE TO CLIMATE CHANGE?

U.S. agricultural and forest production are sensitive to changes in climate, including changes in temperature and precipitation, more frequent and severe extreme weather events, and increased stress from pests and diseases.[5] At the same time, climate change poses an added risk to many forests due to ecosystem disturbance and tree mortality through wildfire, insect infestations, drought, and disease outbreaks.[6] Climate change has the potential to both positively and negatively affect the location, timing, and productivity of agricultural and forest systems, with economic consequences for and effects on food security and timber production both in the U.S. and globally.[7,8] Adaptation measures, such as changes in crop selection, field and forest management operations, and use of technological innovations, have the potential to delay and reduce some of the negative impacts of climate change, and could create new opportunities that benefit the sector.

WHAT DOES CIRA COVER?

The CIRA analysis estimates climate change impacts on the agriculture and forestry sectors using both biophysical and economic models. The agriculture analyses demonstrate effects on the yield and productivity of major crops, such as corn, soybean, and wheat, but do not include specialty crops, such as tree fruits, or livestock. Further, the analysis does not explicitly model impacts on biofuel production or include technological advances in agricultural management practices. The analyses include yield and productivity impacts, but do not simulate the effects of changes in wildfire, pests, disease, and ozone. Future work to improve the multiple interactions among the CIRA energy, water, and agriculture analyses will aid in better understanding potential impacts to these sectors.



Market Impacts

Crop & Forest Yields

KEY FINDINGS

1. Unmitigated climate change is projected to result in substantial decreases in yields for most major agricultural crops.

2. Global GHG mitigation is projected to substantially benefit U.S. crop yields compared to the Reference scenario.

3. Without considering the influence of wildfires, the effect of GHG mitigation on forest productivity is less substantial compared to the response for crops. The direction of the effect depends strongly upon climate model and forest type (hardwood vs. softwood).

Risks of Inaction

Without significant global GHG mitigation, climate change is projected to have a large negative impact on the U.S. agriculture sector. Table 1 presents the projected percent change in national crop yields in 2100 due to unmitigated climate change under the Reference scenario. For all major irrigated crops, with the exception of hay, climate projections from both the IGSM-CAM and MIROC models result in decreased yields, with very substantial declines projected for soybeans, sorghum, and potatoes. For rainfed crops, climate projections using the drier MIROC climate model result in substantial declines for all crops, particularly cotton, sorghum, hay, wheat, and barley. Rainfed yields using the wetter IGSM-CAM climate model are more varied, ranging from a substantial decrease in hay yields to moderate gains in cotton, sorghum, and wheat yields.[9] Projected declines in crop productivity resulting from unmitigated climate change over the longer term are consistent with the findings of the assessment literature.[10]

As shown in Figure 1, the effect of unmitigated climate change on forest productivity in the U.S. varies over time and depends on the climate model used. Using the IGSM-CAM projections, hardwood yields increase by 2100, while the change in softwood yields is very small. Projections using the drier MIROC climate model result in increased hardwood and softwood yields by the end of the century, though the gains are smaller than those projected under the Mitigation scenario.

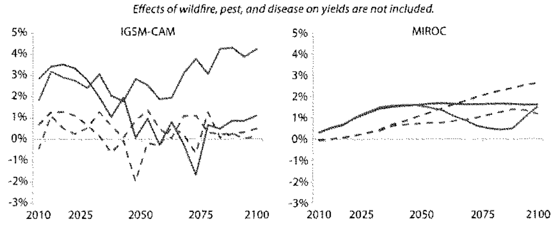
Table 1. Projected Percent Change in U.S. Crop Yields in 2100 without Global GHG Mitigation

Estimates in this table assume no technological improvements in yields over time such that crop productivity in future periods relative to a scenario with no climate change is based purely on differences in climatic conditions. This assumption allows the analysis to isolate and evaluate climate change impacts on crops without confluence with other factors. Results do not include effects from changes in ozone, pests, and disease. Rice and potatoes are simulated under irrigated management only.[11]

CROP	IGSM-CAM		MIROC	
	RAINFED	IRRIGATED	RAINFED	IRRIGATED
Cotton	17%	-11%	-27%	-17%
Corn	6%	-3%	-8%	-10%
Soybean	-5%	-20%	-19%	-23%
Sorghum	18%	-17%	-29%	-22%
Rice	n/a	-3%	n/a	-3%
Hay	-62%	29%	-65%	32%
Potato	n/a	-33%	n/a	-39%
Wheat	18%	-8%	-19%	-13%
Barley	-16%	-22%	-29%	-11%

Figure 1. Projected Change in Potential Forestry Yields with and without Global GHG Mitigation

Percent change in potential hardwood and softwood yields across the U.S. relative to the base period (1980-2009) under the Reference and Mitigation scenarios for the IGSM-CAM and MIROC climate models. Effects of wildfire, pest, and disease on yields are not included.



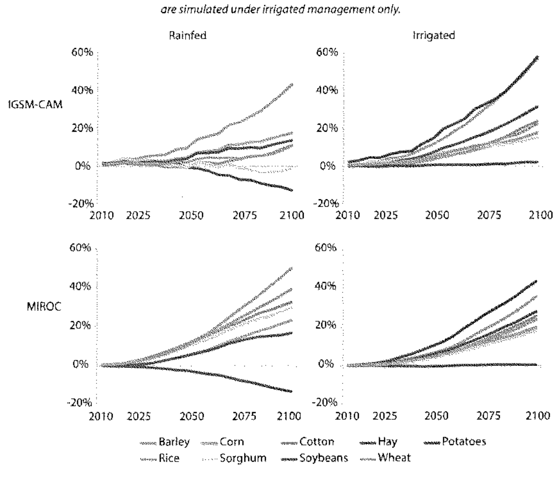
Reducing Impacts through GHG Mitigation

Global GHG mitigation is estimated to substantially benefit U.S. crop yields. Figure 2 presents the projected change in national crop yields for key crops under the Mitigation scenario compared to the Reference. The figure shows changes in rainfed and irrigated yields using projections from the IGSM-CAM climate model and the relatively drier MIROC model. In general, the benefits to crop yields of global GHG mitigation increase over the course of the century, with the exception of rainfed hay (for both climate models) and rainfed sorghum (for IGSM-CAM). Global GHG mitigation is projected to have a particularly positive effect on the future yields of irrigated soybeans, irrigated potatoes, and irrigated and rainfed barley.

The projected effect of GHG mitigation on forest productivity is less substantial compared to the response for crops. Figure 1 shows the estimated percent change in average national forest productivity (contiguous U.S.) under the Reference and Mitigation scenarios relative to the base period. Although forest productivity generally increases with climate change under both scenarios, projections using the relatively wetter IGSM-CAM climate model result in larger gains under the Reference scenario, particularly for hardwoods. Higher forest productivity under the IGSM-CAM Reference in the future is likely driven by the enhanced positive effects of CO_2 fertilization under the high-emission Reference, along with the response to increases in precipitation in many areas of the contiguous U.S. that are forested. The MIROC climate projections, on the other hand, result in slightly rising yields of both hardwoods and softwoods through 2100 under the Mitigation case. It is important to note that these yield estimates do not include the effects of wildfire, pests, or disease, which would likely decrease simulated productivity based on the findings of the assessment literature,[12] especially under the Reference scenario (See Wildfire section of this report).[13]

Figure 2. Projected Impacts of Global GHG Mitigation on Crop Yields

Percent change in crop yields from the EPIC model in the contiguous U.S. under the Mitigation scenario compared to the Reference for the IGSM-CAM and MIROC climate models.[14] Rice and potatoes are simulated under irrigated management only.



APPROACH

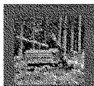
The analysis uses the Environmental Policy Integrated Climate (EPIC) model[15,16] to simulate the effects of climate change on crop yields in the contiguous U.S. The analysis examines agricultural crop productivity for multiple crops, including corn, soybean, wheat, alfalfa hay, sorghum, cotton, rice, barley, and potatoes. Yield potential is simulated for each crop for both rainfed and irrigated production with the exception of rice and potatoes, which are assumed to be irrigated.[17] Because production regions may change over time in response to climate change, EPIC simulates potential cultivation and production in areas within 100 km (62 miles) of historical production regions.

EPIC is driven by changes in future climate from both the IGSM-CAM[18] and MIROC climate models under the Reference and Mitigation scenarios. The results presented in this section include the effect of CO_2 fertilization on crop yields; Beach et al. provide a sensitivity analysis of the effect of CO_2 fertilization on the crop yield results from EPIC.

Changes in forest growth rates are simulated using the MC1 dynamic vegetation model, consistent with the approach described in Mills et al. (2014)[19] and the Wildfire and Carbon Storage sections of this report.[20] MC1 is also driven by the IGSM-CAM and MIROC models, and assumes full CO_2 fertilization effects.

The effects of changes in wildfires, pests, disease, and ozone are not captured in this analysis.[21] Inclusion of these effects on crop and forest yields would likely result in increased benefits of GHG mitigation compared to those presented in this section.

For more information on the CIRA approach and results for agriculture and forestry crop yields analysis, please refer to Beach et al.[22]



Market Impacts

KEY FINDINGS

1. Based on the projected changes in yields, global GHG mitigation is estimated to result in lower crop prices over the course of the 21st century compared to the Reference.

2. Changes in crop and forest productivity alter related market dynamics, land allocation, crop mix, and production practices, which in turn affect GHG emissions and carbon sequestration from the agriculture and forestry sectors. Global GHG mitigation has a large effect on emissions fluxes in managed forests; however, the magnitude and direction of the effect are sensitive to climate model projection.

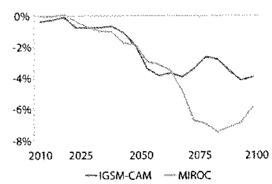
3. Under both climate model projections, global GHG mitigation increases total economic welfare in the agriculture and forestry sectors by \$43-\$59 billion (discounted at 3%) through 2100 compared to the Reference. The magnitude of estimated economic welfare impacts in the agricultural sector is much larger than in the forestry sector.

Changes in Crop Price

As described in the Crop and Forest Yields section of this report, global GHG mitigation is projected to result in generally higher crop yields in the U.S. relative to the Reference. As a result, mitigation is projected to result in less pressure on land resources and declining commodity prices. As shown in Figure 1, climate projections from both the IGSM-CAM and MIROC climate models show steep declines in a broad index of crop prices starting around 2040. Projections using the drier MIROC climate model result in greater declines in crop prices by the end of the century than those using the wetter IGSM-CAM model. Adverse effects of climate change on crop and food prices, which are largely avoided in the Mitigation scenario, are consistent with the findings of the assessment literature.[23]

Figure 1. Projected Change in National Crop Price Index Due to Global GHG Mitigation

Percent change in crop price index under the Mitigation scenario relative to the Reference for the IGSM-CAM and MIROC climate models.



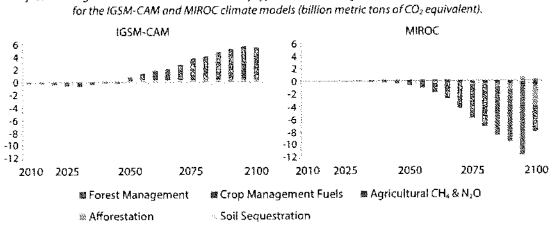
Changes in Emissions

Changes in land allocation, crop mix, and production practices in turn affect GHG emissions from agriculture and forestry practices. Figure 2 shows the estimated changes in cumulative GHG emissions under the Mitigation scenario compared to the Reference using projections from the IGSM-CAM and MIROC climate models. Under the IGSM-CAM projections, GHG mitigation is estimated to increase net GHG emissions from these sectors in the second half of the century. The increase is due in large part to the generally lower forest productivity that is projected to occur under the Mitigation scenario compared to the Reference, as the latter has higher productivity driven by the generally warmer and wetter future climate, as well as the enhanced positive effects of CO_2 fertilization (see the Crop and Forest Yields section). Thus, global GHG mitigation results in less forest carbon sequestration over time. Higher levels of carbon storage in forests under the generally warmer and wetter future of the IGSM-CAM Reference scenario are consistent with the findings presented in the Carbon Storage section of this report.

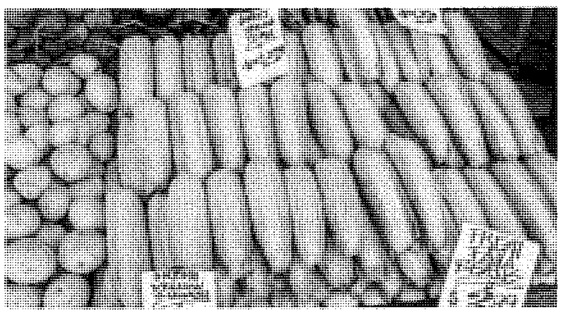
Under the MIROC climate projections, on the other hand, forest productivity is enhanced under the Mitigation scenario relative to the Reference, and forests take up and store more carbon. In addition, although emissions from livestock agriculture rise, GHG emissions related to crop production generally decline as less area is devoted to crops due to higher yields.

Figure 2. Projected Changes in Accumulated GHG Emissions in the Agriculture and Forestry Sectors Due to Global GHG Mitigation

Projected change in cumulative GHG emissions by type under the Mitigation scenario relative to the Reference for the IGSM-CAM and MIROC climate models (billion metric tons of CO_2 equivalent).



Changes in Consumer and Producer Surplus



The changes in crop prices and the level of production and consumption of agriculture and forestry products have important implications for the economic welfare of consumers and commodity producers. The analysis measures these effects through changes in consumer and producer surplus,[24] as summarized in Table 1. Using both climate model projections, global GHG mitigation increases total economic welfare (well-being) in the agriculture and forestry sectors by $43 to $59 billion (discounted at 3%) through 2100 compared to the Reference. Estimated consumer surplus is higher under the drier MIROC conditions than it is under the IGSM-CAM, primarily due to the larger crop yields under the Mitigation scenario compared to the Reference (see the Crop and Forest Yields section).

The effect of global GHG mitigation on producer surplus varies depending on the climate model used. The IGSM-CAM climate projections result in an increase in producer surplus, though not as substantial as the projected increase in consumer surplus. The drier MIROC projections result in a slight decrease in producer surplus due to the substantial increase in crop yields and resulting decrease in prices.

Table 1. Projected Effect of Global GHG Mitigation on Consumer and Producer Surplus in the Agriculture and Forestry Sectors

Change in cumulative consumer and producer surplus from 2015-2100 under the Mitigation scenario compared to the Reference (million 2014$, discounted at 3%). Results are rounded to two significant digits and therefore may not sum. In addition, the agriculture and forestry results do not sum to totals due to rounding, and because the table reflects independently calculated average values for agriculture, forestry, and combined totals.

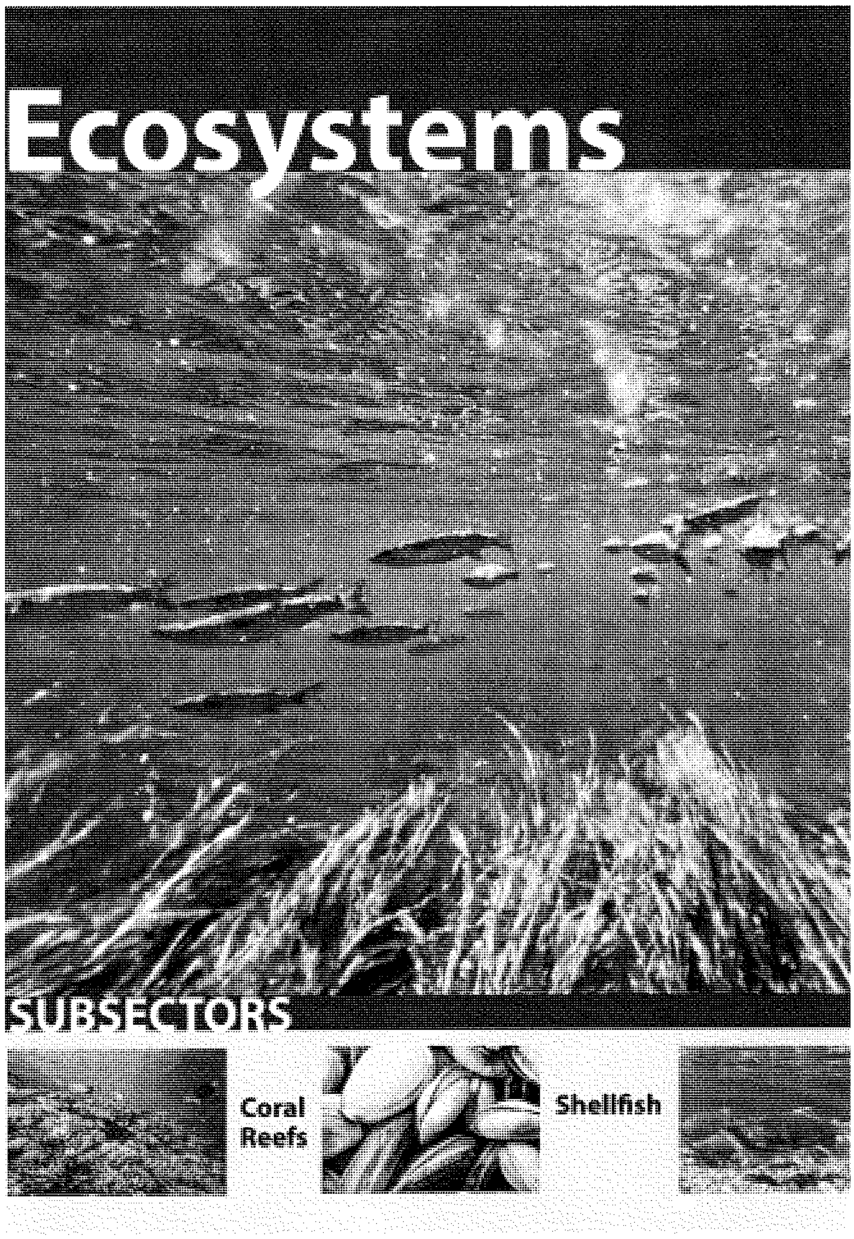
	CONSUMER SURPLUS	PRODUCER SURPLUS	TOTAL
IGSM-CAM			
Agriculture	$29,000	$13,000	$43,000
Forestry	$67	$350	$420
TOTAL	$29,000	$14,000	$43,000
MIROC			
Agriculture	$62,000	-$3,300	$59,000
Forestry	-$160	$920	$750
TOTAL	$62,000	-$2,400	$59,000

APPROACH

The CIRA analysis uses the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG)[25,26] to estimate changes in market outcomes associated with projected impacts of climate change on U.S. crop and forest yields. As described in the previous section, projected yields across regions and crop/forest types are generated by the EPIC and MC1 models. FASOM-GHG is driven by changes in potential yield from EPIC and MC1 for each of the five initializations of the IGSM-CAM climate model for both the Reference and Mitigation scenarios,[27] as well as the drier MIROC climate model.

FASOM-GHG simulates landowner decisions regarding crop mix and production practices, and projects the allocation of land over time to competing activities in both the forest and agricultural sectors and the associated impacts on commodity markets.[28] Given the changes in potential yields projected by EPIC and MC1, FASOM-GHG uses an optimization approach to maximize consumer and producer surplus over time.[29,30] The model is constrained such that total production is equal to total consumption, total U.S. land use remains constant (with the potential movement of land from forest to agriculture and vice versa), and non-climate drivers in the agriculture and forestry sectors are consistent between the scenarios to isolate the effect of climate change. In addition, the analysis assumes no price incentives for avoiding GHG emissions or carbon sequestration in the agriculture and forestry sectors (i.e., the sectors do not participate in the global GHG mitigation policy). Finally, although the EPIC simulations assume that crops can be irrigated to a level that eliminates water stress, the FASOM-GHG simulations include shifts in water availability for irrigation based on data obtained from the water supply/demand framework described in the Water Quality section of this report.[31]

For more information on the CIRA approach and results for the FASOM-GHG agriculture and forestry market impacts analysis, please refer to Beach et al.[32]


Ecosystems
SUBSECTORS
Coral
Reefs
Shellfish

An ecosystem is a community of organisms interacting with each other and their environment. People, animals, plants, microbes, water, and soil are typical components of ecosystems. We constantly interact with the ecosystems around us to derive and maintain services that sustain us and contribute to our livelihoods. Clean air and water, habitat for species, and beautiful places for recreation are all examples of these goods and services. With the diversity of ecosystem types in the U.S. being so great—from the tidal marshes of the East Coast to the desert valleys of the Southwest to the temperate rainforests of the Pacific Northwest—climate change is likely to fundamentally alter our nation's landscape and natural resources.[1]

HOW ARE ECOSYSTEMS VULNERABLE TO CLIMATE CHANGE?

Ecosystems are held together by the interactions and connections among their components. Climate is a central connection in all ecosystems. Consequently, changes in climate will have far-reaching effects throughout Earth's ecosystems. Climate change can affect ecosystems and species in a variety of ways; for example, it can lead to changes in the timing of seasonal life-cycle events, such as migrations; habitat shifts; food chain disruptions; increases in pathogens, parasites, and diseases; and elevated risk of extinction for many species.[2]

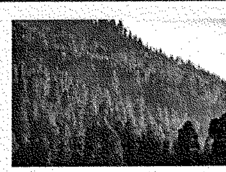
Climate change directly affects ecosystems and species, but it also interacts with other human stressors on the environment. Although some stressors cause only modest impacts by themselves, the cumulative impact of climate and other changes can lead to dramatic ecological impacts. For example, coastal wetlands already in decline due to increasing development will face increased pressure from rising sea levels.

WHAT DOES CIRA COVER?

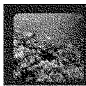
CIRA analyzes the potential benefits of global GHG mitigation on coral reefs and freshwater fisheries in the U.S., focusing on changes in recreational use of coral reefs and recreational fishing. This section also examines the projected impacts of ocean acidification on the U.S. shellfish market. Lastly, CIRA quantifies the physical and economic impacts of climate change on wildfires and terrestrial ecosystem carbon storage. Climate change will affect many species and ecosystems beyond what is explored in this report; consequently, CIRA captures only a glimpse of the potential benefits of GHG mitigation on this sector.

Freshwater Fish

Wildfire



Carbon Storage



Coral Reefs

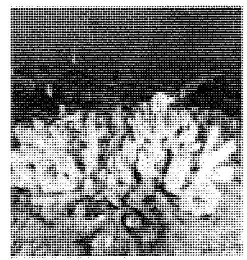
KEY FINDINGS

1. Coral reefs are already disappearing due to climate change and other non-climate stressors. Temperature increases and ocean acidification are projected to further reduce coral cover in the future.

2. Without global GHG mitigation, extensive loss of shallow corals is projected by 2050 for major U.S. reef locations. Global GHG mitigation delays Hawaiian coral reef loss compared to the Reference scenario, but provides only minor benefits to coral cover in South Florida and Puerto Rico, as these reefs are already close to critical thresholds of ecosystem loss.

3. GHG mitigation results in approximately $22 billion (discounted at 3%) in recreational benefits through 2100 for all three regions, compared to a future without emission reductions.

Climate Change and Coral Reefs



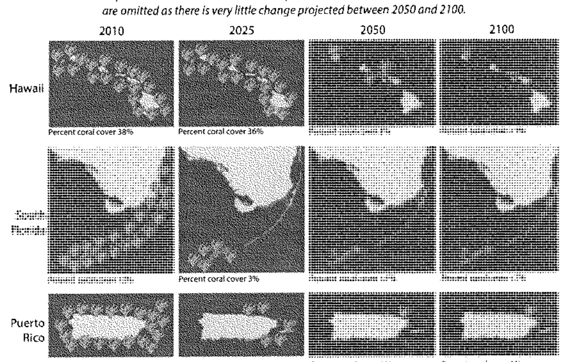
Coral reefs, including those found in Hawaii and the Caribbean, are unique ecosystems that are home to large numbers of marine plant and animal species. They also provide vital fish spawning habitat, protect shorelines, and are valuable for recreation and tourism. However, shallow-water coral reefs are highly vulnerable to climate change.[3] High water temperatures can cause coral to expel the symbiotic algae that provide nourishment and vibrant color for their hosts. This coral bleaching can cause the coral to die. In addition, ocean acidification (ocean chemistry changes due to elevated atmospheric CO_2) can reduce the availability of certain minerals in seawater that are needed to build and maintain coral skeletons.

Risks of Inaction

Without GHG mitigation, continued warming and ocean acidification will have very significant effects on coral reefs. For major U.S. reefs, projections under the Reference show extensive bleaching and dramatic loss of shallow coral cover occurring by 2050, and near complete loss by 2100. In Hawaii, coral cover is projected to decline from 38% (current coral cover) to approximately 5% by 2050, with further declines thereafter. In Florida and Puerto Rico, where present-day temperatures are already close to bleaching thresholds and where these reefs have historically been affected by non-climate stressors, coral is projected to disappear even faster.[4] This drastic decline in coral reef cover, indicating the exceedance of an ecosystem threshold, could have significant ecological and economic consequences at regional levels. These projections of shallow coral loss for major U.S. reefs are consistent with the findings of the assessment literature.[5]

Figure 1. Projected Impact of Unmitigated Climate Change on Coral Reef Cover in the U.S.

Approximate reduction in coral cover at each location under the Reference scenario relative to the initial percent cover. Coral icons do not represent exact reef locations. Results for 2075 are omitted as there is very little change projected between 2050 and 2100.

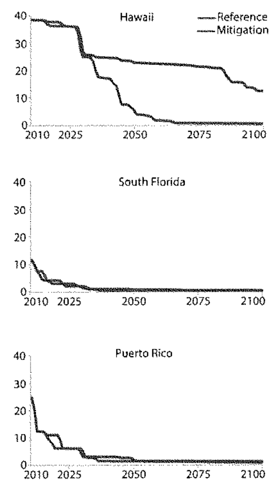


Reducing Impacts through GHG Mitigation

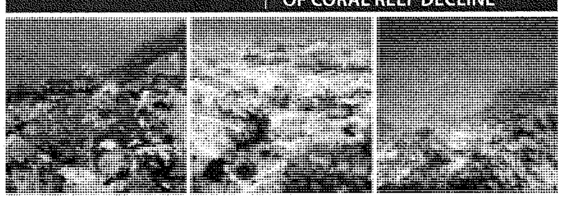
Mitigating global GHG emissions can reduce only some of the projected biological and economic impacts of climate change on coral reefs in the U.S. Figure 2 shows projected coral reef cover over time in Hawaii, South Florida, and Puerto Rico under the Reference and Mitigation scenarios. In Hawaii, the decline in reef cover slows under the Mitigation scenario compared to the Reference, as some of the extensive bleaching episodes and effects of ocean acidification are avoided. But even under the Mitigation scenario, Hawaii is projected to eventually experience substantial reductions in coral cover. In South Florida and Puerto Rico, the projected GHG emission reductions associated with the Mitigation scenario are likely insufficient to avoid multiple bleaching and mortality events by 2025, and coral cover declines thereafter nearly as fast as in the Reference.

The delay in the projected decline of coral results in an estimated $22 billion in economic benefits for recreation across the three sites through 2100 (discounted at 3%). The majority of these recreational benefits are projected for Hawaii, with an average value through 2100 of approximately $20 billion (95% confidence interval of $10-$30 billion). In Florida, where coral reefs have already been heavily affected, recreational benefits are also positive, but notably lower at approximately $1.4 billion (95% confidence interval of $0.74-$2.1 billion). In Puerto Rico, benefits are estimated at $0.38 million (95% confidence interval of $0.20-$0.57 million), but only represent recreational benefits for permanent residents, and therefore are not directly comparable to the other locations where visits from nonresident tourists are also included. Including the economic value of other services provided by coral reefs, such as shoreline protection and fish-rearing habitat, would increase the benefits of mitigation.

Figure 2. Percent Change in Coral Reef Cover with and without Global GHG Mitigation at Major U.S. Reefs



CORAL COVERAGE | REPRESENTATIVE PHOTOS OF CORAL REEF DECLINE



HEALTHY REEF
40-75% live coral cover

SEVERELY DEGRADED REEF
10-25% live coral cover

NEARLY DEAD REEF
<10% live coral cover

APPROACH

The CIRA analysis examines the physical and economic impacts of climate change and ocean acidification on coral reefs in Hawaii, South Florida, and Puerto Rico. Using the COMBO (Coral Mortality and Bleaching Output) model,[6,7] the analysis first estimates declines in coral reef cover (a measure of coral reef health and density) using projections of future ocean temperature (from the IGSM-CAM) and chemistry under the CIRA Reference and Mitigation scenarios.[8] The effects of future bleaching events are also estimated.

Next, the analysis quantifies the economic impacts associated with coral reef cover loss based on declines in reef-based recreation. The analysis estimates these impacts using a benefit-transfer approach; that is, it draws on reef-related recreation benefits measured in previously published studies conducted at a range of coral reef sites to estimate the value of reef-related recreation benefits in the areas considered in this study.[9] Projected impacts to recreation at each site are provided with confidence intervals based on the 95% interval for per-trip recreational values.

For more information on the CIRA approach and results for the coral reef sector, please refer to Lane et al. (2013)[10] and Lane et al. (2014).[11]

Shellfish

KEY FINDINGS

1. Without global GHG mitigation, the harvests of some shellfish in the U.S. are projected to decline by 32%-48% by the end of the century due to ocean acidification, though estimated impacts vary by species.

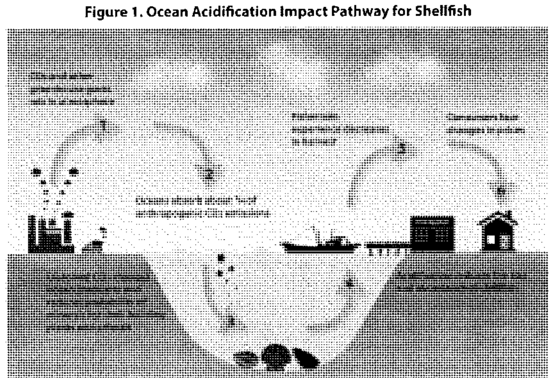
2. Demand for shellfish is projected to increase through the end of the century with a growing population and rising incomes, exacerbating the economic impacts in this sector.

3. Global GHG mitigation is projected to avoid $380 million in consumer losses in 2100 compared to the Reference scenario by preventing most of the decreases in the supply of select shellfish and the resulting price increases.

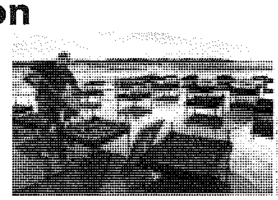
Ocean Acidification and Shellfish

The ocean absorbs about one quarter of the CO_2 released into the atmosphere by human activities, primarily from the combustion of fossil fuels. Although the ocean's ability to absorb CO_2 prevents atmospheric levels from climbing even higher, measurements made over the last few decades have demonstrated that marine CO_2 levels have risen, leading to an increase in acidity (Figure 1).[12] Ocean acidification is projected to adversely affect a number of valuable marine ecosystem services by making it more difficult for many organisms to form shells and skeletons.[13] Some shellfish are highly vulnerable to ocean acidification[14] and any impacts to these species are expected to negatively affect the economy. Certain species have high commercial value; for example, each year in the U.S., oysters, clams, and scallops supply 170 million pounds of seafood valued at $400 million.[15]

Figure 1. Ocean Acidification Impact Pathway for Shellfish



Risks of Inaction



The pace of ocean acidification is accelerating. Since the Industrial Revolution, the average pH of surface ocean waters has fallen by 0.1, representing a nearly 30% increase in acidity.[16] Under the Reference scenario, ocean acidification is projected to cause pH to drop an additional 0.3, representing a 100% increase in acidity from pre-industrial times. Continued ocean acidification is estimated to reduce the supply of oysters, scallops, and clams in 2100 by 45% (13 million pounds per year), 48% (21 million pounds), and 32% (31 million pounds), respectively (Figure 2). These decreases in supply are projected to result in price increases by 2100 of approximately $2.20 (a 68% increase from 2010), $9.10 (140%), and $1.30 (123%) per pound, respectively, and lead to consumer losses of roughly $480 million per year by the end of the century. These projections are consistent with the findings of the assessment literature, which describe reduced growth and survival of U.S. shellfish stocks due to unmitigated ocean acidification.[17]

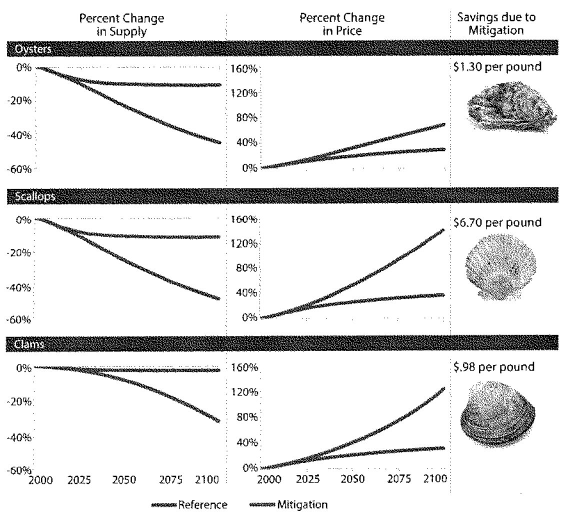
Reducing Impacts through GHG Mitigation

Reducing global GHG emissions can mitigate the ecological and economic impacts of ocean acidification. Figure 2 shows how the supplies of oysters, scallops, and clams are projected to fall with ocean acidification under the Reference and Mitigation scenarios. Although supplies are estimated to decrease under both scenarios relative to present-day supplies, the Mitigation scenario avoids a majority of the impacts, particularly for clams. In 2100, global GHG mitigation is projected to avoid the loss of 54 million pounds of oysters, scallops, and clams, or 34% of the present-day U.S. oyster supply, 37% of the scallop supply, and 29% of the clam supply.

Figure 2 also indicates how the increase in demand and the decrease in supply are estimated to affect prices by 2100 for these shellfish under the two scenarios. Consumers are likely to substitute away from these shellfish as their prices increase, but not entirely, and not without some decrease in satisfaction. The Mitigation scenario keeps prices much closer to current levels, as indicated in Figure 2, resulting in smaller consumer losses in the shellfish market. In 2100, the benefits to shellfish consumers from global GHG emissions reductions under the Mitigation scenario are estimated at $380 million. The cumulative benefits over the century are estimated at $1.9 billion (discounted at 3%).

Figure 2. Estimated Impacts on the U.S. Shellfish Industry

Projected changes in the supplies and prices of oysters, scallops, and clams through 2100 under the Reference and Mitigation scenarios relative to the base period.



APPROACH

The CIRA analysis models the entire "impact pathway" shown in Figure 1, which can be divided into biophysical and economic components. The biophysical impacts are estimated using the CIRA CO_2 and sea surface temperature projections from the IGSM-CAM in the CO2SYS model[18] to simulate seawater chemistry conditions through the 21st century. These conditions are then used to estimate how the growth rates of oysters, scallops, and clams will change over time.

The economic analysis uses the projected growth rates of these species to estimate changes to the U.S. supply of shellfish. A consumer demand model of the shellfish market, described in Moore (2014),[19] projects changes in prices and consumer behavior under the Reference and Mitigation scenarios. This model does not estimate producer or supply-side welfare effects, which could also show benefits of mitigation. Comparing the model results under the two scenarios provides an estimate of the benefits to the shellfish market of avoiding significant amounts of CO_2 from being added to ocean waters. By considering impacts to these three species, this approach estimates just a fraction of the potential economic damages from ocean acidification, but, nonetheless, provides some insight into the benefits of global GHG mitigation.

In addition, by preventing the loss of shellfish populations, global GHG mitigation would preserve ecosystem services provided by these species (e.g., water filtration). Inclusion of these effects would likely increase the total benefits of GHG mitigation in this sector.

For more information on the CIRA approach to estimating the economic impacts of ocean acidification in the shellfish market, see Moore (2015).[20]

Freshwater Fish

KEY FINDINGS

1 Warming waters and changes in stream flow due to climate change will likely alter the distribution of freshwater fisheries across the country. Without global GHG mitigation, coldwater species are projected to be replaced in many areas by less economically valuable fisheries over the course of the 21st century, especially in the Mountain West and Appalachia.

2 Habitat suitable for coldwater fisheries is estimated to decline nationally by approximately 62% through 2100 under the Reference, but by only 12% under the Mitigation scenario. Global GHG mitigation is projected to preserve coldwater habitat in most of Appalachia and the Mountain West.

3 GHG mitigation avoids an estimated $380 million to $1.5 billion in total recreational fishing damages through 2100 compared to the Reference (discounted at 3%).

Climate Change and Freshwater Fish

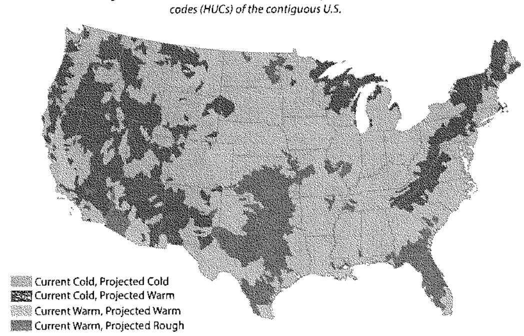
Freshwater fishing is an important recreational activity that contributes significantly to local economies in many parts of the country. Most fish species thrive only in certain ranges of water temperature and stream flow conditions. For example, trout and salmon can only tolerate coldwater streams, while shad and largemouth bass thrive in warmwater habitats (see below infographic). Climate change threatens to disrupt these habitats and affect certain fish populations through higher temperatures and changes in river flow.[21]

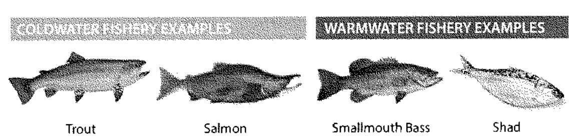
Risks of Inaction

Without GHG mitigation, climate change is projected to have a significant impact on freshwater fishing in the contiguous U.S. Increasing stream temperatures and changes in stream flow are likely to transform many habitats that are currently suitable for coldwater fish into areas that are only suitable for warmwater species that are less recreationally valuable. Under the IGSM-CAM climate projections, coldwater fisheries are estimated to be limited almost exclusively to the mountainous West in 2100, and would almost disappear from Appalachia. In addition, substantial portions of Texas, Oklahoma, Kansas, and Florida would shift from warmwater to rough habitat (Figure 1). Overall, unmitigated climate change is projected to result in a 62% decline in coldwater fish habitat by 2100, which includes approximately 440,000 acres of lost stream habitat. Meanwhile, warmwater and rough stream habitats are projected to increase by 1.3 million and 450,000 acres, respectively. The projected loss of coldwater fish habitat and expansion of warmwater and rough fisheries are consistent with the findings of the assessment literature.[22,23]

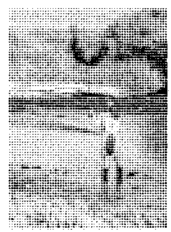
Figure 1. Projected Impact of Unmitigated Climate Change on Potential Freshwater Fish Habitat in 2100

Change in distribution of areas where stream temperature supports different fisheries under the Reference scenario using the IGSM-CAM climate model. Results are presented for the 8-digit hydrologic unit codes (HUCs) of the contiguous U.S.





Reducing Impacts through GHG Mitigation

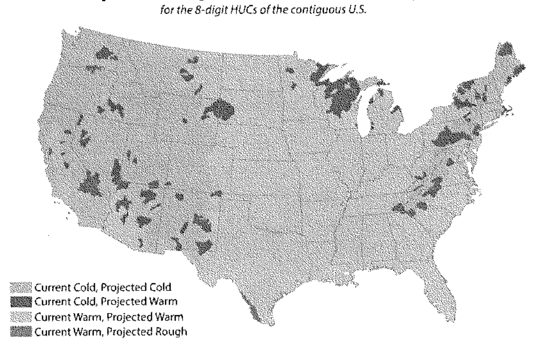


Global GHG mitigation is projected to prevent much of the loss of coldwater fish habitat that occurs in the Reference (Figure 2). Although coldwater stream habitat will likely still be reduced under the Mitigation scenario (by approximately 85,000 acres by 2100), mitigation avoids approximately 81% of the losses incurred under the Reference, preserving an area equal to approximately 360,000 acres of suitable stream habitat nationally. This habitat supports valuable recreational fishing, especially in Appalachia and large areas of the Mountain West. Also, fewer acres are converted to less economically valuable warmwater and rough fisheries under the Mitigation scenario than under the Reference. Specifically, stream habitat suitable for warmwater and rough fisheries increase by 450,000 and 13,000 acres, respectively, under the Mitigation scenario, which is 36% and 3% of the expansions estimated under the Reference.

Compared to the Reference, the Mitigation scenario provides economic benefits of approximately $1.5 billion through 2100 for coldwater fishing only, and $380 million when all three freshwater fishery types (cold, warm, and rough) are considered (discounted at 3%). These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model. The projected benefits of global GHG mitigation through 2100 are lower with the drier MIROC model (not shown) for coldwater fishing only, at approximately $1.2 billion, but higher when all three fisheries are considered, at approximately $1.5 billion (discounted at 3%).[24]

Figure 2. Projected Impact on Potential Freshwater Fish Habitat in 2100 with Global GHG Mitigation

Change in distribution of areas where stream temperature supports different fisheries under the Mitigation scenario using the IGSM-CAM climate model. Results are presented for the 8-digit HUCs of the contiguous U.S.



ROUGH FISHERY EXAMPLES

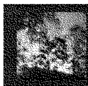
Largemouth Bass | Bluegill | Carp | Catfish

APPROACH

The CIRA analysis assesses the impacts of climate change on the distribution of habitat suitable for freshwater fish across the U.S. and estimates the economic implications of these changes. Water temperature changes are simulated for the CIRA emissions scenarios using the IGSM-CAM and MIROC climate models to estimate changes in suitable habitat (in stream acres) for three types of freshwater fisheries: cold, warm, and rough (species tolerant to warmest stream temperatures). Each fishery type represents a categorization of individual species based on their tolerance for different river and stream water temperatures. This analysis does not evaluate impacts to fisheries in lakes and reservoirs, which are vulnerable to climate change in different ways compared to streams and rivers.[25] As shown at the bottom of this section, the coldwater fish guild contains species that are the least tolerant to increasing stream temperatures, and are therefore the most vulnerable to climate change.

Results from habitat modeling considering projected changes in both water temperature and streamflow serve as input to an economic model to analyze the impacts of habitat change on the value of recreational fishing. The model estimates fishing behavior as the likelihood that an adult in a particular state is an angler and the likelihood that an angler fishes for species in each fishery type. The fishing value for each fishery type is derived by multiplying the number of fishing days by the value of a fishing trip.[26] As implications of changes to the distribution of freshwater fisheries extend beyond recreational use by humans, this analysis underestimates the economic benefits of GHG mitigation.

For more information on the CIRA approach and results for the freshwater fish sector, please refer to Lane et al. (2014)[27] and Jones et al. (2012).[28]



Wildfire

KEY FINDINGS

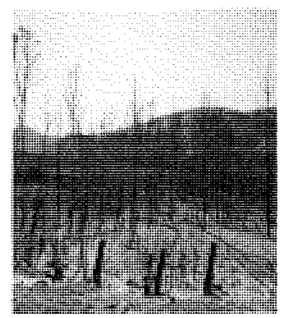
1. Without global GHG mitigation efforts, climate change is projected to dramatically increase the area burned by wildfires across most of the contiguous U.S., especially in the West.

2. Global GHG mitigation is projected to reduce the cumulative area burned by wildfires over the course of the 21st century by approximately 210-300 million acres compared to the Reference.

3. Global GHG mitigation avoids an estimated $8.6-$11 billion in wildfire response costs and $3.4 billion in fuel management costs on conservation lands (discounted at 3%) through 2100 compared to the Reference. Other impacts, such as property damage or health effects from decreased air quality, are not estimated, but could have large economic implications.

Climate Change and Wildfire

Terrestrial ecosystems in the U.S. provide a wealth of goods and services such as timber, wildlife habitat, erosion management, water filtration, recreation, and aesthetic value. Climate change threatens these ecosystems as heat, drought, and other disturbances bring larger and more frequent wildfires. Wildfires can damage property, disrupt ecosystem services, destroy timber stocks, impair air quality, and result in loss of life.[29] In the last decade (2004-2013), more than 72 million acres of forest have burned due to wildfires, and the U.S. government has spent in excess of $15 billion on wildfire suppression.[30] Additionally, wildfires release carbon stored in terrestrial ecosystems, potentially further accelerating climate change.[31, 32]

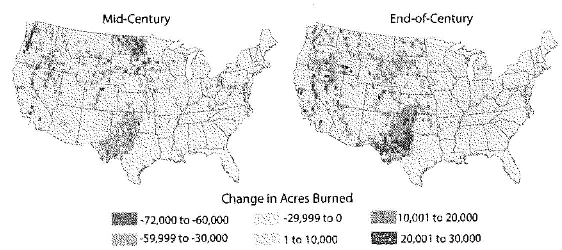


Risks of Inaction

Without GHG mitigation, climate change is projected to dramatically increase the area burned by wildfires across most of the contiguous U.S., a finding that is consistent with the assessment literature.[33] Under the Reference using the IGSM-CAM climate projections, approximately 5.3 million[34] more acres—an area greater than the state of Massachusetts—are projected to burn each year at the end of the century compared to today. This represents a doubling of acres burned compared to today's rates.[35] However, the estimated impacts vary across regions and through time (Figure 1). Consistent with the assessment literature,[36] the western U.S.[37] is projected to experience large increases in burned area by the end of the century (an increase of approximately 43%). In particular, the Southwestern region (comprising Arizona, New Mexico, and West Texas) is projected to experience increases of 140% on average.[38] Wildfire in other regions is not projected to change significantly compared to today, and some regions, such as the Northeast, are estimated under the IGSM-CAM projections to experience decreases in wildfire activity.

Figure 1. Projected Impact of Unmitigated Climate Change on Wildfire Activity

Change in average annual acres burned under the Reference scenario by mid-century (2035-2064) and end of century (2085-2114) compared to the historic baseline (2000-2009) using the IGSM-CAM climate model. Acres burned include all vegetation types and are calculated at a cell resolution of 0.5° x 0.5°.

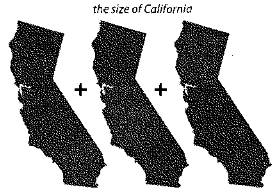


Reducing Impacts through GHG Mitigation

As shown in Figure 2, global GHG mitigation significantly reduces the area burned by wildfire in the U.S. over the course of the 21st century. By 2100, the Mitigation scenario reduces the cumulative area burned by approximately 210-300 million acres, depending on the climate model used. This corresponds to a 13-14% reduction relative to the Reference. As shown, the combined area of wildfires avoided in the contiguous U.S. due to GHG mitigation is equivalent to two to three times the size of California. These benefits of GHG mitigation would largely occur in the West, where approximately 64%-75% of the avoided burned area is located.

Benefits of GHG Mitigation

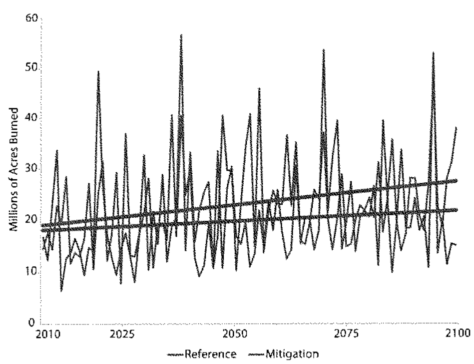
210-300 million fewer acres burned *over the course of the 21st century, an area* ***2-3 times*** *the size of California*



Nationally, the avoided wildfire due to GHG mitigation corresponds $11 billion in reduced wildfire response costs and $3.4 billion[39] in avoided fuel management costs for conservation lands through 2100 (both discounted at 3%). Other economic damages from wildfire that are not estimated in this analysis, such as human health effects from decreased air quality, could have large implications at national and regional scales. These results rely upon climate projections from the IGSM-CAM, which projects a relatively wetter future for most of the U.S. compared to the MIROC climate model (see the Levels of Certainty section of this report for more information). The projected benefits of global GHG mitigation are slightly lower for the drier MIROC model, with wildfire response cost savings estimated at $8.6 billion through 2100 (discounted at 3%).[40]

Figure 2. Estimated Acres Burned with and without Global GHG Mitigation

Estimated acres burned by wildfire in the contiguous U.S. over the course of the 21st century under the Reference and Mitigation scenarios using the IGSM-CAM climate model, with trends shown in bold. The large inter-annual variability reflects simulated periods of fuel accumulation followed by seasons of large wildfire activity.

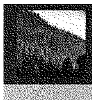


APPROACH

To estimate the effect of climate change on areas burned by wildfires, the CIRA analysis uses the MC1 dynamic global vegetation model. The model simulates future terrestrial ecosystem cover and burned area across the contiguous U.S. in the 21st century. The vegetation model is driven by changes in future climate (e.g., temperature, precipitation, humidity) based on five initializations of the IGSM-CAM climate model for the Reference and Mitigation scenarios.[41,42] Results presented in this section represent the average of the initializations. Simulations using the drier MIROC model were also performed. Projected changes in fire regime over time are adjusted to account for fire suppression tactics.

The projected impacts of wildfires are summarized by scenario and geographic area, and then monetized using average wildfire response costs for each region. These costs include the costs associated with labor (e.g., fire crews) and equipment (e.g., helicopters, bulldozers) that are required for fire-fighting efforts.[43] Using the approach described in Lee et al. (2015),[44] the analysis also estimates the environmental damages resulting from moderate and severe wildfires on conservation lands (e.g., Forest Service lands, national parks and preserves, and other protected lands) across the contiguous U.S. under the Reference and Mitigation scenarios. To estimate the value of the lost ecosystem services resulting from these wildfires, the analysis quantifies the costs of fuels management needed to offset the injury caused by wildfires. Air quality impacts, property loss, loss of recreation, and the effects of pest infestations (e.g., pine bark beetles) on wildfire activity are additional and important impacts, but are not included in the reported estimates.

For more information on the CIRA approach and results for wildfires, please refer to Mills et al. (2014)[45] and Lee et al. (2015).[46]



Carbon Storage

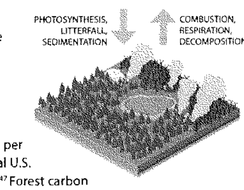
KEY FINDINGS

1. Changes in vegetative carbon storage in the contiguous U.S. are highly dependent on the projected future climate, with the magnitude, regional distribution, and directionality of impacts changing over time.
2. The estimated effect of global GHG mitigation on carbon storage ranges from a decrease in carbon stocks of 0.5 billion metric tons to an increase in carbon stocks of 1.4 billion metric tons by the end of the century, depending on the climate model used. The economic value of these changes in carbon storage ranges from $9 billion in disbenefits to $120 billion in GHG mitigation benefits (both discounted at 3%).

Climate Change and Terrestrial Carbon Storage

Terrestrial ecosystems influence the climate system through their important role in the global carbon cycle. These ecosystems capture and store carbon from the atmosphere, thereby reducing its climate impact. However, they can also act as a source, releasing carbon through decomposition and wildfires (Figure 1). Terrestrial ecosystems in the U.S., which include forests, grasslands, and shrublands, are currently a net carbon sink. Today, forests store more than 227 million tons of carbon per year, which offsets approximately 16% of all annual U.S. carbon dioxide emissions from fossil fuel burning.[47] Forest carbon storage has increased due to net increases in forest area, improved forest management, as well as higher productivity rates and longer growing seasons driven by climate change.[48] However, climate-driven changes in the distribution of vegetation types, wildfire, pests, and disease are affecting, and will continue to affect, U.S. terrestrial ecosystem carbon storage.[49]

Figure 1. Carbon Storage Basics

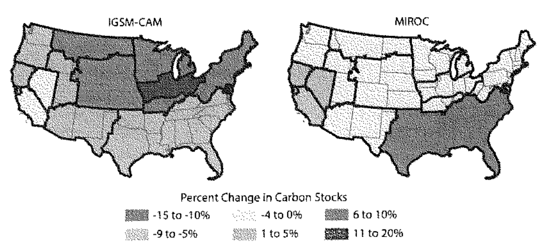


Risks of Inaction

Climate change impacts on terrestrial ecosystem carbon storage under the Reference are on the order of billions of tons of carbon from 2000 to 2100, with some regions showing substantial changes in terrestrial carbon stocks (total amount of carbon in the vegetation). Under the IGSM-CAM climate projections, terrestrial ecosystem storage across the contiguous U.S. is projected to increase 3.4% from 2000 to 2100 (equal to 2.9 billion metric tons),[50] primarily due to generally warmer, wetter, and CO_2-rich future conditions that are favorable to vegetative growth. Much of the national trend is driven by the Rocky Mountains, South, and East regions, which have the largest projected increases in terrestrial ecosystem carbon. However, as shown in Figure 2, there is substantial regional variation, and projections for carbon storage vary greatly depending on the projected future climate. Results using the drier MIROC climate model project net reductions in stored carbon under the Reference in most regions. These results are consistent with the findings of the assessment literature.[51]

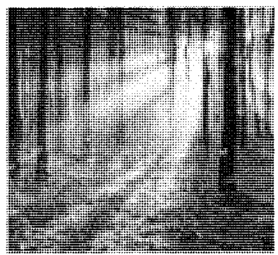
Figure 2. Projected Impact of Unmitigated Climate Change on Stored Carbon in 2100

Simulated changes in carbon stocks from the baseline (2000-2009 average) projected by the IGSM-CAM and MIROC climate models are aggregated by U.S. Forest Service Geographic Area Coordination Center region.



Reducing Impacts through GHG Mitigation

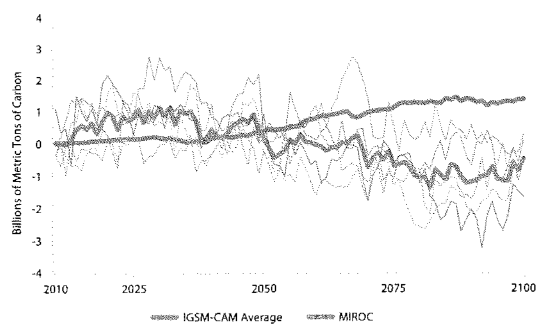
The impacts of GHG mitigation on national terrestrial ecosystem carbon storage are highly dependent upon the projected future climate, with the magnitude and even directionality of impacts varying over time (Figure 3). Across the contiguous U.S., average results across the IGSM-CAM initializations show that GHG mitigation reduces stored carbon compared to the Reference by 0.5 billion metric tons over the course of the century. The economic value of this lost carbon under the Mitigation scenario is an estimated $9.0 billion (discounted at 3%). As shown in Figure 3, carbon stocks under the Mitigation scenario are larger than the Reference in the first half of the century under the IGSM-CAM, but the trend reverses after 2050, as climate conditions under the Reference (generally warmer and wetter) are more favorable for vegetative growth. There is an early savings from the near-term gain in stored carbon of approximately 1.1 billion metric tons, estimated at $170 billion by 2030 (discounted at 3%). However, these initial gains are not large enough to offset projected losses in the second half of the century.



The projected impacts of climate change on vegetative carbon storage and the effects of GHG mitigation are different when using the relatively drier climate projections from the MIROC model (Figure 3). The MIROC results project a consistent increase in carbon storage benefits when comparing the Mitigation scenario to the Reference, with a carbon stock increase of 1.4 billion metric tons by 2100. The economic value of this carbon gain under the Mitigation scenario is an estimated $120 billion (discounted at 3%). Results using IGSM-CAM projections show much more variability over time than the MIROC results, which is primarily a reflection of the climate projection method.[52]

Figure 3. Projected Impact of Global GHG Mitigation on Carbon Stocks in the Contiguous U.S.

Estimated change in the size of terrestrial ecosystem carbon stocks under the Mitigation scenario compared to the Reference. Positive values indicate larger carbon stocks under the Mitigation scenario compared to the Reference, and vice versa. The thin lines represent estimated changes in carbon stocks under the different initializations of the IGSM-CAM climate model.



APPROACH

To estimate climate change impacts on terrestrial ecosystem carbon storage, the MC1 dynamic global vegetation model was used to simulate terrestrial vegetative growth and cover (e.g., grasses, shrubs, hard and softwood forests) for the contiguous U.S. from 2000 to 2100.[53] Vegetative cover estimates from MC1 reflect simulated changes in climate, biogeography, biogeochemistry, and fire dynamics. MC1 was run using the five initializations of the IGSM-CAM climate model for both the Reference and Mitigation scenarios (see the CIRA Framework section of this report for more information).[54] The results described in this section represent the average of these initializations. Because IGSM-CAM projects a wetter future for a majority of the nation, MC1 was also run using the MIROC climate model. These drier climate projections for the U.S. were used to capture a broader range of possible precipitation futures under the same GHG emissions scenarios.

Projected annual changes in terrestrial carbon storage for non-agricultural, non-developed lands across the contiguous U.S. were summarized by scenario and geographic area, and then monetized using the central estimate of the U.S. Government's updated social cost of carbon (SCC) values for the years 2010-2050, with extrapolation to 2100.[55]

This analysis did not consider the effects of future changes in ozone, pests, and disease, which could influence the ability of U.S. terrestrial ecosystems to store carbon.

For more information on the CIRA approach and results for carbon storage, please refer to Mills et al. (2014).[56]

Overview of Results

This section provides an overview of the national and regional results for all sectors included in the report. The National Highlights section presents the estimated physical and monetary benefits (avoided impacts) to the U.S. of the global GHG mitigation scenario compared to the Reference scenario in 2050 and 2100.

The Regional Highlights section shows regional impacts that are particularly notable, presenting changes in both the Reference and Mitigation scenarios to highlight the potential benefits of global GHG mitigation. The individual monetized estimates presented in these sections are not aggregated, as there are differences in the types of costs being quantified across sectors; furthermore, not all potential impacts of climate change are represented in this report.

OVERVIEW OF RESULTS

National Highlights

This section provides an overview of the national-scale results presented throughout this report. It presents the estimated physical and monetary benefits (avoided impacts) to the U.S. of global GHG mitigation compared to the Reference scenario in the years 2050 and 2100. Although not available for all sectors, cumulative benefits for the entire 21st century would likely be much larger than the annual estimates presented here. In addition, the individual monetized estimates are not aggregated, as only a subset of climate change impacts is quantified in this report, and there are differences in the types of costs being quantified across the sectors. For detailed information on the results, and a summary of the methodologies used, please refer to the Sectors section of this report.

	In the year 2050, global GHG mitigation is projected to result in...	In the year 2100, global GHG mitigation is projected to result in...
HEALTH		
AIR QUALITY	An estimated 13,000 fewer deaths from poor air quality, valued at $160 billion.*	An estimated 57,000 fewer deaths from poor air quality, valued at $930 billion.*
EXTREME TEMPERATURE	An estimated 1,700 fewer deaths from extreme heat and cold in 49 major U.S. cities, valued at $21 billion.	An estimated 12,000 fewer deaths from extreme heat and cold in 49 major U.S. cities, valued at $200 billion.
LABOR	An estimated avoided loss of 360 million labor hours, valued at $18 billion.	An estimated avoided loss of 1.2 billion labor hours, valued at $110 billion.
WATER QUALITY	An estimated $507-$700 million in avoided damages from poor water quality.†	An estimated $2.6-$3.0 billion in avoided damages from poor water quality.†
INFRASTRUCTURE		
BRIDGES	An estimated 160-960 fewer bridges made structurally vulnerable, valued at $0.12-$1.5 billion.†	An estimated 720-2,200 fewer bridges made structurally vulnerable, valued at $1.1-$1.6 billion.†
ROADS	An estimated $0.56-$2.3 billion in avoided adaptation costs.†	An estimated $4.2-$7.4 billion in avoided adaptation costs.†
URBAN DRAINAGE	An estimated $56 million to $2.9 billion in avoided adaptation costs from the 50-year, 24-hour storm in 50 U.S. cities.†	An estimated $50 million to $6.4 billion in avoided adaptation costs from the 50-year, 24-hour storm in 50 U.S. cities.†
COASTAL PROPERTY	An estimated $0.14 billion in avoided damages and adaptation costs from sea level rise and storm surge.	An estimated $3.1 billion in avoided damages and adaptation costs from sea level rise and storm surge.
ELECTRICITY		
DEMAND AND SUPPLY	An estimated 1.1%-4.0% reduction in energy demand and $10-$34 billion in savings in power system costs.‡	Not estimated.

* These results do not reflect the additional benefits to air quality and human health that would stem from the co-control of traditional air pollutants along with GHG emissions.

† For sectors sensitive to changes in precipitation, the estimated range of results is generated using projections from two climate models showing different patterns of future precipitation in the contiguous U.S. The IGSM-CAM model projects a relatively "wetter" future for most of the contiguous U.S. compared to the "drier" MIROC model (see the CIRA Framework section of this report for more information).

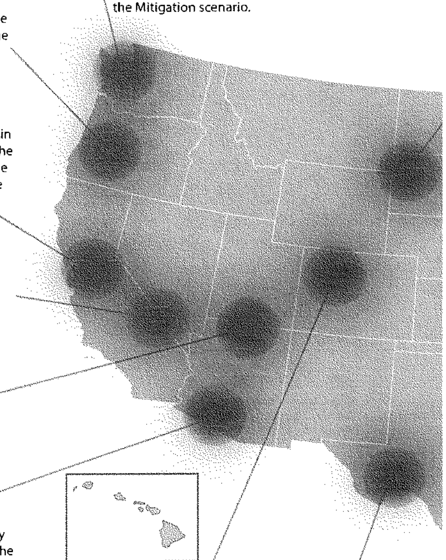
‡ Estimated range of benefits from the reduction in demand and system costs resulting from lower temperatures associated with GHG mitigation. The electricity section in this report presents an analysis that includes the costs to the electric sector of reducing GHG emissions.

	In the year 2050, global GHG mitigation is projected to result in...	In the year 2100, global GHG mitigation is projected to result in...
WATER RESOURCES		
INLAND FLOODING	An estimated change in flooding damages ranging from $260 million in damages to $230 million in avoided damages.[†]	An estimated change in flooding damages ranging from $32 million in damages to $2.5 billion in avoided damages.[†]
DROUGHT	An estimated 29%-45% fewer severe and extreme droughts, with corresponding avoided damages to the agriculture sector of approximately $1.2-$1.4 billion.[†]	An estimated 40%-59% fewer severe and extreme droughts, with corresponding avoided damages to the agriculture sector of $2.6-$3.1 billion.[†]
WATER SUPPLY AND DEMAND	An estimated $3.9-$54 billion in avoided damages due to water shortages.[†]	An estimated $11-$180 billion in avoided damages due to water shortages.[†]
AGRICULTURE & FORESTRY		
AGRICULTURE	An estimated $1.5-$3.8 billion in avoided damages.	An estimated $6.6-$11 billion in avoided damages.
FORESTRY	Estimated damages of $9.5-$9.6 billion.	An estimated $520 million to $1.5 billion in avoided damages.
ECOSYSTEMS		
CORAL REEFS	An estimated avoided loss of 53% of coral in Hawaii, 3.7% in Florida, and 2.8% in Puerto Rico. These avoided losses are valued at $1.4 billion.	An estimated avoided loss of 35% of coral in Hawaii, 1.2% in Florida, and 1.7% in Puerto Rico. These avoided losses are valued at $1.2 billion.
SHELLFISH	An estimated avoided loss of 11% of the U.S. oyster supply, 12% of the U.S. scallop supply, and 4.6% of the U.S. clam supply, with corresponding consumer benefits of $85 million.	An estimated avoided loss of 34% of the U.S. oyster supply, 37% of the U.S. scallop supply, and 29% of the U.S. clam supply, with corresponding consumer benefits of $380 million.
FRESHWATER FISH	An estimated change in recreational fishing ranging from $13 million in avoided damages to $3.8 million in damages.[†]	An estimated $95-$280 million in avoided damages associated with recreational fishing.[†]
WILDFIRE	An estimated 2.1-2.2 million fewer acres burned and corresponding avoided wildfire response costs of $160-$390 million.[†]	An estimated 6.0-7.9 million fewer acres burned and corresponding avoided wildfire response costs of $940 million to $1.4 billion.[†]
CARBON STORAGE	An estimated 26-78 million fewer metric tons of carbon stored, and corresponding costs of $7.5-$23 billion.[†]	An estimated 1-26 million fewer metric tons of carbon stored, and corresponding costs of $880 million to $12 billion.[†]

OVERVIEW OF RESULTS

Regional Highlights

This section highlights regional impacts of climate change in the U.S. For each sector, the map presents a region where substantial benefits of global GHG mitigation are projected to occur in the years 2050 or 2100.* Note that the geographic scale at which impacts are →



SHELLFISH

Acidification in the Pacific Northwest is already affecting U.S. shellfish harvests. The U.S. supplies of oysters, clams, and scallops are projected to decline 45%, 32%, and 48%, respectively, in the Reference scenario in 2100, compared to 11%, 3%, and 11%, respectively, in the Mitigation scenario.

CARBON STORAGE

The Northwest is projected to experience a 6.1% decrease in terrestrial carbon storage in 2100 under the Reference scenario, compared to a 2.4% decrease in the Mitigation scenario.

WATER SUPPLY AND DEMAND

California is projected to incur $4.5 billion in damages in 2100 due to changes in water supply and demand in the Reference scenario. However, climate change under the Mitigation scenario is projected to result in an increase in welfare of $40 million.

LABOR

In 2100, the Southwest is projected to experience a 3.4% decrease in high-risk labor hours worked in the Reference scenario, compared to a decrease of 0.82% in the Mitigation scenario.

DROUGHT

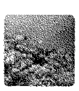
In the Southwest, the number of severe and extreme droughts is projected to nearly quadruple by the end of the century in the Reference scenario compared to today. In the Mitigation scenario, the incidence of drought is not projected to change substantially from present day.

WATER QUALITY

The Southwest is projected to experience water quality damages of approximately $1.8 billion in 2100 under the Reference scenario, compared to $470 million in the Mitigation scenario.

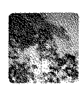
CORAL REEFS

By the end of the century, Hawaii is projected to lose 98% of its current shallow-water coral in the Reference scenario, compared to 64% in the Mitigation scenario.



WILDFIRE

In the Rocky Mountains, an estimated 1.9 million more acres are projected to burn in 2100 under the Reference scenario compared to today. In the Mitigation scenario, an estimated 1.5 million fewer acres are projected to burn compared to today.



INLAND FLOODING

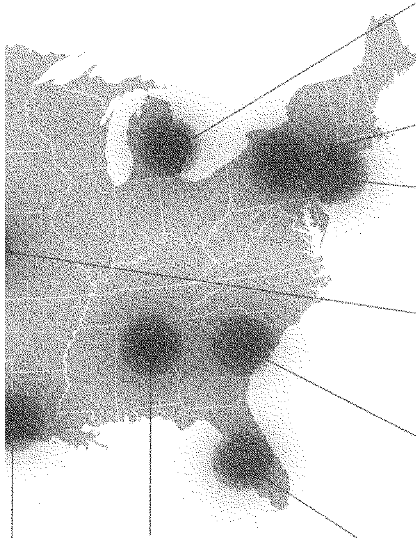
In Texas, projected damages associated with the 100-year flood event are $3.6 billion in 2100 under the Reference scenario, compared to $2.6 billion in the Mitigation scenario.

* Estimates are presented in undiscounted 2014 dollars and rely upon climate projections from the IGSM-CAM climate model. Results using projections from other climate models, such as the MIROC model used throughout this report, could lead to variations in results for some sectors.

quantified in the sectoral analyses vary. For example, some of the analyses calculate impacts for large watersheds, while others use the National Climate Assessment regions. For purposes of highlighting regional impacts, this section approximates the regions.

ROADS
In 2100, the Great Plains region is projected to incur road damages of approximately $3.5 billion in the Reference scenario, compared to $1.1 billion in the Mitigation scenario.

BRIDGES
In the Great Lakes region, approximately 520 bridges are projected to be vulnerable in 2100 under the Reference scenario, compared to 65 in the Mitigation scenario.



FRESHWATER FISH
Throughout the Appalachians, global GHG mitigation is projected to preserve approximately 70% of habitat for coldwater fish species (e.g., trout) that would otherwise be lost by the end of the century to rising temperatures from unmitigated climate change.

EXTREME TEMPERATURE
Without mitigation, major cities in the Northeast from D.C. to Boston are projected to suffer a combined 2,600 extreme temperature mortalities in 2100, compared to 190 in the Mitigation scenario.

URBAN DRAINAGE
In 2100, major cities analyzed in the Great Plains are estimated to incur $2.1 million per square mile in damages associated with urban drainage systems in the Reference scenario, compared to $750,000 per square mile in the Mitigation scenario.

AIR QUALITY
In 2100, areas of the Southeast are projected to experience an annual increase in ozone (O_3) and fine particulate matter ($PM_{2.5}$) of 0.7 ppb and 1 μg/m^{-3}, respectively. In the Mitigation scenario, the levels of O_3 and $PM_{2.5}$ are projected to decrease by 120% and 88%, respectively, compared to the Reference.

ELECTRICITY DEMAND
The South Central region is projected to experience a 2.0% to 4.2% increase in electricity demand under the Reference scenario in 2050. In the Mitigation scenario, the projected change in demand ranges from -1.4% to 1.6%.

COASTAL PROPERTY
In 2100, the Tampa Bay area is projected to incur $2.8 billion in damages from sea level rise and storm surge in the Reference scenario without adaptation. When adaptation measures are implemented, total costs in 2100 fall to $500 million in the Reference scenario, compared to $450 million in the Mitigation scenario.

AGRICULTURE
In the Southeast, yields of irrigated soybeans are projected to decrease 23% in 2100 under the Reference scenario. Under the Mitigation scenario, yields are projected to increase 4.7%.

Conclusion

Understanding the potential timing and magnitude of climate change impacts in the U.S., and how they could be reduced or avoided through GHG mitigation, informs near- and long-term policies to address these risks. This report describes climate change damages in the U.S. across multiple sectors using a consistent set of scenarios and underlying assumptions.[1] In doing so, the study estimates the physical and economic risks of unmitigated climate change and the potential benefits to the U.S. of reducing global GHG emissions. Importantly, only a small portion of the impacts of climate change are estimated, and therefore this report captures just some of the total benefits of reducing GHGs. Looking across the large number of sectoral impacts described in this report, a number of key findings emerge:

- **Unmitigated climate change is projected to profoundly affect human health, the U.S. economy, and the environment.** The CIRA analyses demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly at the end of the century—with negative consequences for a large majority of the impact sectors. In addition, the analyses suggest that climate change impacts will not be uniform across the U.S., with most sectors showing a complex pattern of regional-scale impacts.
- **Global action to mitigate GHG emissions is projected to reduce and avoid impacts in the U.S. that would otherwise occur in a future with continued high growth in GHG emissions.** Importantly, these benefits are projected to increase over the course of the century. The analyses indicate that risks and impacts over the long term will not be avoided unless there is near-term action to significantly reduce GHG emissions. This report presents benefits for one illustrative global GHG mitigation scenario. More stringent emissions reductions would likely increase the benefits compared to the Reference scenario, and, conversely, less stringent reductions would likely decrease the benefits.
- **Global GHG mitigation substantially reduces the risk of some extreme weather events and their subsequent impacts on human health and well-being by the end of the century.**
- **Adaptation, especially in the infrastructure sector, can substantially reduce the estimated damages of climate change.** For some impacts, such as those described in the Coastal Property section, well-timed adaptation can have a larger effect on reducing the risks of inaction than global GHG mitigation, particularly in the near term, highlighting the need for concurrent mitigation and adaptation actions.

- **For some impacts, the effects of global GHG mitigation can vary across different projections of future climate.** This is particularly true for those sectors sensitive to changes in precipitation. For a few of these sectors, mitigation results in either benefits or disbenefits depending upon the simulated level of future precipitation.[2] By analyzing multiple types of impacts by sector, such as flooding, drought, water quality, and supply/demand in the water realm, and using a range of projections for future precipitation, a more comprehensive understanding of potential impacts and mitigation benefits is gained.

Next Steps

This report represents a significant and important contribution to estimating the multi-sectoral benefits to the U.S. of global GHG mitigation. Although the results presented in this report do not provide comprehensive coverage of all potential impacts, the breadth and depth of the analyses will expand in future work within the CIRA project. Comprehensive and quantitative estimates of climate change impacts are not only needed to evaluate the benefits of GHG mitigation, but also to evaluate the cost-effectiveness of adaptation responses, and to support the improvement of other economic tools used to analyze climate and energy policies. Although CIRA only begins to capture many of the dynamics and uncertainties involved in impact analysis (e.g., interactions among sectoral models), this report provides timely and quantitative estimates as the science continues to advance in this field. Future work to refine projections of how GHG emissions affect the climate, and how these changes affect society and the environment, will improve our understanding and confidence in the estimates presented in this report.

Additional Climate Change Resources

EPA's Climate Change website (www.epa.gov/climatechange) provides a good starting point for further exploration of this topic. From this site, you can:

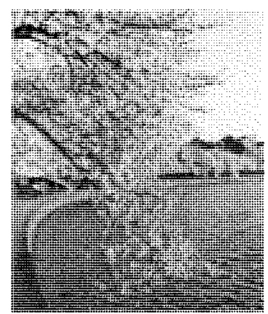
- Read about greenhouse gas emissions, look through EPA's greenhouse gas inventories, and explore EPA's Greenhouse Gas Data Publication Tool.
- Learn about EPA's regulatory initiatives and partnership programs.
- Find out what you can do at home, on the road, at work, and at school to help reduce greenhouse gas emissions.

Other government and nongovernment websites also provide information about climate change. Here are some examples:

- The Intergovernmental Panel on Climate Change (IPCC) is the international authority on climate change science. The IPCC website (www.ipcc.ch/index.htm) summarizes the current state of scientific knowledge about climate change and includes links to their most recent Fifth Assessment Report.
- The U.S. Global Change Research Program (www.globalchange.gov) is a multi-agency effort focused on improving our understanding of the science of climate change and its potential impacts on the U.S. through reports like the National Climate Assessment.

Finally, other groups are working to estimate the impacts of climate change in the U.S. and/or other world regions. Here are some examples:

- The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip) is an international, community-driven modelling effort bringing together impact models across sectors and scales.
- The Risky Business Project (http://riskybusiness.org/) focuses on quantifying and publicizing the economic risks from the impacts of a changing climate in the U.S.
- The European Commission Joint Research Centre's PESETA II project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis; http://peseta.jrc.ec.europa.eu/) is a consistent multi-sectoral assessment of the impacts of climate change in Europe.



- AVOID (http://www.metoffice.gov.uk/avoid/) is a research program that provides modeling and scientific information to the U.K. Government on avoiding dangerous climate change brought on by greenhouse gas emissions.
- The project on the Benefits of Reduced Anthropogenic Climate Change (BRACE; https://chsp.ucar.edu/brace) focuses on differences in impacts resulting from climate change driven by high and low emissions scenarios.

Observed Climate Change

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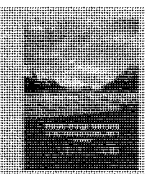

Endnotes

INTRODUCTION

1 Martinich, J., J. Reilly, S. Waldhoff, M. Sarofim, and J. McFarland, Eds. 2015. Special Issue on "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." *Climatic Change*.

2 While beyond the scope of this report, analyses of the adequacy of current GHG mitigation efforts, at domestic and global scales, relative to the magnitude of climate change risks are described in the assessment literature. See: 1) Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, ... and J. West. 2014. Ch. 27: Mitigation. In *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0C8276J; and 2) IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

3 United Nations Framework Convention on Climate Change. 2013. Report of the Conference of the Parties on its nineteenth session, held in Warsaw from November 11-23, 2013. Part one: Proceedings. FCCC/CP/2013/10.

4 CIRA uses sectoral impact models driven by consistent climate and socioeconomic scenarios to analyze both physical impacts and economic damages of climate change at national and regional scales in the U.S. This unique multi-model design allows for 'apples-to-apples' comparisons of impacts and benefits of global GHG mitigation across sectors, but is not comprehensive in scope. The impact estimates presented in this report are consistent with the key findings of the U.S. Global Change Research Program's Third National Climate Assessment. See Section H of the Technical Appendix for this report for a more detailed comparison of key findings.

5 The Social Cost of Carbon (SCC) is a metric that estimates the economic value of impacts associated with the global emission of one ton of carbon dioxide (CO_2) or, conversely, the economic benefit of avoiding or reducing one ton of CO_2 (in dollars per ton of CO_2 in a given year). Unlike CIRA, the SCC draws from models of anticipated climate change impacts and benefits across the entire globe, not just for the U.S. The SCC has already been applied to estimate the global economic benefits of CO_2 emission reductions from certain U.S. regulations, but it does not provide explicit information about how the actual physical impacts in specific sectors of the U.S. may change over time and space. For more information, see: U.S. Interagency Working Group on the Social Cost of Carbon. 2013. Technical support document: Technical update of the social cost of carbon for regulatory impact analysis under Executive Order 12866.

6 The CIRA project estimates the benefits to the U.S. of global action on climate change. Importantly, the costs of GHG mitigation are not assessed in the project. As such, the analysis presented in the report does not constitute a cost-benefit assessment of climate policy. The costs of reducing GHG emissions have been well examined in the scientific literature (see references below), where recent assessments have used multiple economic models to investigate the sensitivity of costs to policy design, assumptions about the availability of low carbon-emitting energy technologies, socioeconomic and demographic changes, and other important sources of uncertainty. The one instance in the CIRA project where mitigation costs are considered is in the electricity sector (see Electricity section for details). For that sector, the impact of climate change on costs to the U.S. electric power system is estimated along with the costs associated with GHG emission reductions in that sector. See: Fawcett, A., L. Clarke, and J. Weyant. 2013. Introduction to EMF 24. *The Energy Journal*. DOI:10.5547/01956574.35.SI1.1; White House Council of Economic Advisors. 2014. The Cost of Delaying Action to Stem Climate Change. Executive Office of the President of the United States; CCSP. 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B). *A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, Clarke, L., J. Edmonds, J. Jacoby, H. Pitcher, J. Reilly, R. Richels, ... and M. Webster (Authors). Washington, DC: Department of Energy; Kriegler, E., J.P. Weyant, G.J. Blanford, V. Krey, L. Clarke, J. Edmonds, ... and D.P van Vuuren. 2013. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*. DOI:10.1007/s10584-013-0953-7; and Kriegler, E., K. Riahi, N. Bauer, V.J. Schwanitz, N. Petermann, V. Bosetti, ... and O. Edenhofer. 2015. Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. *Technological Forecast and Social Change*. DOI:10.1016/j.techfore.2013.09.021; *Energy Economics*. Volume 31, Supplement 2, Pages S63-S306 (2009). International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22. Edited by Leon Clarke, Christoph Böhringer and Tom F. Rutherford.

7 Example of co-benefit literature: IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

SUMMARY OF KEY FINDINGS

1 This section draws upon conclusions described in the overview paper for the CIRA special issue: Waldhoff, S., J. Martinich, M. Sarofim, B. DeAngelo, J. McFarland, L. Jantarasami, K. Shouse, A. Crimmins, S. Ohrel, and J. Li. 2014. Overview of the Special Issue: A multi-model framework to achieve consistent evaluation of climate change impacts in the United States. *Climatic Change*. DOI:10.1007/s10584-014-1206-0.

2 Changes in extreme weather events across the CIRA scenarios are discussed in more detail in: Monier, E. and X. Gao. 2014. Climate change impacts on extreme events in the United States: an uncertainty analysis. *Climatic Change*. DOI:10.1007/s10584-013-1048-1.

3 See, for example: 1) Ciscar, J-C, A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, ... and A. Soria. 2011. Physical and economic consequences of climate change in Europe. *Proc Natl Acad Sci USA*. DOI:10.1073/pnas.1011612108; 2) Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, and D.J. Wuebbles. 2007. Confronting climate change in the U.S. Northeast: science, impacts, and solutions. Report of the Northeast Climate Impacts Assessment. Cambridge, MA: Union of Concerned Scientists; and 3)Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, ... and J.H. Verville. 2004. Emissions pathways, climate change, and impacts on California. *Proc Natl Acad Sci USA*. DOI:10.1073/pnas.0404500101.

4 Throughout the report, future benefits—i.e., the annual time series of avoided costs—are discounted at a 3% rate to reflect their value in the present day, which is defined as the year 2015 in this report. In short, discounting provides an equal basis to compare the value of benefits (and costs) that occur in different time periods. The discount rate itself reflects the trade-off between consumption today and consumption tomorrow, meaning that with a positive discount rate, benefits that occur today are worth more than they would be tomorrow. A higher discount rate implies a greater preference for present-day consumption and a lower present value of future damages. A lower discount rate implies a greater value on future damages. That is, the present value of future damages calculated at a 5% rate will be lower than those calculated using a 3% rate. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing benefits that span multiple generations. Therefore, we selected 3%, a commonly employed rate in the climate impacts and benefits literature. This rate was also used to calculate two of the U.S. Government's four Social Cost of Carbon estimates (including the central value), which estimate climate damages that occur over long time horizons. In particular, the U.S. Government review found that it was consistent with estimates provided in the economics literature and noted that 3% roughly corresponds to the after-tax riskless interest rate. For a detailed discussion on discount rate selection, please see the Social Cost of Carbon Technical Support Document, available at http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf.

CIRA FRAMEWORK

1 Martinich, J., J. Reilly, S. Waldhoff, M. Sarofim, and J. McFarland, Eds. 2015. Special Issue on "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." *Climatic Change*.

2 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. Appendix 5: Scenarios and Models. U.S. Global Change Research Program. DOI:10.7930/J0Z31WJ2.

3 While beyond the scope of this report, analyses of the adequacy of current GHG mitigation efforts, at domestic and global scales, relative to the magnitude of climate change risks are described in the assessment literature. See, for example: 1) Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, ... and J. West. 2014. Ch. 27: Mitigation. *Climate Change Impacts in the United States: The Third National*

Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0C8276J; and 2) IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

4 A third emissions scenario was applied in most CIRA sectoral analyses, as described and presented in the research papers supporting the project. In 2100, this scenario, called Policy 4.5 in the CIRA project, achieves a radiative forcing of approximately 4.2 W/m^2 with an atmospheric GHG concentration of 600 ppm (CO_2 equivalent). This radiative forcing value reflects GHG radiative forcing (i.e., not including aerosols) and uses a baseline of 1750 (both of which are necessary adjustments for comparing to the IPCC RCPs), therefore making it slightly different than the value reported previously in the CIRA literature (4.5 W/m^2).

5 Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) model: version 4. Report 125, MIT Joint Program on the Science and Policy of Global Change. http://globalchange.mit.edu/publications.

6 By 2100 (using a baseline of 1750), the CIRA Reference scenario has a total radiative forcing of 9.8 W/m^2, which appears considerably larger than RCP 8.5. However, the contrast is primarily due to differences in how forcing is calculated by different GCMs used in developing those scenarios. The IGSM radiation code was derived from the GISS climate model, and therefore when calculating radiative forcing due to increased concentrations in the IGSM, forcing functions fit to the GISS code were used rather than the more common approach of using simplified equations, such as those defined in IPCC's Third Assessment Report. Using these simplified equations, total radiative forcing for the CIRA Reference is 8.6 W/m^2, and 3.2 W/m^2 for the Mitigation scenario. Other differences between the IGSM scenarios and the RCPs are due to differences in anthropogenic emissions, natural emissions responses to warming, and atmospheric chemistry.

7 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2013. Integrated economic and climate projections for impact assessment. *Climatic Change*. DOI:10.1007/s10584-013-0892-3. We also note that the Reference scenario is calibrated using historic GHG emissions through 2010; see Paltsev et al. (2013) for more information.

8 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2013. Integrated economic and climate projections for impact assessment. *Climatic Change*. DOI:10.1007/s10584-013-0892-3.

9 Radiative forcing (including CO_2, CH_4, N_2O, PFCs, SF_6, HFCs, CFCs and HCFCs) for the Reference and Mitigation scenarios (see Paltsev et al. 2013), compared to the four RCPs (data from Meinshausen et al. 2011). The negative forcing effects of aerosols are not included. See: Meinshausen, M., S. J. Smith, K. V. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F. Lamarque, ... and D. van Vuuren. 2011. The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300. *Climatic Change*. DOI:10.1007/s10584-011-0156-z.

10 Please see the literature underlying the CIRA project for information on post-processing and bias-correction of climate outputs for use in the sector analyses.

11 Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change*. DOI:10.1007/s10584-014-1112-5.

12 Adaptive actions modeled in the sectoral analyses of this report should not be interpreted as recommendations of these particular strategies.

13 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Chapter 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, R.C. Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.

14 The U.S. Global Change Research Program's National Climate Assessment (NCA) results are reported for the RCP 8.5 scenario, using a range (5th-95th percentile) of results from a suite of climate models, adjusted to match the same baseline period used for the IGSM-CAM model. The NCA also presents results from the older SRES models: the A2 scenario from SRES was projected to warm by 5-8°F by 2100.

15 Future climate change depends on the response of the global climate system to rising GHG concentrations (i.e., how much temperatures will rise in response to a given increase in atmospheric CO_2). Assumptions about this relationship are referred to as climate sensitivity.

16 IPCC. 2014. Summary for Policymakers. In: Climate Change 2014, Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY.

17 IPCC. 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, ... and P.M. Midgley, Eds. New York, NY.

18 The estimate of warming from the historical period (0.65°C) used in Figure 1 of the Temperature Projections section is slightly less than the IPCC's estimate of 0.85°C because the former utilizes a 30-yr average (1980-2009) to represent the current period.

19 Warming from the historical period (0.65°C) comparing 1880-1909 to 1980-2009 was calculated using the NOAA Global Historical Climatology Network GHCN-3 dataset of Global Land and Ocean Temperature Anomalies (available at http://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/ytd/12/1880-2014.csv). Combined with this historical warming, the 2°C target (relative to preindustrial) is equivalent to a warming of 2.43°F (relative to the 1980-2009 baseline period), as shown in Figure 1 of the Temperature Projections section. This value is consistent with the average of the last two decades of the century (2081-2100) for the CIRA Mitigation scenario: 2.23°F.

20 Monier, E. and X. Gao. 2014. Climate change impacts on extreme events in the United States: an uncertainty analysis. *Climatic Change*, DOI:10.1007/s10584-013-1048-1.

21 Ibid.

22 The CIRA sea level rise scenarios are at the high end of projected sea level rise rates for similar scenarios based on recent publications (Horton et al. 2014, Kopp et al. 2014). However, we also note that the effect of GHG mitigation on reducing the increase in future sea level was found to be larger in these studies. The use of a smaller sea level rise would likely lead to a decrease in total damages, but a larger reduction in sea level rise due to the Mitigation scenario would likely yield larger economic benefits than those presented in this report. See: 1) Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quaternary Science Reviews*. DOI:10.1016/j.quascirev.2013.11.002; and 2) Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H.Strauss, and C. Tebaldi. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*. DOI:10.1002/2014EF000239.

23 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Chapter 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, R.C. Richmond, and G. W. Yohe, Eds. U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.

24 Meier, M.F., M.B. Dyurgerov, U.K. Rick, S. O'Neel, W.T. Pfeffer, R. S. Anderson, S.P. Anderson, and A.F. Glazovsky. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*. DOI:10.1126/science.1143906.

25 Vermeer, M., and S. Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*. DOI:10.1073/pnas.0907765106.

26 The CIRA sea level rise projections were estimated following the methodology of Vermeer and Rahmstorf (2009). The methodology of Vermeer and Rahmstorf builds off that from Rahmstorf (2007) and is described in detail in those papers. In short, projections were estimated using an empirical relationship between global air temperature and sea level change, including contributions from glaciers and ice sheets. This relationship was then applied to the ambient average air temperature trajectories from the IGSM-CAM model (Paltsev et al. 2013) to project future sea levels.

27 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly. 2013. Integrated economic and climate projections for impact assessment. *Climatic Change*. DOI:10.1007/s10584-013-0892-3.

28 For each scenario, a site-specific, fixed annual rate of land subsidence or uplift is estimated, which combines with the SLR scenario to yield site-specific relative sea level rise. Historical vertical land movement is based on annual average measurements from National Oceanic and Atmospheric Administration (NOAA) tide gauge data from 68 sites with at least 25 years of continuous measurements and linear interpolation of subsidence rates for all cells that lie between the selected sites. An estimated 1.7 mm/year is subtracted from the tide gauge annual average to account for the component of relative sea level rise that is accounted for by 20th century sea level change, yielding the site-specific subsidence/uplift rate.

29 The CIRA approach for calculating relative sea level rise assumes that the difference in rate between global and relative sea level change will continue into the future. Because some physical processes (e.g., changes in differential ocean heating) will likely change in the future at rates different from what is reflected in historical tide gauge data, the CIRA approach does not capture all of these dynamics. For more information, see: Neumann, J., D. Hudgens, J. Herter, and J. Martinich. 2010. The Economics of Adaptation along Developed Coastlines. *Wiley Interdisciplinary Reviews: Climate Change*. DOI:10.1002/wcc.90.

30 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Appendix 3: Climate Science Supplement. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, T.C. Richmond, and G.W. Yohe, Eds., U.S. Global Research Program. DOI:10.7930/J0KS6PHH.

31 Ibid.

32 Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change*. DOI:10.1007/s10584-014-1112-5.

Endnotes

33 Ibid.

34 All three CIRA emissions scenarios contain the same level of global and U.S. population change over time.

35 For each emissions scenario, values represent the ensemble mean of the five IGSM-CAM initializations using a climate sensitivity of 3°C.

36 IPCC. 2013. Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, ... and P.M. Midgley, Eds. New York, NY: Cambridge University Press.

37 A climate sensitivity of 6°C is considered "low probability" when considering feedbacks expected over the next century. However, there is literature suggesting that slower feedbacks involving ice sheet and vegetation changes can lead to higher "Earth System Sensitivity" on timescales of several centuries, such that a sensitivity of 6°C will have a higher probability on these longer timescales. Additional feedbacks including methane and carbon cycles are not included in the climate sensitivity definition.

38 Mapped values represent the ensemble mean of the five IGSM-CAM initializations with different climate sensitivities under the Reference scenario.

39 All five maps assume a climate sensitivity of 3°C under the Reference scenario.

40 A method by which the average change produced by running a climate model is combined with the specific geographic pattern of change calculated from a different model in order to approximate the result that would be produced by the second model.

41 Please refer to: 1) Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change.* DOI: 10.1007/s10584-014-1112-5; and 2) Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, ... and M. Rummukainen. 2013. Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Eds. New York, NY: Cambridge University Press.

42 Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change.* DOI:10.1007/s10584-014-1112-5.

43 This section draws upon conclusions described in the overview paper for the CIRA special issue: Waldhoff, S., J. Martinich, M. Sarofim, B. DeAngelo, J. McFarland, L. Jantarasami, K. Shouse, A. Crimmins, S. Ohrel, and J. Li. 2014. Overview of the Special Issue: A multi-model framework to achieve consistent evaluation of climate change impacts in the United States. *Climatic Change.* DOI:10.1007/s10584-014-1206-0.

44 For more information on these types of impacts, see: National Research Council. 2013. Abrupt Impacts of Climate Change: Anticipating Surprises. Washington, DC: The National Academies Press.

45 Monier, E., X. Gao, J.R. Scott, A.P. Sokolov, and C.A. Schlosser. 2014. A framework for modeling uncertainty in regional climate change. *Climatic Change.* DOI:10.1007/s10584-014-1112-5.

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47 For a discussion of interactions among the energy, water, and land use sectors, see: Hibbard, K., T. Wilson, K. Averyt, R. Harriss, R. Newmark, S. Rose, E. Shevliakova, and V. Tidwell. 2014. Ch. 10: Energy, Water, and Land Use. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0JW8BSF.

SECTORS
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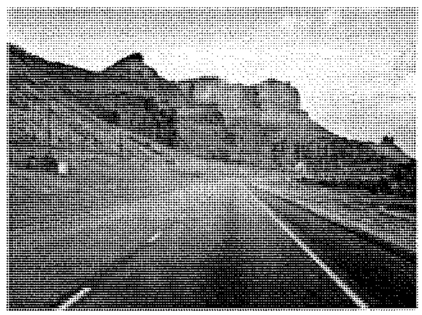
1 The economic estimates described throughout this report are presented in constant 2014 dollars. The literature underlying the CIRA project presents results primarily in 2005 dollars. This should be noted when comparing the results presented in this report with those in the CIRA literature. Dollar years were adjusted using the U.S. Bureau of Economic Analysis' Implicit Price Deflators for Gross Domestic Product. Source: U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, http://www.bea.gov/national/index.htm.



2 Throughout the report, future benefits—i.e., the annual time series of avoided costs—are discounted at a 3% rate to reflect their value in the present day, which is defined as the year 2015 in this report. In short, discounting provides an equal basis to compare the value of benefits (and costs) that occur in different time periods. The discount rate itself reflects the trade-off between consumption today and consumption tomorrow, meaning that with a positive discount rate, benefits that occur today are worth more than they would be tomorrow. A higher discount rate implies a greater preference for present-day consumption and a lower present value of future damages. A lower discount rate implies a greater value on future damages. That is, the present value of future damages calculated at a 5% rate will be lower than those calculated using a 3% rate. There are many ways to select a discount rate and little consensus about which discount rate is most appropriate, particularly when assessing benefits that span generations. Therefore, we selected 3%, a commonly employed rate in the climate impacts and benefits literature. This rate was also used to calculate two of the U.S. Government's four Social Cost of Carbon estimates (including the central value), which estimate climate damages that occur over long time horizons. In particular, the U.S. Government review found that it was consistent with estimates provided in the economics literature and noted that 3% roughly corresponds to the after-tax riskless interest rate. For a detailed discussion on discount rate selection, please see the Social Cost of Carbon Technical Support Document, available at http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf.

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8 U.S. Environmental Protection Agency. 2013. Integrated Science Assessment of Ozone and Related Photochemical Oxidants (Final Report). EPA/600/R-10/076F.

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10 A climate-induced drop in ozone is caused by increased atmospheric water vapor under a warmer climate. Higher humidity shortens the atmospheric lifetime of ozone in low-NOx (typically less densely-populated) conditions by enhancing its breakdown. Projected reductions in ground-level concentrations over the northern and western parts of the country are largely driven by this decline in background ozone.

11 For comparison, the current national 8-hour daily maximum ozone standard is 75 parts per billion: primary and secondary standard in the form of annual fourth-highest daily maximum 8-hour concentration averaged over 3 years.

12 Changes in ozone and $PM_{2.5}$ concentrations in the Risks of Inaction section and in Figures 1 and 2 are not population-weighted.

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Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0PN93H5.

14 The ranges in mortality estimates are based on ensemble means and reflect the 95% confidence interval in concentration response functions. See Garcia-Menendez et al. (2015) for more information.

15 An additional mortality valuation approach using years of life saved is provided in Garcia-Menendez et al. (2015).

16 Reductions in $PM_{2.5}$ largely drive the change in mortality. However, the contribution of ozone pollution to these estimates increases towards the end of the century and accounts for 40% of the projected life years saved by 2100. See Garcia-Menendez et al. (2015) for more information.

17 For example: 1) Thompson, T.M., Rausch S., Saari R.K., and Selin N.E. 2014. A systems approach to evaluating the air quality co-benefits of U.S. carbon policies. *Nature Climate Change*. DOI: 10.1038/nclimate2342; 2) West, J., S. Smith, R. Silva, V. Naik, Y. Zhang, Z. Adelman, ... and J. Lamarque. 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*. DOI: 10.1038/nclimate2009; and 3) U.S. Environmental Protection Agency. 2014. Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for Modified and Reconstructed Power Plants. Office of Air Quality Planning and Standards, Health & Environmental Impacts Division, Air Economics Group. Research Triangle Park, North Carolina.

18 IPCC. 2014. Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... and J.C. Minx, Eds. New York, NY: Cambridge University Press.

19 Fine particulate matter constituents analyzed include sulfate, elemental carbon, organic aerosol and ammonium nitrate.

20 Changes in mortality are estimated by applying the differences in daily-maximum 8-hour ozone (8-hr-max ozone) between May and September and daily average $PM_{2.5}$ to the concentration response functions.

21 At the time of this report's release, the U.S. Environmental Protection Agency's Guidelines for Preparing Economic Analyses report recommends a VSL of $7.9 million (2008$), based on 1990 incomes. To create a VSL using 2014$ and based on 2010 incomes, the standard value was adjusted for inflation using BEA implicit price inflator for gross domestic product and for income growth adjustment based on a method described in the user manual of EPA's BenMAP model (pg. 109). The resulting value, $9.45 million for 2010 (2014$), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of GDP and population for the CIRA Reference scenario were employed. Using this approach, the VSL in 2050 is estimated at $12.53 million and $16.39 million in 2100. Finally, we note that the VSL values used in this report differ slightly from those used in Garcia-Menendez et al. (2015), which therefore affects the valuation estimates reported in each. Sources: 1) U.S. Environmental Protection Agency. 2014. Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf; 2) U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, http://www.bea.gov/national/index.htm; and 3) U.S. Environmental Protection Agency. 2012. BenMAP Users Manual. Office of Air Quality Planning and Standards.

22 Garcia-Menendez, F., R.K. Saari, E. Monier, and N.E. Selin. (2015) U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation. Environmental Science & Technology. DOI:10.1021/acs.est.5b01324.

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27 Ibid.

28 Average results for the 49 cities included in the study.

29 See Mills et al. (2014) and Bierwagen et al. (2010) for details on usage of ICLUS population projections. Sources: 1) Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, M. Duckworth, and L. Deck. 2014. Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States. *Climatic Change*. DOI: 10.1007/s10584-014-1154-8; and 2) Bierwagen, B.G., D.M. Theobald, C.R. Pyke, A. Choate, P. Groth, J.V. Thomas, and P. Morefield. 2010. National housing and impervious surface scenarios for integrated climate impact assessments. *Proc Natl Acad Sci*. DOI: 10.1073/pnas.1002096107.

30 At the time of this report's release, the U.S. Environmental Protection Agency's Guidelines for Preparing Economic Analyses report recommends a VSL of $7.9 million (2008$), based on 1990 incomes. To create a VSL using 2014$ and based on 2010 incomes, the standard value was adjusted for inflation using BEA implicit price inflator for gross domestic product and for income growth adjustment based on a method described in the user manual of EPA's BenMAP model (pg. 109). The resulting value, $9.45 million for 2010 (2014$), was adjusted to future years by assuming an elasticity of VSL to GDP per capita of 0.4. Projections of GDP and population for the CIRA Reference scenario were employed. Using this approach, the VSL in 2050 is estimated at $12.53 million and $16.39 million in 2100. Finally, we note that the VSL values used in this report differ slightly from those used in Garcia-Menendez et al. (2015), which therefore affects the valuation estimates reported in each. Sources: 1) U.S. Environmental Protection Agency. 2014. Guidelines for Preparing Economic Analyses. National Center for Environmental Economics. http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-52.pdf/$file/EE-0568-52.pdf; 2) U.S. Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, March 27, 2015, http://www.bea.gov/national/index.htm; and 3) U.S. Environmental Protection Agency. 2012. BenMAP Users Manual. Office of Air Quality Planning and Standards.

31 The approach described in Mills et al. (2014) was updated in several ways to develop the results presented here. First, the analysis was expanded from 33 cities to encompass a total of 49 out of 50 of the cities (excluding Honolulu) analyzed in tbe Medina-Ramon and Schwartz (2007) paper that was the foundation of the Mills et al. (2014) work. Medina-Ramon and Schwartz did not calculate heat mortality response functions for cities where the minimum temperature for the 99 percentile hottest day was equal to or below 20°C (8 cities), or cold mortality response functions where the maximum temperature for the 1 percentile coldest day was greater than or equal to 10°C (7 cities), and the choice was made in the Mills et al. (2014) work to not include those cities in the projections of future mortality. In a warming climate, cities that were too warm to meet the criteria for the cold threshold will continue to be too warm, so the lack of a cold mortality response function will not make a difference. However, most of the cities that were too cool to meet the criteria for the hot threshold are expected to warm enough that their 99 percentile hottest days will exceed 20°C in the future. Therefore, inclusion of cities without a heat mortality response function will lead to an underestimate of the change in future mortality in those cities, and therefore an underestimate of the benefit of GHG mitigation. However, inclusion of a wider range of cities gives a more complete picture of impacts in the U.S. There were a couple of additional updates. The first involved limiting the analysis to the actual counties corresponding to the cities specified in Medina-Ramon and Schwartz, rather than the MSAs used in Mills et al. (2014). This reduces the total population considered within the original 33 cities. The second involved updating to the most recent BenMAP data for the all-age mortality rates in the cities, which resulted in some small differences in the calculations.

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36 This analysis uses the term labor supply to refer to hours worked, but cannot determine whether that choice is driven by employees or employers.

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39 Bureau of Labor Statistics, Quarterly Census of Employment and Wages, data accessible at http://www.bls.gov/cew/. High-risk workers were defined as those employed in agriculture, forestry, and fishing; hunting, mining, and construction; and manufacturing, transportation, and utilities industries.

40 Bureau of Labor Statistics, Quarterly Census of Employment and Wages, data accessible at http://www.bls.gov/cew/. Average wage ($23.02) calculated using high-risk labor categories only, as the majority of extreme temperature impacts on labor hours occur in these industries.

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2 Congress of the United States, Congressional Budget Office. 2010. Public Spending on Transportation and Water Infrastructure. http://www.cbo.gov/sites/default/files/cbofiles/attachments/11-17-10-Infrastructure.pdf.

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10 Wright et al. (2012) provides estimates of the total costs for repairing deficient bridges both in advance of climate change and as adaptation to climate change. Neumann et al. (2014) presents the results of repairing bridges in advance of climate change. The results presented in this report are the results of repairing bridges as adaptation to climate change.

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21 The adaptation costs per square mile, calculated by city, storm, scenario, and year, were aggregated to the regions used in the Third National Climate Assessment and weighted by area. For example, for a region with 2 cities, each with an area of 100 square miles, each city's area is divided by the sum of the areas, resulting in a proportion value of 0.5 for each city. This proportion value is then multiplied by each calculation of per-square-mile adaptation costs (calculated by storm, scenario, and year) to produce a weighted average adaptation cost per square mile.

22 More detailed models are often used by municipalities for local stormwater management planning, but applying these models across the 50 cities examined in this analysis was not practicable.

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28 Underlying vulnerability exists in both the Reference and the Mitigation scenarios within the base or historic period (i.e., today). This vulnerability is depicted for the Reference scenario in Figure 1 as costs occurring in 2000. Removing costs associated with baseline vulnerability yields cost estimates with adaptation of $530 billion under the Reference scenario and $500 billion under the Mitigation scenario. We've included the baseline vulnerability costs in our estimates because they may affect future decisions about coastal development. We also note that some damages to coastal property are due to the effects of land subsidence that occurs regardless of climate change.

29 The CIRA sea level rise scenarios are at the high end of projected sea level rise rates for similar scenarios based on recent publications (Horton et al. 2014, Kopp et al. 2014). However, we also note that the effect of GHG mitigation on reducing the increase in future sea level was found to be proportionally larger in these studies. The use of smaller sea level rise rates would likely lead to a decrease in total damages, but a larger reduction in sea level rise due to the Mitigation scenario compared to the Reference would likely yield larger economic benefits than those presented in this report. See: 1) Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment

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30 Without discounting, the cumulative effect of mitigation is larger, reducing impacts by about 10% (from $1.2 trillion to $1.0 trillion), and the annual benefits rise rapidly from approximately $140 million in 2050 to nearly $3.1 billion in 2100.

31 The CIRA analysis evaluates risks of inaction and benefits of mitigation through the end of the 21st century. The high degree of inertia in processes leading to sea-level rise (i.e., the oceans and ice sheets respond slowly to warming conditions at the Earth's surface) suggest that the absence of 21st century GHG mitigation is likely to result in sea level rise rates equal to or larger than those experienced this century, with subsequent large and long-term implications for coastal development (Horton et al. 2014 and Levermann et al. 2013 provide projections of sea level rise beyond 2100). Therefore, the difference in sea level change rise between the CIRA Reference and Mitigation scenarios will only increase after 2100. This would likely result in larger GHG mitigation benefits to the coastal property sector, and it is important to note that these benefits would only be realized from GHG reductions occurring in this century. See: Horton, B.J., S. Rahmstorf, S.E. Engelhart, and A.C. Kemp. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quaternary Science Reviews* 84:1-6; and Levermann, A., P. Clark, B. Marzeion, G. Milne, D. Pollard, V. Radic, and A. Robinson. 2013. The multimillenial sea-level commitment of global warming. *PNAS*, DOI: 10.1073/pnas.1219414110.

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37 Neumann, J., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich. 2014a. Joint Effects of Storm Surge and Sea-level Rise on U.S. Coasts. *Climatic Change*. DOI: 10.1007/s10584-014-1304-z. .

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45 The adaptation responses projected by the National Coastal Property Model are developed using a cost-benefit framework comparing the costs of protection relative to the property value. Developed as a simple metric to estimate potential adaptation responses in a consistent manner for the entire coastline, the estimates presented here should not be construed as recommending any specific policy or adaptive action. Further, additional adaptation options not included in this analysis, such as marsh restoration, may be appropriate for some locales.

Electricity

1 The transportation sector accounts for 27 percent of emissions, followed by the residential, commercial, and industrial sectors at 21 percent. The remaining 22 percent of emissions come from biomass and various other sectors. The share of electricity generated by fossil fuels from 2009-2013 was 69% (42% from coal, 26% from natural gas, 0.8% from petroleum). U.S. Department of Energy. 2014. Electric Power Monthly: Table 1.1. Net Generation by Energy Source: Total (All Sectors), 2004-February 2014.

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3 Ibid.

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18 Total generation across the models varies because electricity demand is independently calculated by each model based on changes in population, GDP, technology costs, and other factors.

19 McFarland, J., Y. Zhou, L. Clarke, P. Sullivan, J. Colman, W. Jaglom, ... and J. Creason. 2015. Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change.* DOI: 10.1007/s10584-015-1380-8.

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5 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.

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9 Ibid.

10 Across the contiguous U.S., damages are projected to decrease relative to the baseline period in the following Water Resource Regions (WRRs): Upper Colorado, Lower Colorado, Pacific Northwest, and California.

11 Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, T.C. Richmond, K. Reckhow, K. White, and D. Yates, D. 2014. Chapter 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T.C. Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, DOI:10.7930/J0G44N6T.

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20 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, ... and R. Somerville. 2014. Ch. 2: Our Changing Climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0KW5CXT.

21 Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert. 2010. Characterizing changes in drought risk for the United States from climate change. *Environ. Res. Lett.* DOI:10.1088/1748-9326/5/4/044012.

22 Boehlert, B., E. Fitzgerald, J. Neumann, K. Strzepek, and J. Martinich. 2015. The Effect of Greenhouse Gas Mitigation on Drought Impacts in the U.S. *Weather, Climate and Society.* DOI: 10.1175/WCAS-D-14-00020.1.

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24 Strzepek, K., J. Martinich, J. Neumann, B. Boehlert, J. Henderson, M. Hejazi, ... and J. Yoon. 2014. Benefits of Greenhouse Gas Mitigation on the Supply, Management, and Use of Water Resources in the United States. *Climatic Change.* DOI: 10.1007/s10584-014-1279-9.

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27 Ibid.

28 Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich. 2013. Economic impacts of climate change on water resources in the coterminous United States. *Mitig Adapt Strateg Glob Change.* DOI:10.1007/s11027-013-9483-x.

29 In-stream flows are modeled such that flows below minimum levels required to sustain vulnerable aquatic species are assessed a penalty. In addition, it should be noted that the agricultural water use simulated in the CIRA Water Supply and Demand model does not link with the model used to estimate impacts in that sector of this report.

30 While the Water Supply and Demand analysis accounts for reactive adaptation in response to changes in water supply, the effects from water resources technology improvements and proactive adaptation planning are not included. Adaptation planning in the water resource sector has increased at the federal level in the U.S., e.g., EPA National Water Program's Response to Climate Change and NOAA's Regional Integrated Sciences & Assessments (RISA) program.

31 Strzepek, K., J. Martinich, J. Neumann, B. Boehlert, J. Henderson, M. Hejazi, ... and J. Yoon. 2014. Benefits of Greenhouse Gas Mitigation on the Supply, Management, and Use of Water Resources in the United States. *Climatic Change.* DOI: 10.1007/s10584-014-1279-9.

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Agriculture and Forestry

1 Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R.C. Izaurralde, T. Mader, E. Marshall, and D. Liverman. 2014. Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J02Z13FR.

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3 Ibid.

4 Joyce, L.A., S.W. Running, D.D. Breshears, V.H. Dale, R.W. Malmsheimer, R.N. Sampson, B. Sohngen, and C.W. Woodall. 2014. Ch. 7: Forests. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/JOZ60KZC.

5 Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R.C. Izaurralde, T. Mader, E. Marshall, and D. Liverman. 2014. Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 150-174. DOI:10.7930/J02Z13FR.

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9 A wetter future climate, as projected under the IGSM-CAM for many crop-growing parts of the U.S., will tend to reduce water stress such that some yields may increase even with higher temperatures. In the EPIC modeling, irrigated crops are assumed to be able to meet their water needs regardless of climate change effects on precipitation, so a wetter/hotter climate scenario just increases their temperature stress without reducing their water stress. This tends to make impacts on rainfed crops more negative than for irrigated yields. In addition, the ability of climate models to simulate precipitation as severe storms or as heavy rainfall rather than frequent drizzle is an emerging area of research in the climate modeling community. As such, the results presented here should be interpreted with acknowledgement of this uncertainty.

10 Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R.C. Izaurralde, T. Mader, E. Marshall, and D. Liverman. 2014. Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 150-174. DOI:10.7930/J02Z13FR.

11 The EPIC simulations assume that crops can be irrigated at a level that eliminates water stress. A particular concern for climate change is that in areas where the need for irrigation is greatest due to reduction in precipitation, the supply of water for irrigation will also be reduced. To fully consider this risk requires integration of crop modeling with hydrologic modeling for projections of future water supply, which was not modeled in this biophysical crop yield analysis.

12 Joyce, L.A., S.W. Running, D.D. Breshears, V.H. Dale, R.W. Malmsheimer, R.N. Sampson, B. Sohngen, and C.W. Woodall. 2014. Ch. 7: Forests. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/JOZ60KZC.

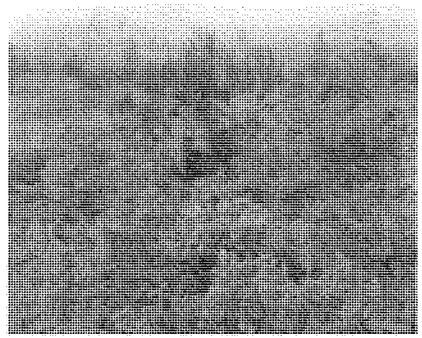
13 Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins ... and E. Monier. 2014. Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, DOI:10.1007/s10584-014-1118-z.

14 The results in Figure 2 from the EPIC model show projected crop yields that do not reflect production and market adjustments.

15 Williams, J.R. 1995. The EPIC Model. In Computer Models in Watershed Hydrology, V.P. Singh (ed.), pp. 909-1000. Highlands Ranch, CO: Water Resources Publication.

16 Thomson, A.M., R.A. Brown, N.J. Rosenberg, R.C. Izaurralde, and V. Benson. 2005. Climate Change Impacts for the Conterminous USA. Part 3: Dryland production of grain and forage crops. *Climatic Change*. DOI:10.1007/1-4020-3876-3.

17 The EPIC simulations assume that crops can be irrigated at a level that eliminates water stress. A particular concern for climate change is that in areas where the need for irrigation is greatest due to reduction in precipitation, the supply of water for irrigation will



also be reduced. To fully consider this risk requires integration of crop modeling with hydrologic modeling for projections of future water supply, which was not modeled in this biophysical crop yield analysis.

18 The analysis uses climate projections from all five initializations of the IGSM-CAM. Given the sensitivity of the EPIC and MC1 models to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of crop and vegetation changes in the future. Please refer to the Levels of Certainty section of this report for more information.

19 Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins ... and E. Monier. 2014. Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, DOI:10.1007/s10584-014-1118-z.

20 The change in forest yield was assumed to be equal to the percentage difference in net primary productivity between future years and the average for the baseline (1980-2009).

21 While beyond the scope of this analysis, the effects of CO_2 fertilization on forest growth and productivity may be limited by the availability of nitrogen, which could influence the results estimated here.

22 Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl,… and B. Boehlert. (In review). Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*.

23 Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R.C. Izaurralde, T. Mader, E. Marshall, and D. Liverman. 2014. Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, Terese (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 150-174. DOI:10.7930/J02Z13FR.

24 Consumer and producer surplus are used to estimate impacts on total economic welfare. Consumer surplus is the monetary gain obtained by consumers because they are able to purchase a product for a price that is less than the highest price that they would be willing to pay. Producer surplus or producers' surplus is the amount that producers benefit by selling at a market price that is higher than the least that they would be willing to sell for.

25 Beach, R., D. Adams, R. Alig, J. Baker, G. Latta, B. McCarl, ... and E. White. 2010. Model documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG). Prepared for U.S. Environmental Protection Agency.

26 EPIC, MC1, and FASOM results in the Agriculture and Forestry sections using the IGSM-CAM climate projections represent the average of the five initializations.

27 FASOM has perfect foresight of future climate change effects, and thus can optimize near term land owner behavior. The model also simulates changes in agricultural and forestry commodities beyond those modeled in EPIC (9 crops) and MC1 (hard and softwoods).

28 This analysis does not reflect climate change impacts on international forests and agriculture, which would also affect relative returns to different uses of land and trade patterns and therefore affect land use decisions. Also, numerous uncertainties remain regarding issues such as future changes in crop technology, energy policy, and other interactions that could affect market outcomes.

Endnotes

29 FASOM-GHG is optimized to maximize consumer and producer surplus in the base, but re-adjusts production and consumption patterns to re-optimize in response to changes in potential yields.

30 FASOM directly models changes to productivity on private timberland, although timber from public lands enters the market exogenously based on public lands policy. Impacts on productivity due to climate change are only applied to the private timberland.

31 Boehlert, B., K. Strzepek, S. Chapra, Y. Gebretsadik, M. Lickley, C. Fant, ... and J. Martinich. (In review). Greenhouse Gas Mitigation Effects on Water Quality Impacts from Climate Change in the U.S. *Journal of Advances in Modeling Earth Systems.*

32 Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl,... and B. Boehlert. (In review). Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters.*

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2 Ibid.

3 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. DOI:10.7930/J0Z31WJ2.

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6 Buddemeier, R.W., P.L. Jokiel, K.M. Zimmerman, D.R. Lane, J.M. Carey, G.C. Bohling, and J.A. Martinich. 2008. A modeling tool to evaluate regional coral reef responses to changes in climate and ocean chemistry. *Limn Oceanogr Methods.* DOI: 10.4319/lom.2008.6.395.

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9 Lane, D.R., R.C. Ready, R.W. Buddemeier, J.A. Martinich, K.C. Shouse, and C.W. Wobus. 2013. Quantifying and valuing potential climate change impacts on coral reefs in the United States: Comparison of two scenarios. *PLoS ONE.* DOI:10.1371/journal.pone.0082579.

10 Ibid.

11 Lane, D., R. Jones, D. Mills, C. Wobus, R.C. Ready, R.W. Buddemeier, E. English, J. Martinich, K. Shouse, and H. Hosterman. 2014. Climate change impacts on freshwater fish, coral reefs, and related ecosystem services in the United States. *Climatic Change.* DOI: 10.1007/s10584-014-1107-2.

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14 In early life stages, some species will have higher mortality rates and more developmental abnormalities under acidification conditions expected over the next several decades. In addition, adult shellfish tend to grow more slowly and have thinner, more fragile shells under these conditions.

15 National Marine Fisheries Service Commercial Landings for the years 1990-2010. http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index.

16 Doney, S., A. A. Rosenberg, M. Alexander, F. Chavez, C. D. Harvell, G. Hofmann, M. Orbach, and M. Ruckelshaus. 2014. Ch. 24: Oceans and Marine Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program. DOI:10.7930/J0RF5RZW.

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18 Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center. Program Developed for CO2 System Calculations: CO2SYS. http://cdiac.ornl.gov/oceans/co2rprt.html.

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24 Global GHG mitigation is projected to preserve 230,000 acres of coldwater fish habitat in 2100 under the MIROC climate projections. For all freshwater fishing guilds, the total damages in 2100 are estimated at $1.7 billion in the Reference scenario and $200 million in the Mitigation scenario.

25 This analysis does not project changes to fish distribution in lakes and reservoirs, as these bodies provide thermal stratification/refugia, and are oftentimes heavily managed (i.e., water level and fish stocking).

26 Jones, R., C. Travers, C. Rodgers, B. Lazar, E. English, J. Lipton, ... and J. Martinich. 2012. Climate Change Impacts on Freshwater Recreational Fishing in the United States. *Mitigation and Adaptation Strategies for Global Change.* DOI: 10.1007/s11027-012-9385-3.

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33 Ibid.

34 Change in annual acres burned at end of century (2085-2114) compared to the historic baseline (2000-2009).

35 National Interagency Fire Center. 2013. Federal Firefighting Costs (Suppression Only). https://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf.

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37 Comprised of the following Geographic Area Coordination Center regions: Northern Rockies, Rocky Mountain, Southwest, Eastern Great Basin, Western Great Basin, Northwest, California North, and California South.

38 Percent changes calculated by comparing acres burned under the Reference scenario at the end of the century (average of 2085-2114) compared to the historic baseline (average of 2000-2009).

39 Fuel management costs are estimated at $15 billion under the Reference and $12 billion under the Mitigation scenario through 2100 (average across all IGSM-CAM initializations, 2014$, discounted at 3%), corresponding to avoided costs (benefits) of $3.4 billion under the Mitigation scenario.

40 Fuel management costs were not estimated using the MIROC climate model.

41 The CIRA results simulated in the MC1 vegetation model suggest a substantial change to the wildfire regime we experience today. For example, unmitigated climate change is projected to increase area burned by wildfire annually by approximately 45% in California by the end of the century, 64% in the Mountain West, and 95% in the Northwest. Given the sensitivity of the MC1 climate model to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of vegetation changes in the future.

42 Because the IGSM-CAM projects a wetter future for a majority of the nation, pattern-scaled output from two additional climate models were simulated in MC1 to encompass a broader range of possible climate futures. While all three sets of climate projections show increases in the area burned by wildfire compared to the historic period, only the IGSM-CAM and MIROC climate model results are presented in this report. For an in-depth discussion of the results, see: Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, ... and E. Monier. 2014. Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*. DOI:10.1007/s10584-014-1118-z.

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54 Given the sensitivity of the MC1 climate model to natural variability, the use of the five initializations of the IGSM-CAM climate model, each of which has an equally plausible future climate, aids in understanding and constraining the potential magnitude of vegetation changes in the future.

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CONCLUSION

1 The few efforts to date that have estimated multi-sector impacts in a consistent framework include the European Commission's PESETA project (http://peseta.jrc.ec.europa.eu), and the Risky Business Initiative (http://riskybusiness.org), a project focusing on economic risks in the U.S. Integrated assessment models, such as FUND (http://fund-model.org), are also being used to estimate the multi-sector social costs of GHG emissions.

2 The use of a climate model that generates a relatively higher amount of future precipitation may strongly influence results in a particular sector. For example, inland flooding damages may be larger under these wetter climate projections compared to those under a drier model. This same sensitivity of sectoral results to the choice of climate model could affect a different part of the water sector in complementary ways, such that drought damages could be smaller compared to those under a drier model.

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June 2015
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Senator CARPER. Thank you, Madam Chair.

Dr. Rice, mother of three, you mentioned in your testimony the many different ways that climate change is already impacting the health of Americans. Who would you say are the most vulnerable to the health effects of climate change and who would have the most to gain from reductions in carbon pollution?

Dr. RICE. Thank you for this question, Senator Carper.

A number of groups are especially vulnerable to the health consequences of climate change. The ones I would identify would be the elderly because many of them already have chronic health conditions like heart and lung disease that makes them especially vulnerable to the health effects of high heat and high air pollution levels.

Another very important group is low income people. People who have less income have less access to air conditioning during heat waves. There have been a number of studies looking at cities which suffer the most in some ways from extreme heat because of an island effect of the buildings in the cities. The poor neighborhoods of cities have been found to have the worse urban heat problem.

People who have low income also are the same people who are often exposed more to higher levels of air pollution to begin with and have less access to health care and resources to help them manage climate change.

There is a third group. I know I am short on time, but that is children. Asthma is especially prevalent in children. They are at high risk from all of the issues I identified, high heat, high ozone levels, air pollution from wildfire, and higher pollen levels. It is going to be a major consequence for American children.

Senator CARPER. One quick yes or no answer, if you will. In a study released last week by the Lancet, one of the world's oldest and best known German medical journals concluded that the impacts of climate change threaten to undermine the last half-century of gains in development and global health. Would you agree with this conclusion, yes or no?

Dr. RICE. I certainly agree it is a major public health problem facing the planet.

Senator CARPER. Thank you.

My time has expired. Thank you.

Senator CAPITO. Thank you.

Senator Fischer.

Senator FISCHER. Thank you, Madam Chairman and Ranking Member Carper.

Mr. Cicio, Nebraska is a public power State. One hundred percent of our power is owned by the people of Nebraska. We are going to be hit especially hard by these regulations proposed in the Clean Power Plan. We are going to see rate increases that I believe will be substantial.

What do you believe will be the impact of the increase we are going to have in the electricity rates on business operations like manufacturing? What will be the impact there?

Mr. CICIO. All of these companies compete globally. There is almost no exception anymore. As I specifically alluded, the competition is very fierce. Companies win or lose business based on a cents a pound or pennies on a ton of product they make, so all of these costs are additive.

When we get to the Clean Power Plan, it is not just the cost of the Clean Power Plan. Embedded in those electricity rates that give your State a problem, there is already the cost of $PM_{2.5}$ and there is already the mercury rule cost.

For us in industrials, there is already the industrial boiler MATS cost. Now there is the Clean Power Plan cost. On top of that is coming the ozone cost. It is a cumulative cost of doing business that our competitors do not have overseas.

There is no way around higher costs and loss of competitiveness. Eventually it impacts jobs. Most of our jobs are middle class jobs.

Senator FISCHER. What is the impact then on American families? When we see these costs on businesses continue to increase, that has a direct cost on American families, correct? How would you say the ARENA Act will address some of these issues? What specifically is in the proposed legislation?

Mr. CICIO. I would like to say from a commonsense standpoint, everyone in the Country that has followed this knows this is going to be litigated, 100 percent sure. There is no doubt about it.

The EPA knows there are costs. The EPA does not want to hurt people by higher energy costs but this rule will. It is commonsense to say let us wait until we have this settled by the courts before States act to particularly shut down, as the EIA report of last month said, they are not going to shut down 40,000 gigawatts, it is now 90,000 gigawatts of coal fired power plants prior to 2020. That will have a dramatic impact on increasing electricity costs.

Senator FISCHER. Thank you.

Mr. Alford, I think most of us in this room take our ability to have electricity for granted. As you mentioned, there is a large number of Americans who are balancing whether they can afford an electric bill or pay rent or put food on the table for their families. As you mentioned, that is going to lead, I think, to those hard choices that people make and send some of them to the streets where they become homeless.

Can you talk more about those tough choices that low income families have to make when they look at their electricity bills, why you think the costs are going to be driven up through this action by EPA, and why it will be so harmful?

Mr. ALFORD. Dr. Rice is a mother of three. I am a father of six. I guess I am up to 11 grandchildren. My wife and I have been the godmothers and godfather of the very extended family.

There are a lot out there who need help and we do all we can to connect them with some of our members who can create jobs for them, but it is an ongoing task. It is rough out there.

I have children in Mobile, Atlanta and Los Angeles and it gets worse and worse and worse. Lord knows what happens to someone who does something wrong and gets into the judicial system, they will never have a job unless I create a job for them. It is very rough out there.

I think we need a government that is sensitive to what is going on in these communities and will come up with some policy that builds a greater America and a more secure America and not put people on thin ice.

Senator FISCHER. Well said, well said. We all want clean air, we all want clean water, but we need to be aware of what these regulations will do to American families.

Thank you, sir.

Mr. ALFORD. I have been having discussions with the Omaha Black Chamber of Commerce too.

Senator FISCHER. Great. Thank you.

Senator CAPITO. Senator Merkley.

Senator MERKLEY. Thank you very much, Madam Chair.

I wanted to follow up with Dr. Rice. The statistics that I have seen say that 78 percent of African-Americans live within 30 miles of a coal-fired power plant and that an African-American child is three times more likely to go to an emergency room for an asthma attack than a White child and twice as likely to die from an asthma attack.

Is there a correlation or connection between the coal-fired power plants and the higher death rate for African-American children?

Dr. RICE. The health effects of air pollution from coal-fired power plants and other sources of particle air pollution are very well documented. It is now well established in the scientific community that air pollution causes increases in hospitalization for asthma, asthma attacks, and more medication to treat the asthma symptoms.

There are also inequities in where people live and where the sources of air pollution are located. That is an issue called environmental justice. Communities of color and low income communities are disproportionately exposed to air pollution from coal-fired power plants and other sources of air pollution. Therefore, if we reduce greenhouse gas emissions, those communities stand the most to benefit locally, right there where the pollution is emitted.

Senator MERKLEY. To summarize, you are saying yes, there is a connection between the coal-fired power plant pollution and the illnesses and deaths that are disproportionately occurring?

Dr. RICE. The simple answer is yes. I do agree with you.

Senator MERKLEY. It sounded like you were withdrawing the explanation of why that was indeed the case.

You ended on the note that disproportionate benefits from changing the quality of the air go to those who are most affected and that would be those closest to sources of pollution. Public health and climate benefits from this law are estimated to be somewhere between $55 billion to $93 billion per year 15 years from now. That is compared to the estimates of $7.3 billion to $8.8 billion for the rule.

On the order of 8 to 1 or 10 to 1 of health benefits versus cost, that seems a pretty good tradeoff for an investment when you can get an eightfold return. It is a huge quality of life issue. Would you share that opinion?

Dr. RICE. Senator, I agree that the public health benefits of reducing greenhouse gas emissions are tremendous. They have been studied in a number of different ways, including the report you just cited that showed the public health benefits for mortality and other health issues far outweighed the implementation costs.

That is just one study but there have been many other studies. There is one done by Jason West and a group at UNC, Chapel Hill, looking at just the mortality benefits of the better air quality from reducing greenhouse gas emissions, not even looking at all the health effects I talked about from climate change, but just the air pollution benefits that would be gained right away. They estimated that those mortality benefits would exceed abatement costs by 2030.

Senator MERKLEY. In your testimony, you noted the impact of forest fires. This is particularly occurring out west where we have large coniferous forests that are a major part of our rural lifestyle with our lumber and timber industries.

In the last 40 years, we have seen an increase in the fire season by about 60 days with a huge correlation of more acres of timber burning. In your testimony, you pointed out the health impacts of that smoke and the smoke plumes basically traveling across the Nation.

Dr. RICE. Senator, I can give an example. Wildfire smoke can travel very far distances. There are health effects for communities right there where the fires take place, but there are also respiratory and heart health effects in very distant places.

The wildfires that affected Russia some years ago, those plumes traveled the distance from Chicago to San Francisco, that equivalent difference. That means that thousands and thousands of people in the regions of wildfires are experiencing health effects due to the reduced air quality.

Senator MERKLEY. Since the prevailing winds go from west to east, when our forests are burning out in Oregon, California and Washington State, the rest of the Nation is experiencing those impacts. There is also an impact on our rural economy because when we lose both to fire and pine beetles, and I realize that is not your expertise, but with the warmer winters, the pine beetles are doing very well and the timber not so well.

I am over my time, so thank you very much for your feedback.

Senator CAPITO. Thank you.

I would like to turn it over to the Chairman of our full committee, Chairman Inhofe.

Senator INHOFE. Thank you, Madam Chairwoman.

I remember when we had the first appointed Director of the EPA, Lisa Jackson in the room. It was during the COP in Copenhagen. I asked her, if we are to pass the legislation that has been proposed here, let us keep in mind it started way back in 1997 when we passed the Byrd-Hagel rule by 95 to zero, that if you come back from Rio de Janeiro or one of these places with a treaty that either hurts our economy or does not require the same thing from China and other countries, then we would not ratify it. Consequently, they never put it forward for ratification.

I said if we were to pass either by regulation or by legislation these reductions, is this going to have the effect of lowering CO_2 emissions worldwide? Her answer was no, because it only affects us here in the United States. This is not where the problem is. The problem is in India, China, Mexico and other places.

In fact, would you say, Mr. Cicio, that it would actually have the effect of increasing CO_2 worldwide emissions if we were to unilaterally reduce our emissions here by an amount that is going to be driving our manufacturers overseas, where do they go, they go to places where they have the least restrictions. Am I missing something there?

Mr. CICIO. No, you are not missing anything. As a matter of fact, I testified before the House Energy and Power Subcommittee, and one of the key points I made is if we want to be serious about reducing global greenhouse gas emissions, the single most important thing we need to do is increase the manufacturing of products in the United States versus China, for example.

Senator INHOFE. Exactly.

Mr. CICIO. When China produces goods, they emit 300 percent more CO_2 than we do here. If energy cost goes up here, then it is going to result in more imports of these energy intensive products. As a reminder, 70 percent of our manufacturing imports is from one country, China.

Senator INHOFE. That is right.

Mr. Alford, it is good to see you again. I asked for the printed copy of your study. The key findings are fascinating. It concentrates on the regressive nature of this type of legislation or rule. Is that right?

Mr. ALFORD. That is absolutely correct, sir.

Senator INHOFE. I have not seen it done specifically like this before, so this is something we will use. Was this done for you by an outside group?

Mr. ALFORD. It was done by Dr. Roger Bezdek of Management Information Systems. We do a study about every two or 3 years with that group. They are very on the money.

Senator INHOFE. I appreciate that.

Mr. Trisko, I think you made a vague reference to a study of decisions to middle or low income people. I asked to get the written copy. Could you elaborate a bit on that? I do not think you had a chance to do that in your opening statement.

Mr. TRISKO. The study I attached to the statement is one of a long running series going back to the time of the Kyoto Protocol. We wanted to know what American families spent on energy defined as residential utilities and gasoline. I have been updating that study more or less on annual basis ever since. We found, as a general matter, the percentage of after tax income that American households spend on energy has more than doubled over the course of the last 10 to 15 years.

You mentioned the regressive aspects of energy costs and energy price increases. The study I have attached to my statement today looks in particular at the percentage of after tax income for energy spent by households with gross incomes of $30,000 or less. That is about 30 percent of our population. Those households are spending 23 percent of their after tax income on energy.

Senator INHOFE. Of their expendable income?

Mr. TRISKO. Twenty-three percent of their after tax income goes to residential utilities and gasoline. That compares with an average of 7 percent for households earning more than $50,000 a year, so it is three times greater for the low income category of $30,000 or less.

The impact of energy price increases is three times greater on those households than it is for households making $50,000 or more per year.

Senator INHOFE. That is good and is almost exactly what you are saying, Mr. Alford, that it is regressive in that respect.

Mr. ALFORD. Yes, it is. You brought up asthma. If you look at the Mayo Clinic, there is no prevention for asthma and there is no correlation of asthma and air. Asthma has been increasing even though through the Clean Air Act, we have been good stewards and decreasing and decreasing ozone and all the emissions, asthma continues to rise. No one knows why.

There is this big false projection that global warming causes asthma. We do not know what is causing asthma. Most of the people who have it get out of it by the time they are adults because their lungs and bodies are strong enough to fight it off.

I am getting very sick of people saying asthma and dirty or global warming. It is a myth.

Senator INHOFE. Thank you, Mr. Alford.

My time has expired.

[The prepared statement of Senator Inhofe follows:]

STATEMENT OF HON. JAMES M. INHOFE, U.S. SENATOR FROM THE STATE OF OKLAHOMA

We are here today to talk about the President's climate agenda with a particular focus on its impacts to American businesses and families. There is no doubt, and wide reaching consensus that the price of power would increase under the President's latest regulations, with primary attribution to the so-called Clean Power Plan.

Despite the rhetoric from President Obama and his EPA, his domestic climate agenda has nothing to do with improving the environment or the lives of American citizens. His carbon regulations for new, modified and reconstructed, and existing power plants are nothing more than high-cost, unprecedented power grabs. The Clean Power Plan alone would cost $479 billion, result in double digit electricity price increases in 43 States and reduce grid reliability. Some regions would not only be dealing with cascading outages and voltage collapse, but paying for long-term investments in power generation that is prematurely shut down.

Although these policies make up the core components of President Obama's climate agenda they would have a negligible impact on the environment—impacts the EPA did not even bother to measure—and would be rendered completely pointless by business as usual in India in China. Further, both of these countries stand to inherit the economic activity and jobs that would be shipped overseas, which has the projected result of actually increasing overall emissions.

When it comes to the climate science this President relies on, I would like to remind everyone that he is using the same science from the same institution that was caught up in the Climategate scandal of 2009. The UK Telegraph described Climategate as "the "worst scientific scandal of our generation" when it was discovered scientists were manipulating temperature data to produce the outcomes they wanted.

When it comes to health benefits, much of what the EPA relies on comes from benefits associated with reductions in particulate matter (PM), not carbon. Further, PM is already regulated under the Clean Air Act and set at a standard the EPA itself identifies as safe.

When it comes to the legality of this proposal, it is on equally questionable ground. The EPA relies on a reimagined interpretation of the Clean Air Act that is counter to the law's historical application and extends far beyond what Congress ever intended.

It makes sense that 32 States oppose the President's climate proposals and 16 have already challenged the EPA in court. While preliminary challenges have hit a minor, technical speed bump, once the rule is final and the courts get to the merits of these legal challenges, the Clean Power Plan will not withstand judicial scrutiny. It does not make sense for States to spend limited resources planning out how to comply with a rule that we know will ultimately be stricken down.

As an original cosponsor to the Clean Air Act Amendments of 1990, I know what good environmental policy looks like. It balances environmental improvements with economic growth. It improves our standard of living while strengthening access to the American dream. It builds on existing partnerships and opens up the doors for new ones. Most importantly, it comes from Congress.

Good environmental policy looks nothing like the Clean Power Plan or any of the climate regulations this Administration has proposed. I thank Senator Capito for drafting S. 1324, the Affordable Reliable Electricity Now Act of 2015 to address these problems. Her bill sends the EPA back to the drawing board and provides a host of new requirements that will ensure future proposals actually improve the environment in a balanced and healthy way. Her bill increases transparency, protects the role of States, and provides certainty to the regulated community. Finally, it protects energy consumers—from industrial manufacturers to the kitchen table—from unnecessary costs and unjustified price increases.

I have no doubt this Country will continue down the path of an ever improving and healthier environment, but these gains will be achieved through American ingenuity and innovative advancements, not Government mandates.

I thank the witnesses for being here today and I look forward to your testimony.

Senator CAPITO. Thank you.

Senator Markey.

Senator MARKEY. Thank you very much.

Dr. Rice, you are here from Harvard Medical School. People are getting sick, are they not? They are not getting sick the way Harry Alford is getting sick. They are really getting sick, aren't they?

Maybe you can bring to us a little bit of your information about the increased hospitalizations, the respiratory related diseases and all of the things that are actually implicated in having this additional pollution in our atmosphere. Can you talk a bit about how it is impacting especially children in our Country?

Dr. RICE. Thank you, Senator Markey.

This is certainly an area where I feel I have a lot to add to the discussion because I am a lung doctor, I take care of patients with lung disease and I also study air pollution when I am not taking care of patients.

In addition to my personal observations as a doctor, I see patients come to see me more often because the pollen level is worse or the ozone levels in Boston sometimes get very high on very hot days.

We also have the observations of the physicians of the American Thoracic Society and the survey I mentioned. Of the doctors completing the survey, the vast majority of them commented they have personally observed that their patients' lung function is worse and their symptoms are worse during high air pollution days.

Senator MARKEY. There are real implications for the 12 million Americans who already have respiratory illnesses?

Dr. RICE. Certainly. We can look back at the incredible success story of the Clean Air Act. The reductions in air pollution as a result of the Clean Air Act have been astounding. We have really come a long way.

When we look back, researchers look back at the health benefits of the Clean Air Act, they have been astounding, not just for respiratory illness or asthmatic symptom control, but also mortality and heart disease.

Senator MARKEY. Earlier in your testimony, you mentioned your own son who has a respiratory illness. What can additional pollution that we send up, uncontrolled mean for him and for those others of millions of victims across the Country?

Dr. RICE. There are a variety of sources of air pollution. One is the power plants through the burning of greenhouse gases. There is also traffic and other things.

The reality is that if we do not do anything about greenhouse gas emissions, the EPA report looked at just that piece of the pie and found that ozone levels will increase, predict that we will actually have increases in ozone whereas ozone levels have actually declined and we have experienced health benefits as a result of those gains.

Senator MARKEY. Thank you for putting that out there. There is real sickness, not metaphorical sickness, that is occurring because of global warming.

Mr. Martens, you are here representing New York and one of the RGGI States, the Regional Greenhouse Gas Initiative States, all of New England, those six States, New York, Maryland and Delaware, nine States that banded together.

Over the last 7 years, Massachusetts has actually seen a 40 percent reduction in the greenhouse gases that we are sending up while we are seeing a 22 percent growth in our economy.

Can you talk a bit about that virtuous cycle that seems to elude the observation of those who are critical of our ability to be able to increase the health of individuals and the economy simultaneously?

Mr. MARTENS. As I said in my testimony, the RGGI experience has been an extraordinarily successful one. We had an independent study done by the Analysis Group that quantified the benefits over a 3-year period from 2009 to 2011.

There was $1.3 billion in reductions in bills over the RGGI region; $1.6 billion in extra or incremental economic activity. It has been an extraordinarily positive experience, all the while, as you said, the region has experienced economic growth. We have reduced bills for low and moderate income families.

Senator MARKEY. Say that again. You have reduced the electricity bills for low and moderate income people?

Mr. MARTENS. Yes. The cumulative benefit to just New York low and moderate income bill payers has been $60 million to date through the first quarter of this year. Those benefits will continue on into the future because New York has specified income eligible ratepayers in two of its programs.

The beauty of the program is that States have the flexibility to target the revenue from the sale of those allowances to a variety of programs. Industrial customers can benefit; low and moderate income ratepayers can benefit; businesses and your average homeowners can benefit. It has been a tremendous success story.

Senator MARKEY. It is my understanding, Mr. Martens, that under the proposed rulemaking, for example, New Jersey or Pennsylvania could join our Regional Greenhouse Gas Initiative. They can plug into an already existing system that is working, that is lowering costs for low and moderate income, lowering the amount of greenhouse gases while seeing tremendous growth in our GDP. I think there is a reason to be very optimistic.

Listening to the Pope's admonitions to us that we should be the global leader on this, we can use market forces to accomplish the goal while still enjoying tremendous economic growth and taking care of the poor and the moderate income people in our Country.

Mr. MARTENS. I agree with you entirely, Senator. I think there are places around the Country that could benefit from that model.

It may not be identical to the RGGI model but certainly States co-operating makes great sense because the efficiencies of dealing with multiple States and energy systems that cross State boundaries has obviously been a great advantage in the RGGI States. I think it could be elsewhere also.

Senator MARKEY. I am afraid too many people are just pessimistic in general. They are just not optimistic about our ability as Americans to be the global leader, to use new technologies, to invest in the future, protect young people and our economy at the same time. Unfortunately, they harbor a great doubt about our Country's ability to do that.

I thank the two of you for your testimony because you point out the problems and the solutions. You all have done it in a way which I think should really give people some hope.

Thank you, Madam Chair.

Senator CAPITO. I think that concludes our hearing. I want to thank the witnesses for bringing forth some great information and facts and lots for us to think about. I appreciate you all taking time today to be with us.

I want to thank my Ranking Member.

With that, we will conclude the hearing. Thank you.

[Whereupon, at 3:19 p.m., the subcommittee was adjourned.]

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