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Climate Change Vulnerability Assessment for the Chugach National Forest and the Kenai Peninsula



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Cover: Bear Glacier, Alaska. Photo by Isaac Hayward.

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Abstract

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This assessment evaluates the effects of future climate change on a select set of ecological systems and ecosystem services in Alaska's Kenai Peninsula and Chugach National Forest regions. The focus of the assessment was established during a multi-agency/organization workshop that established the goal to conduct a rigorous evaluation of a limited range of topics rather than produce a broad overview. The report explores the potential consequences of climate change for: (a) snowpack, glaciers, and winter recreation; (b) coastal landscapes and associated environments, (c) vegetation, (d) salmon, and (e) a select set of wildlife species. During the next half century, directional change associated with warming temperatures and increased precipitation will result in dramatic reductions in snow cover at low elevations, continued retreat of glaciers, substantial changes in the hydrologic regime for an estimated 8.5 percent of watersheds, and potentially an increase in the abundance of pink salmon. In contrast to some portions of the Earth, apparent sea-level rise is likely to be low for much of the assessment region owing to interactions between tectonic processes and sea conditions. Shrubs and forests are projected to continue moving to higher elevations, reducing the extent of alpine tundra and potentially further affecting snow levels. Opportunities for alternative forms of outdoor recreation and subsistence activities that include sled-dog mushing, hiking, hunting, and travel using across-snow vehicles will change as snowpack levels, frozen soils, and vegetation change over time. There was a projected 66-percent increase in the estimated value of human structures (e.g. homes, businesses) that are at risk to fire in the next half century on the Kenai Peninsula, and a potential expansion of invasive plants, particularly along roads, trails, and waterways.

Keywords: climate change, salmon, glaciers, wildlife, seascapes, vegetation, snow, scenarios.

Summary

Background

We assembled a team of 33 federal resource managers, research scientists, and economists, as well as professionals working in the private sector, to examine the potential consequences of climate change for an extensive portion of south-central Alaska. This collaborative effort, which represents 12 agencies and organizations, developed organically as agencies and groups learned of an initial collaboration by the University of Alaska Anchorage, and the Chugach National Forest. The resulting assessment examines a limited set of biophysical and economic consequences of a changing climate over the next five decades across landscapes that extend from the Copper River Delta on the east, through Prince William Sound to the western Kenai Peninsula on the west, and north to the spine of the Chugach Range. Priority issues were determined early in the process by an interagency group and university personnel; these issues were based on critical problems facing the Chugach National Forest, the specific expertise that could be assembled to address them, and the relevance of issues to stakeholders. Important elements influencing the scope of the assessment include the broad collaboration among diverse partners, the deliberate choice to include economists in the assessment, and the choice to significantly limit discussion to six broad areas that are of keen interest to people of south-central Alaska: (1) snow and ice (glaciers and ice fields), (2) coasts and seascapes, (3) salmon, (4) vegetation, (5) wildlife, and (6) infrastructure. Within these broad areas of investigation, the scope of assessment was further limited, recognizing that future assessments could build from this foundation.

The Chugach/Kenai region occurs within two climatic regions, Cook Inlet and south-central Alaska (Shulski and Wendler 2007). The Cook Inlet climatic region represents a subarctic area in transition between a maritime and continental climate, with moderate temperatures compared to regions in Alaska's interior. Precipitation is substantially lower than in maritime regions, with a growing season longer than 100 days at lower elevations. The south-central climatic region is under a strong maritime influence, with high annual precipitation, very frequent cloud cover, and moderate temperatures (Shulski and Wendler 2007: 27–31). Both regions experience highly variable weather across a range of years, particularly with respect to the timing and amount of precipitation and the depth of snowpack at low elevations (Bieniek et al. 2014). This variability is a consequence of variation in broad-scale ocean circulation patterns and the proximity of the assessment area to the Gulf of Alaska (Hartmann and Wendler 2005).

We assembled a team of 33 federal resource managers, research scientists, and economists, as well as professionals working in the private sector, to examine the potential consequences of climate change.

Long-term measurements of air temperature, sea surface temperatures, and patterns of polar ice all confirm the intense warming of earth's climate over the past 60 years (e.g., IPCC 2014, Melillo et al. 2014, MEA 2005). Over the last 100 years, high-latitude regions have warmed more substantially than the rest of the Earth. In fact, during the last decade, much of Alaska has warmed twice as rapidly as the global average (Chapin et al. 2014, Stewart et al. 2013, Wendler and Shulski 2009). This pattern of warming is far more pronounced in winter and spring than in autumn or summer. For instance, the Cook Inlet climate region has warmed 0.7 °C over the century when looking at average annual temperature (see Shulski and Wendler 2007: 141); however, the average temperature in January and February during this period was 1.7 °C higher than a century earlier. To ask questions about future climate conditions and potential consequences for the biophysical environment and for ecosystem services, we took a scenarios approach, in conjunction with downscale climate modeling, to paint multiple pictures of future climate conditions. Downscaled projections for regions such as south-central Alaska, which experience high interannual and decadal variability, tend to result in significant uncertainty for the first 10 to 20 years of projections, higher confidence for the next 30 years, and less certainty after 50 or 60 years (Hawkins and Sutton 2009). Therefore, we limited our assessment to exploring potential outcomes for the next five to six decades. Then, to create two scenarios, we used the average of five global climate models (GCMs) that have been shown to function best for this region.

Potential Future Climate

Most climate models predict that high latitudes will experience a much larger rise in temperature than the rest of the globe through the remainder of the 21st century. However, the coastal location of the assessment area, with complex weather patterns and tortuous topography, results in patterns of change dissimilar to arctic Alaska (SNAP 2015). Temperature profiles are expected to warm by about 3 °C in the next 50 years. Winter temperature change is expected to be most extreme. In the warmest coastal areas, average temperatures in the coldest month of the year are predicted to rise from only slightly above freezing to well above freezing, or approximately 4.5 °C above current temperatures. Moreover, these warm temperatures will spread inland toward Cordova, Valdez, and Seward, with above-freezing months of January dominating across all coastal regions, and in some areas as much as 20 miles inland. Many rivers will shift from a below-freezing to above-freezing temperature regime. Across the region, winter temperatures are expected to warm by about 3 to 3.5 °C.

Across the assessment area, the date of spring thaw is expected to come earlier. Large areas of coastal and near-coastal land are projected to shift from early spring thaw to the "rarely freezes" category. This shift is likely to correspond to lack of winter snowpack and an altered hydrologic cycle. Farther from the coast and at higher elevations, spring thaw is projected to occur from 3 to 10 days earlier, on average. Autumnal changes are projected to be slightly greater than those seen in spring, with the freezing point shifting to noticeably later in the year in just a single decade. For example, an increase in growing season from about 200 days to about 230 days may be expected in Palmer, Anchorage, Wasilla, and Kenai; and an even more substantial increase may be seen in Seward, Valdez, and Cordova.

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The projected decadal trend is toward greater precipitation in both January and July and a potential increase in the frequency and intensity of strong storms (Graham and Diaz 2001). However, model results for precipitation are less robust than those for temperature, in part because precipitation is intrinsically more geographically and temporally variable. A shift in the percentage of precipitation falling as snow, particularly at low and mid elevations, will alter the annual hydrologic profile.

Potential Biophysical and Economic Change

Context—

The assessment area is composed of three relatively distinct sociopolitical regions. The Municipality of Anchorage and the Kenai Peninsula Borough are each organized as single political jurisdictions equivalent to counties, whereas the Prince William Sound region includes the independent cities of Whittier, Valdez, and Cordova, as well as the predominantly Native villages of Tatitlek and Chenega. Each of the three regions represent distinct social and cultural settings with substantially different demographic and economic characteristics. Anchorage is home to more than 40 percent of Alaskans and is the dominant source of demand for recreation and tourism on the Chugach National Forest and on the Kenai Peninsula. The Kenai Peninsula Borough is a rural area with about 60,000 residents and a limited road system. In contrast, the Chugach census subarea has very little private land and fewer than 7,000 residents, and has limited connection to the population center; for instance, Cordova, Tatitlek, and Chenega are not connected by road to the rest of the state, but are served by the state-run ferry system. The relatively high median household income in the Chugach census subarea (the Prince William Sound region) stems primarily from oil-industry employment at the Valdez terminal of the Trans-Alaska Pipeline. Despite this concentration of high-wage private-sector jobs, the Prince William Sound region is much more dependent than the other two regions on fishing and local government for employment. There is one actively

fished limited-entry permit for every 10 employed residents in Prince William Sound, compared to 1 per 20 employed in the Kenai Peninsula and 3 per 1,000 in Anchorage. Subsistence and personal-use fish harvest are important components of household consumption and well-being for many people, particularly in the Kenai and Prince William Sound portions of the assessment area. Harvest and use of wild native species represents a significant component of the culture across all three regions, but occurs within different social, economic and cultural contexts. Tourism and recreation are also important to the economies of all three regions (Colt et al. 2002, Crone et al. 2002, Fay et al. 2005). An estimated 500,000 people recreate on the Chugach National Forest each year (USDA FS 2014).

The Chugach/Kenai assessment area covers a region in which physical and ecological features reflect incredible geological/physical disturbance. Tectonic forces, glacial scouring, and the influence of annual snow result in regionwide patterns of directional change in topography and ecology. At the last glacial maximum, the vast majority of the assessment area was under ice (Heusser 1983, Kaufman and Manley 2004). The current vegetation represents the outcome of glacial retreat followed by species recolonization. Over the last 14,000 years, directional change has dominated the assessment area and continues today. Deglaciation progressed in Prince William Sound sufficiently to expose low-lying areas by 9,000 BP, resulting in colonization by coastal tundra and sedge tundra (Ager 2001, Heusser 1983). Conifers first become apparent about 2,700 BP. Coastal rain-forest tree species migrated from southeast Alaska (where they persisted through the Holocene) following the prevailing storm tracks northwestward along the gulf coast and across Prince William Sound. This migration of conifer tree species appears to have required thousands of years to travel hundreds of kilometers. About 2,000 BP, coastal rain-forest tree species developed forest communities (Heusser 1983: 349).

Potential biophysical and economic changes—
Characteristics of snowpack and glaciers significantly influence a broad array of ecological and economic features of the Chugach/Kenai assessment area. Therefore, modeling future patterns of snowpack was made a key step in the assessment, influencing most other analyses. However, modeling snow depth from downscaled climate models is extremely difficult. Useful approaches to develop scenarios to understand snowpack include evaluating snow-day fraction (SDF) (the proportion of days when precipitation is expected to fall as snow), and snow-water equivalent (SWE) (the water yield from existing snowpack).

Snow-day fraction is projected to decrease by 23 percent from October to March (the winter period) between sea level and 500 m of elevation.

Snow-day fraction and snow-water equivalent are projected to decline most in late autumn (October to November) and at lower elevations. Snow-day fraction is projected to decrease by 23 percent from October to March (the winter period)

between sea level and 500 m of elevation. From sea level to 1000 m, the winter SDF is projected to decrease by 17 percent. Averaged across the cool season, SWE is expected to decrease at elevations below 1000 m owing to increased temperature, but increase at higher elevations owing to increased precipitation. Compared to the period of 1971–2000, the percentage of the landscape that is snow-dominant in 2030–2059 is projected to decrease, and the percentage of rain and snow being co-dominant (transient hydrology) is projected to increase from 27 to 37 percent. Most of this change is at lower elevations.

Glaciers in the region have been losing mass during the past century. However, the dynamics of glaciers, particularly whether they advance or retreat at a particular time, is extremely complex (see chapter 3). Glaciers in the region are currently losing about 6 km^3 of ice per year; half of this loss comes from Columbia Glacier (Berthier et al. 2010). Over the past decade, almost all glaciers surveyed within the region are losing mass (with one exception), including glaciers that have advancing termini (Larsen et al. 2015). In the future, glaciers not calving into the ocean will retreat and shrink at rates equivalent or higher to current rates of 3 m/year at their termini (Larsen et al. 2015). As an example of the potential rate of glacier retreat, Columbia Glacier will likely retreat another 15 km and break into multiple tributaries over the next 20 years before stabilizing. Other tidewater glaciers have uncertain futures, but will likely not advance significantly in coming decades.

Changes in the timing and depth of snowpack and changes in glacier extent will directly and indirectly influence recreation and tourism. Within the assessment period, the portion of the winter with sufficient snow at trailheads for skiing and snowmobile recreation will decrease significantly in some areas. Viewsheds along roads and trails, and areas visible from marine recreation such as cruise ships, will change as glaciers recede and the season of snowpack decreases.

Negative impacts of sea-level rise on ecological systems and ecological services are unlikely during the assessment period.

In contrast to most coastal areas around the globe, negative impacts of sea-level rise on ecological systems and ecological services are unlikely during the assessment period. As a consequence of tectonic processes associated with active faults and isostatic rebound in response to glacial retreat, the effective sea level has dropped or remained relatively stable in many areas. Furthermore, coasts within the assessment area experience extreme fluctuation in marine inundation because of large tides. Marine systems and economic infrastructure are therefore unlikely to be threatened by climate-change-induced sea-level rise.

Although effective sea level may not change significantly, ecological characteristics of the coast will change. Prince William Sound receives up to 50 percent of its freshwater discharge from glacial runoff, indicating that changes to the region's tidewater glaciers will have profound effects on the coastal environment (e.g.,

Salmon from south-central Alaska support commercial fisheries with an estimated economic impact of $587 million in revenues and 7,944 jobs for Alaskans.

composition of the Alaska coastal current, relative salinity, and pH). Changes in the frequency of harmful algal blooms, the extent of eelgrass beds, and the abundance of food for migrating shorebirds are all features likely to change with highly uncertain outcomes.

Five species of Pacific salmon use the freshwater systems of the assessment area and represent critical ecological, economic, and cultural resources. Salmon from south-central Alaska support commercial fisheries with an estimated economic impact of $587 million in revenues and 7,944 jobs for Alaskans (see chapter 5). Of the 2.5 million days of recreational fishing by anglers in Alaska, 72 percent occurred in south-central Alaska, with salmon being the primary target species. Based on two variables, percentage of glacial cover and an index of spring snowpack, 61 of the 720 watersheds (8.5 percent) were classified as being vulnerable to climate change because of projected reductions in snowpack over the next 60 years and the resulting change in the timing and amount of runoff. This analysis and qualitative evaluation of the status of freshwater systems in the assessment area suggest that the largely intact aquatic systems of the region, with extremely diverse conditions for salmon, are likely to be largely resilient to changing climate during the assessment period, particularly in the short term. Some evidence based on our analysis of long-term salmon abundance in the region suggests the potential for increases in salmon abundance in the future, particularly pink salmon. The consequences of changing marine conditions, however, are particularly uncertain. Some authors expect substantial reductions in quality marine habitat, particularly for sockeye salmon (Abdul-Aziz et al. 2011). Although this assessment is largely oriented toward the terrestrial/freshwater environment, the potential for change in marine systems to influence salmon cannot be overlooked.

Salmon contribute significantly to the lifestyle and character of the region. The importance of salmon to commercial fisheries, sport fisheries, subsistence lifestyles, and personal-use fisheries outlined in the assessment hint at the critical role of salmon to the region. The complex relationships between salmon abundance, salmon harvest, total value of the commercial catch, and the price of salmon make it extremely difficult to assess the consequences of changing climate on economic, social, and cultural systems. Some evidence suggests that potential increases in pink salmon abundance resulting from warmer temperatures might be attenuated by lower prices, with uncertain effects on harvester earnings. The commercial industry has a long history of adapting to both abrupt and gradual changes. The effects of changes in salmon abundance or the timing of runs will influence subsistence and personal-use harvesters differently than commercial harvesters. Current

policy gives subsistence fisheries priority during times of shortage, providing some resilience to changes in abundance. However, changes in run timing and reductions in abundance would likely increase tensions between participation in subsistence, cash jobs, and even school schedules. Personal-use salmon fishing in the region focuses completely on sockeye salmon and accounts for 8 percent of total sockeye harvest. Hence, unlike other harvest users, the potential for subsistence users to substitute other species is small, thus these users appear to be the most vulnerable to a significant decline in sockeye salmon biomass resulting from adverse ocean conditions or warmer air temperatures operating through the freshwater ecosystem because they would not benefit from an increase in pink salmon.

Climate change often affects vegetation both directly and indirectly, manifesting in a strong visible shift in terrestrial environments. The assessment area supports nine broad vegetation cover types, with coastal temperate rain forest dominated by Sitka spruce and transition boreal forest dominated by black and white spruce being most widespread. The largely intact nature of ecological systems results in non-native plant species occurring on a very small portion of the assessment area (0.04 percent), whereas 53 rare or imperiled native plant species were identified. Models examining potential changes in the distribution of vegetation based on the direct effects of climate change suggest that, of ten land cover types, coastal temperate rain forest will retain most of its current distribution and will expand westward, while subalpine shrub and alpine tundra are likely to decline as forest and shrublands move upward in elevation. The area within a suitable climate envelope for alpine tundra land cover may decline by 87 percent by 2060. The consequences of climate change for rare plants differ dramatically across taxa depending on the factors currently limiting their distribution and the current geographic location of the taxa within the assessment area.

Coastal temperate rain forest will retain most of its current distribution and will expand westward, while subalpine shrub and alpine tundra are likely to decline as forest and shrublands move upward in elevation.

The effects of climate change on disturbance regimes, both fire and insects, will indirectly affect vegetation. In addition, disturbance regimes, fire in particular, directly affect humans. The interactions among fire, insect disturbance, and vegetation are important to quantify. Models suggest that while fire will remain rare in coastal rain forest communities, the potential for fire is likely to increase on the western Kenai. As a result, the combined influence of property development (e.g., a 53-percent increase in the number of private structures) and changing climate will increase the vulnerability of the built landscape to fire. The value of structures at risk to fire is projected to grow by 66 percent on private lands by 2065. The projected value of structures in landscapes with high to extreme fire risk may approach $3.8 billion in 2065 (based on 2014 dollars). Defoliating insects that periodically

cause extensive defoliation of conifer and deciduous trees and shrubs have shifted their distribution northward over the past several decades. Rising winter temperatures may facilitate more frequent defoliation events and reductions in tree and shrub vigor.

The assessment area supports a broad range of wildlife ranging from spectacular flocks of migrating shorebirds and waterfowl to large mammals such as brown bear and moose. We limited our assessment of the potential wildlife response to shorebirds (see chapter 4) and three species of ungulate; moose, caribou, and Sitka black-tailed deer. Current distributions of these three ungulate species in the assessment area are artifacts of glacial history and translocations (moose, Sitka black-tailed deer) and reintroduction (caribou) in the 20th century. All three species hold cultural, social, and economic values but differ substantially in their distribution and ecology—hence, they together represent a focused case study into the array of responses that may be realized for wildlife in the region. About 10,000 moose are well distributed throughout the assessment area, mostly on the western Kenai Peninsula and around Anchorage. Their distribution is likely to increase in the near term owing to continued post-introduction colonization of the Prince William Sound area, afforestation of the Kenai lowlands and alpine tundra, and increasing fires on the western Kenai Peninsula. About 1,000 caribou are distributed on the western side of the Kenai Peninsula in four herds. Their distribution is likely to decrease in response to afforestation of alpine tundra and increases in fire. About 20,000 black-tailed deer occur in the Sitka spruce forest along Prince William Sound. Their distribution is likely to increase owing to declining snow depths along the coast and continued post-introduction dispersal onto the Kenai Peninsula. Over the longer term, scenarios for distribution and abundance of these ungulates becomes uncertain because of the expected introduction of novel pathogens and their interaction with changing ecological drivers.

This climate vulnerability assessment highlights a limited subset of changes in socioeconomic and biophysical conditions expected to occur in the Chugach/Kenai region as a consequence of a warming climate. Beyond the specific results for icefields and glaciers, salmon and ungulates, and vegetation and coastlines, the assessment demonstrates several broader principles. These broad messages emerge from other assessments but are worthy of note because they provide a useful generalized framework for evaluating climate change that may be valuable when one is considering resource management and other social responses. First, this assessment illustrates the relationship between global patterns and local responses; it demonstrates that context matters. Second, the assessment shows the value of taming

the firehose of information on climate change—it acknowledges the limitations of human focus and the value of narrowing the conversation. Finally, by honestly acknowledging the significant uncertainty in long-term scenarios, the assessment highlights the ultimate value of reducing the driver of climate change—the emission of greenhouse gases—to address long-term risks.

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Patrician Hayward



With temperatures at about -10 °C, a musher and his team sprint down a long straightaway at the edge of Anchorage during the 2012 World Championship Sled Dog Race. The race was canceled in 2015 and 2016 because of insufficient snow resulting from warm temperatures and rain.

Chapter 1: Introduction

Gregory D. Hayward,[1] Steve Colt,[2] Monica L. McTeague,[3] and Teresa N. Hollingsworth[4]

Long-term measurements of air temperature, sea surface temperatures, and patterns of polar ice mass all confirm the intense warming of earth's climate over the past 60 years (e.g., IPCC 2014, MEA 2005, Melillo et al. 2014). Scientific consensus that fossil fuels contribute to global climate change comes from a combination of physical-system science, long-term measurements of temperature and atmospheric carbon dioxide (CO_2), and paleoproxy reconstructions of past climate. Although global patterns of climate change have been discussed for decades, their positive and negative consequences have recently become more obvious. Examples include sea-level rise in certain portions of the globe that is threatening communities and agriculture (IPCC 2014); Arctic villages near seacoasts that are being undercut by wave action as permafrost thaws and coastal geography changes (ADEC 2010); increased CO_2 and lengthening growing seasons that have increased agricultural productivity for some crops in some locales (Rosenzweig and Hille 1998).

As the potential consequences of rapid, directional climate change become more apparent, individuals, communities, and nations have begun to consider what actions to take—a process often called "climate adaptation"—in response to changing climate. Likewise, land and resource management agencies are developing responses to perceived threats to resource values. Coordinated, effective action, however, requires understanding how the physical and biological environment will respond to climate change and how these biophysical changes will affect ecosystem services. This report, crafted as a climate vulnerability assessment (Glick et al. 2011), represents an important step toward developing effective climate change adaptation for land and resource management agencies and the public with respect to the Kenai Peninsula and Chugach National Forest region of south-central Alaska. Our goal is to examine the potential response of several important features and resources of the Kenai/Chugach region to changing climate over the next 30 to 50 years and to consider the potential consequences of these changes for associated social and economic systems.

Coordinated, effective action requires understanding how the physical and biological environment will respond to climate change and how these biophysical changes will affect ecosystem services.

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Focus of Assessment

A climate vulnerability assessment can best aid resource managers and society in making decisions when it is focused on important ecosystem services (MEA 2005). Ecosystem services are the benefits that people obtain from ecosystems, such as food, clean water, timber, regulation of floods, outdoor recreation, and spiritual values associated with the environment. How will changes in the delivery of ecosystem services, the availability of resources, and physical conditions experienced by individuals and communities influence the lives of people in the immediate and distant future? The Kenai/Chugach assessment area (fig. 1-1) occurs in a region undergoing change as a consequence of major ongoing physical dynamics—tectonics, glaciation, and extreme snowfall.

Regardless of any climate forcing by industrial society, these dynamics result in significant directional change that will influence social decisions. As will be outlined below, ice sheets have been receding for millennia, and mega-earthquakes



Figure 1-1—The Chugach National Forest and Kenai Peninsula assessment area within south-central Alaska.

have periodically stirred the landscape—the Kenai/Chugach is a landscape whose very essence is change, and much of that change is directional at the scale of the entire assessment area over any reasonable time frame. Understanding the potential consequences of climate change demands that we consider the potential influence of human-caused (greenhouse-gas-induced) climate change in the context of an inherently dynamic region, regardless of human-induced climate forcing.

This assessment is written with the goal of informing decisions by resource managers and the public. Two features define its scope. First, unlike many vulnerability assessments that focus on natural resource management, we broaden our scope by evaluating several social and economic outcomes of climate change. Second, rather than examining a plethora of resource elements, we narrow our scope by limiting our discussion to areas that are of particular concern to people of the region.

Of keen interest to natural resource managers in south-central Alaska are six topics: (1) snow and ice (glaciers and ice fields), (2) coasts and seascapes, (3) salmon, (4) vegetation, (5) wildlife, and (6) infrastructure. We begin by asking how a changing climate may influence particular physical and ecological features across these topic areas. The consequences of climate change are examined from the perspective of scenarios (potential futures). Our assessment then attempts to ask how climate-driven changes in the physical/ecological characteristics of south-central Alaska might influence several ecosystem services and associated economic activities. Integrating potential social/cultural consequences into the assessment is an important but difficult task because of the inherent uncertainty in climate scenarios and projected responses of physical/ecological elements. However, considering potential social and economic outcomes, even in light of considerable uncertainty, provides managers a view through a different lens that helps them prioritize their adaptation options.

Limiting the set of assessment topics helped authors explore particular resources and ecosystem services more deeply. However, bounding the assessment necessarily left many important topics unaddressed. We considered this outcome desirable because we see this vulnerability assessment as an initial examination of climate change consequences that will lead to future assessments, which will explore topics more deeply depending on the needs of managers and the public. Therefore, this is the first step in an iterative collaboration among resource managers and scientists intended to foster understanding of the complex outcomes of a changing climate.

Constraints on the Assessment

History of the Assessment

This assessment began with a desire by managers of the Chugach National Forest to understand how climate change may be influencing the resources managed by the forest and how it will affect users of the vast landscape administered by the Chugach. Recognizing the importance of understanding potential social, cultural, and economic consequences of biophysical changes occurring on the land, the Chugach partnered with the University of Alaska's Institute of Social and Economic Research to produce a modest narrative report that integrates this range of consequences. Soon, other agencies learned of the assessment, and an interagency effort developed with an all-lands perspective extending from the western Kenai Peninsula eastward through the Copper River Delta region. This organic development brought together a rich array of scientists and practitioners excited about collaboration. The resulting assessment benefits from their breadth of perspectives and expertise, from the expanded geographic scope, and from the integration of scientists with practitioners. Readers will recognize variations in tone and style resulting from the diversity of participants in our collaboration. We offer this report as a tool for learning about climate change in a portion of Alaska from a range of perspectives.

Uncertainty In a Resource Planning Environment

Resource management requires the art of taking action despite uncertainty. Limitations of knowledge, temporal and spatial variation in resource conditions, changing socioeconomic dynamics, and limited understanding of future resource needs all contribute to an environment of uncertainty. As a result, resource managers have developed planning approaches that aid in identifying acceptable decisions in the face of this uncertainty (fig. 1-2).

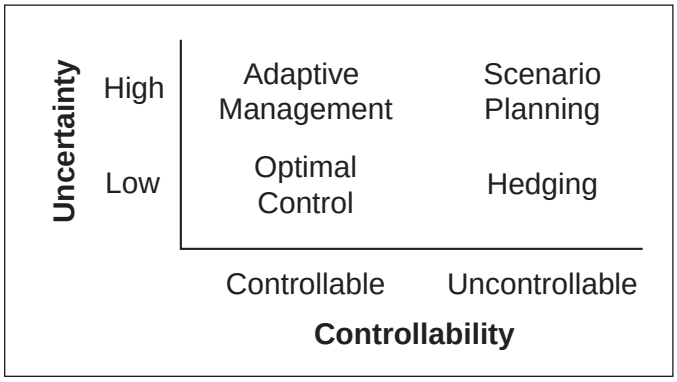


Figure 1-2—Alternative approaches to addressing uncertainty in natural resource management (after Peterson et al. 2003: 365).

Climate change adds to the uncertainty associated with natural resource decisionmaking. Furthermore, several features of climate change differ from most factors that lead to uncertainty in resource management. Climate change is global, it is long-term, and it cannot be managed directly or effectively through local or regional action. Consequently, the tools to address uncertainty in most natural-resource-planning problems may not be effective for addressing uncertainties associated with climate change. For example, adaptive management (Walters 1986) is a planning tool advocated for addressing uncertainty in natural resource management (Julius et al. 2013, Tompkins and Adger 2004). Active adaptive resource management employs models that identify dominant uncertainties, develops management experiments to examine them, and relies on feedback to gain knowledge and revise management to more effectively meet management goals (Walters 1986). However, the long-term nature of climate change suggests that feedback from management experiments will likely occur too slowly to improve management decisions.

As an alternative, some practitioners suggest that scenario planning may be more effective, and a rich literature is developing around this approach (e.g., Knapp and Trainor 2013, Peterson et al. 2003, Rickards et al. 2014). Understanding the use of scenarios in planning may be illustrated most easily through an example from everyday life. Decisions regarding the purchase of insurance, such as life or homeowner's insurance, illustrate the pragmatic use of scenarios in planning. When considering the purchase of life insurance, most people envision several potential futures, each representing a different "story" describing what may happen in the future. None of the stories is a forecast, and often the probability of one or another occurring is unclear. The ultimate decision regarding purchase of the insurance policy occurs after integrating the insights that come from considering the various stories.

Understanding of probabilities plays a minor role in the decision because management of risk is the actual goal. Instead, the insights generated by the scenarios result in thinking that would not occur otherwise. The use of scenarios in resource management in the context of climate change is very similar.

In this assessment, we use the philosophy of scenario planning to help decisionmakers and the users of public lands make better choices despite the uncertainty of how resources, ecosystem services, and other characteristics of south-central Alaska will change as a result of changing climate. We develop "story lines" that outline the potential conditions that will be experienced in the future. These stories are intended to motivate innovative thinking about the interaction between decisions and future conditions. Therefore, when we describe potential snow conditions or streamflow, we are not making forecasts or projections. Rather, we use an understanding of

When we describe potential snow conditions or streamflow, we are not making forecasts or projections. Rather, we are painting a picture, or scenario, that is one plausible rendering of the future.

the current physical and ecological system, along with background on history and current trends, to paint a picture, or scenario, that is one plausible rendering of the future. That scenario is neither the only nor the "best" illustration of the future. The value of the scenario is the degree to which it helps the reader recognize that the future will be different from the present (possibly similar to a subset of scenarios), and therefore that planning must consider potential alternative futures.

Our approach to scenarios begins by examining a range of climate trajectories that in turn generate several climate scenarios. The entire assessment builds on these climate scenarios. Because the various chapters in this report examine different physical and biological resources and ecosystem services, each employs the climate scenarios differently. However, in all cases, the intent is to stimulate an analysis that considers potential outcomes in a changing landscape. In many cases we illustrate only one scenario—one potential future. When it is employed, this single-scenario approach is chosen for simplicity and clarity in communication.

Temporal Scale and Uncertainty

Employing scenarios to examine climate change necessarily requires consideration of future conditions. Climate change models can produce nonintuitive shifts in uncertainty as scenarios are considered for different periods in the future. In this assessment, we explicitly consider scenarios in the context of agency planning horizons; planning generally covers 10 to 20 years but considers the legacy left to future generations. Hence, we examine outcomes in the next 10 to 20 years, but also conditions 50 years in the future. How these time horizons influence uncertainty is a bit complex, but we outline the basics here.

Regions such as south-central Alaska tend to result in significant uncertainty for the first 10 to 20 years of projections, higher confidence for the next 30 years or so, and less certainty after 50 or 60 years

Our assessment employs downscaled projections from climate models as a foundation for developing physically consistent, place-based scenarios for the future (see chapters 2 and 3, along with app. 1, for more details). The downscaled projections for regions such as south-central Alaska, which experience high interannual and decadal variability, tend to result in significant uncertainty for the first 10 to 20 years of projections, higher confidence for the next 30 years or so, and less certainty after 50 or 60 years (Hawkins and Sutton 2009). In some cases, the near-term uncertainty (first decade or two) results from what might be called model "wind up." The downscaled model develops a set of initial conditions or a baseline as it begins—this results in an initial climate that is different than what actually occurs (owing to regional climate variability, for example) and thus "uncertainty" in the results. Following this "wind up" period, these models tend to produce more stable results based on the basic responses of the global climate model (sometimes referred to as a general circulation model; hereafter GCM) that forms their backbone, and

the largest source of uncertainty is model-to-model parameterization (for example, the ways that internal feedbacks are handled or the fundamental temperature sensitivity to greenhouse-gas concentrations). After 50 years or so, however, uncertainty in social (government policy) response to climate change begins to become a major driver in the outcome of the GCMs (owing to the magnitude of greenhouse-gas emissions) and therefore uncertainty increases. Additional uncertainty that results from "model uncertainty" is described in more detail in appendix 1. In this assessment, we explicitly address uncertainty by considering the time scales important to decisionmaking and by using them to calculate future scenarios that are resilient to the uncertainty associated with decadal climate variability and model variability (Littell et al. 2011, Snover et al. 2013).

Characteristics of the Chugach National Forest and the Kenai Peninsula Assessment Area

Climatic Setting

The climate in south-central Alaska is subarctic, with short, cool summers and long winters. Cloud cover is frequent through the summer, particularly after mid-June, and temperatures rarely exceed 26.7 °C. Winter snowpack, even near sea level, can extend from October through May. Winters have periods of deep cold but also periods with temperatures well above freezing. Extensive coastline, in combination with complex topography resulting from mountain ranges extending north-south and east-west, result in extremely complex weather patterns and a mixture of continental and maritime influences. Precipitation, snowpack, and temperature maps from Blanchet (1983), along with climate descriptions from Davidson (1996) and DeVelice et al. (1999), provide some detail regarding differences in climate among three portions of the Kenai/Chugach assessment area.

In the Kenai Mountains portion of the Kenai Peninsula, the climate is transitional between maritime and continental, with mean annual temperatures of 3.9 °C at low elevations and -6.7 °C at upper elevations. The annual precipitation ranges from 50 to 200 cm with a mean maximum snow pack of 50 to 300 cm, depending on elevation and location. Climate at the Cooper Lake Hydroelectric Project weather station on the Kenai shows a decline in monthly precipitation from January through June, followed by an abrupt increase in precipitation from July through September. There is a brief period of relative drought in June. This dry period reduces fuel moisture and increases fire frequency in the Kenai Mountains.

Storm tracks tend to move in a counterclockwise pattern from the Gulf of Alaska into Prince William Sound, resulting in abundant precipitation and cool,

but not cold, temperatures. The lands around Prince William Sound feature mean annual temperatures ranging from 4.4 °C at shoreline to 0 °C at upper elevations. Mean annual precipitation ranges from 200 cm at sea level to more than 760 cm at some upper elevation locations. The mean maximum snowpack ranges from 150 to 400 cm depending on location and elevation. Precipitation at the Main Bay weather station in the Sound exceeds 200 mm for each month of the year.

In the Copper River Delta area, mean annual temperature varies from 1.1 to 5.6 °C. Average precipitation ranges from 200 cm at the seashore to 500 cm farther inland. The mean maximum snowpack ranges from 25 to 200 cm, with depth increasing with distance from the seashore. Strong continental winds, which drain the Alaska interior in the winter, flow out of Copper River Canyon, cooling the temperatures in this area. Climate measurements at the Federal Aviation Administration (FAA) weather station at Cordova are similar in overall pattern to those found at Main Bay in western Prince William Sound. However, monthly precipitation at the Cordova FAA station ranges between 125 to 450 cm, while it is between 250 to 650 cm at Main Bay, demonstrating the increased precipitation farther west in the Sound.

The northern portion of the assessment area, represented by the high Chugach and Saint Elias Mountains, features snow accumulations that range up to 800 cm annually.

The northern portion of the assessment area, represented by the high Chugach and Saint Elias Mountains, features cold, wet summers and winters. The annual precipitation occurs mainly as snow at elevations above 2500 m. The snow accumulations range up to 800 cm annually.

The southern and eastern coasts of the Kenai Peninsula have a maritime climate characterized by heavy precipitation falling as snow in the higher altitudes (up to 10 m on the ice fields). The Kenai Mountains create a partial rain shadow for the western, particularly northwestern, peninsula (Ager 2001).

Physical and Ecological Setting

The Chugach/Kenai assessment area covers a region whose physical and ecological characteristics reflect incredible geological and physical disturbances. Tectonic forces, glacial scouring, and the influence of annual snow produce a legacy of disturbance that results in regionwide patterns of directional change in topography and ecology. Episodic mega-earthquakes along with broad-scale subsidence result in periodic resetting of plant succession and rearranging of plant communities, while the steady progression of the region from almost complete glacial cover to the current interglacial condition results in the steady colonization of exposed land by plants and animals and a migration of biota through the region that is still occurring today. In this section, we provide a brief introduction to the directional patterns of ecological change experienced in the region over the past ten or more millennia—a

changing ecological canvas that informs us of the potential consequences of human-induced climate change.

As described by Plafker et al. (1992), mega-earthquakes resulting from the sudden shifting of the Pacific and North American plates every 400 to 1,300 years result in instantaneous movement of shorelines by up to 11.3 m. The lateral and vertical shift in the Earth's crust simultaneously eliminates and creates conditions for saltwater marsh landscapes and intertidal zones, while drowning forest communities. The consequences of large quakes are clear in environmental legacies—the presence of terraces along shorelines of islands such as Middleton and Montague Islands, and of stands of dead trees in coastal areas of the Kenai/Chugach assessment area. The periodic nature of large quakes and associated subsidence results in cyclic patterns of vegetation succession along coastal areas. In contrast, the retreat of glaciers since their maximum extent 10,000 to 14,000 years ago has led to strong directional (rather than cyclic) changes in geomorphology, hydrology, and ecology.

At the last glacial maximum, the vast majority of our assessment area was under ice … Hence, current vegetation represents the outcome of glacial retreat followed by species recolonization. Over the past 14,000 years, directional change dominated the assessment area and continues today.

At the last glacial maximum, the vast majority of our assessment area was under ice. Nunataks appear to have occurred on Knight, Montague, and Hinchinbrook Islands, resulting in isolated terrestrial refugia in Prince William Sound (Heusser 1983). These sites would not have supported trees and likely few shrub species persisted. The western Kenai Peninsula, in the snowshadow of the Kenai Mountains, appears to have maintained several large biological refugia including sites in the northwest Kenai Mountains, the upland between Skilak and Tustumena Lakes, and in the Caribou Hills north of Homer (Reger et al. 2007). Other refugia in the Copper River basin and Talkeetna Mountains, along with low passes in the Alaska Range, provided sources for species to establish in newly exposed terrestrial habitat. Hence, the current vegetation represents the outcome of glacial retreat followed by species recolonization. Over the past 14,000 years, directional change dominated the assessment area and continues today. These directional processes began earlier on the western Kenai than around the Sound. Earlier deglaciation and substantial refugia (that occurred in a variety of life zones) west of the Kenai Mountains facilitated more rapid plant migration than in the Sound. Retreating ice on the Kenai allowed the expansion of birch (*Betula* sp.) and herb tundra beginning 14,200 years ago. Early postglacial vegetation included dwarf birch (*Betula nana*), alder (*Alnus* spp.), willow (*Salix* spp.), grasses (Poaceae), sage (*Artemisia*), herbs, and ferns. Boreal spruce, likely white spruce (*Picea glauca*) from refugia, along with paper birch (*Betula papyrifera*) was present 8,500 years ago and began expanding significantly about 5000 BP on the Kenai (Ager 2001, Ager et al. 2010, Jones et al. 2009). By about 2,900 BP, mountain hemlock (*Tsuga mertensiana*) and Sitka spruce (*Picea sitchensis*) began invading the eastern and northern valleys of the Kenai Mountains.

Deglaciation progressed in Prince William Sound sufficiently to expose low-lying areas by 9,000 BP, resulting in colonization by coastal tundra and sedge tundra (Heusser 1983). In many areas, alder established early following deglaciation and persisted for more than 1,000 years before tundra again dominated in areas such as College Fjord. Conifers first become apparent about 2,700 BP. Coastal rain forest tree species migrated from southeast Alaska (where they persisted through the Holocene) following the prevailing storm tracks northwestward along the gulf coast and across Prince William Sound. This migration of Sitka spruce, mountain hemlock, black cottonwood (*Populus balsamifera* ssp. *trichocarpa*), yellow-cedar (*Callitropsis nootkatensis*), and western hemlock (*Tsuga heterophylla*) appears to have required thousands of years to travel hundreds of kilometers. About 2,000 BP, alder pollen declined and western hemlock and associated coastal rain forest species developed forest communities (Heusser 1983: 349).

Although the preceding summary of transition from Pleistocene ice cover to contemporary vegetation is portrayed as a unidirectional conversion, the dynamic nature of the region is further demonstrated by short-term changes that have also been observed in records of environmental history. Periods of glacial advance occurred 3,200 and 2,500 BP and again quite recently with the Little Ice Age, resulting in glacial advances and subsequent retreat (Jones et al. 2009). Although not as obvious in the glacial record, significant warm periods occurred. Patterns of high temperatures in the Northern Hemisphere during the Medieval Warm Period (about 950 to 1100 CE) appear similar to those of the late 20th century (1961–1990), and the rate of increase was comparable to that of the past couple decades (Mann et al. 2008, 2009). Figure 1-3 illustrates both the variability in global temperatures (note the Medieval Warm Period [~1000 CE] and the Little Ice Age [centered about 1700 CE]) over the past 1,700 years and the unique nature of the pattern in the last couple of decades.

Clearly, the physical and biological systems of the Kenai/Chugach have experienced radical change in the past, prior to the dramatic climate shifts being explored in this assessment. The vegetation currently occurring in the region is different from the past, and resulted from directional change that began with the exposure of land following the last glacial maximum (fig. 1-4). This tapestry of change represents critical context for interpreting the scenarios for future dynamics the region may experience as a result of human-induced climate change in the next half century. Strong abiotic drivers—ice, snow (depth and slides), tectonics, and geology interacting with climate, the historical legacy of species colonization, and the formation of new vegetation communities—have resulted in the environment that

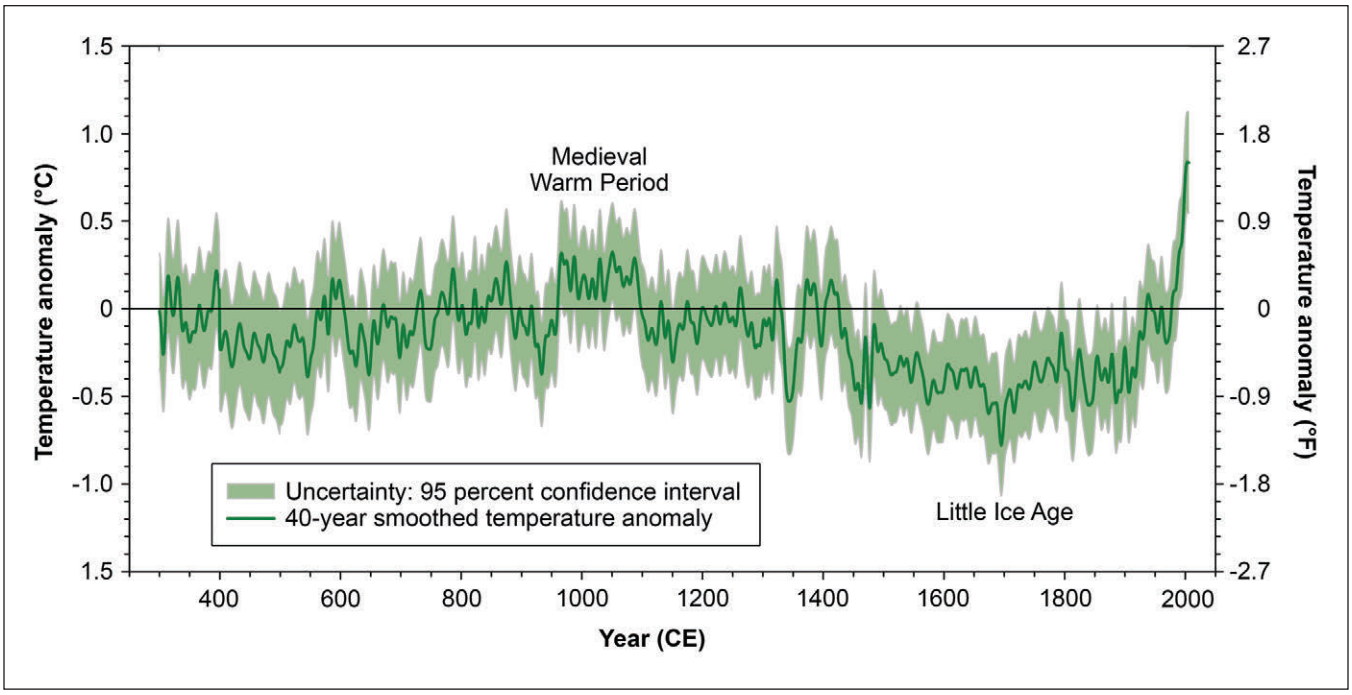


Figure 1-3—Pattern of surface air temperatures for the northern Hemisphere over the past 1,700 years (based on data published in Mann et al. 2008).

people use across the Chugach/Kenai region today. This document seeks to explore the character of this environment in the future as a consequence of continued but accelerated climate change.

Social, Economic, and Cultural Setting

The assessment area is composed of three relatively distinct regions. The Municipality of Anchorage and the Kenai Peninsula Borough are each organized as single political jurisdictions equivalent to counties, whereas the Prince William Sound region includes the independent cities of Whittier, Valdez, and Cordova, as well as the predominantly Native villages of Tatitlek and Chenega. These communities comprise the Chugach census subarea, a geographic area with no regional government (fig. 1-5).

Each of the three regions represent distinct social and cultural settings with substantially different demographic and economic characteristics (table 1-1). Anchorage is home to more than 40 percent of Alaskans and is the dominant source of demand for recreation and tourism on the Chugach National Forest and on the Kenai Peninsula. The Kenai Peninsula Borough is a rural area with about 60,000 residents, with four major population centers—Kenai (population 7,100), Homer (population 5,003), Soldotna (population 4,163), and Seward (population 2,693)—

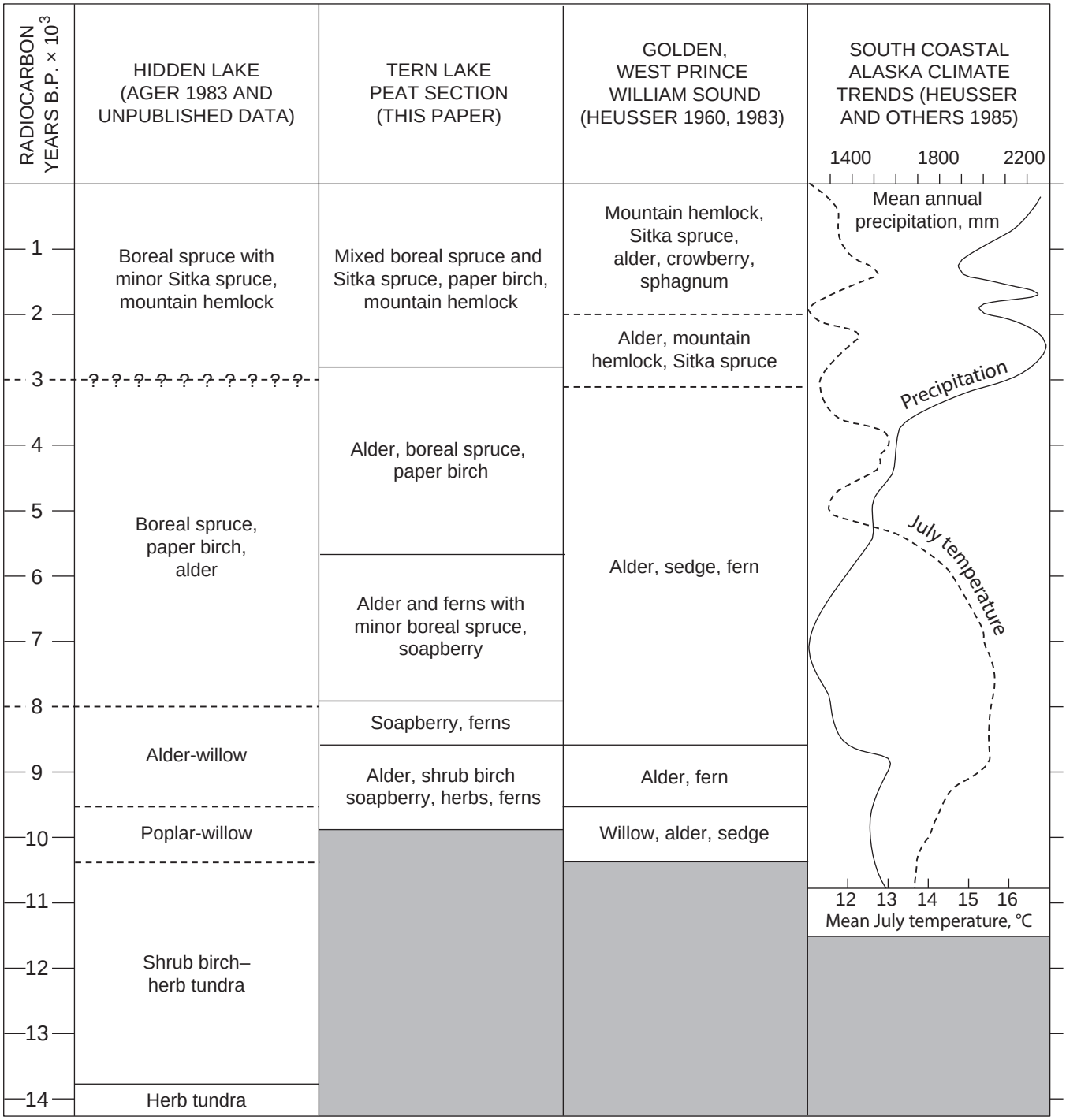


Figure 1-4—Illustration (adapted from Ager 2001) of postglacial vegetation histories from three sites located in different climatic regimes across the northern Kenai Peninsula and northwest Prince William Sound: (1) Hidden Lake, in the partial precipitation shadow of the Kenai Mountains, (2) Tern Lake peat section, north-central Kenai Mountains, near the boundary between transitional and maritime climate types, and (3) Golden, a peat section from a coastal maritime climate. Holocene climate trends for the southern coast of Alaska (modified from Heusser et al. 1985 as cited by Ager 2001) show the coincidence between relatively warm, dry climate and the spread of boreal-forest plants during the early Holocene and cool, wet climate and the development of coastal forest vegetation along the coast of Prince William Sound and the eastern Kenai Peninsula during the late Holocene.



Figure 1-5—Administrative setting of the assessment area illustrating the context of the Kenai Peninsula Borough, Municipality of Anchorage, and Chugach census subarea in Alaska, 2013.

supporting most of the population but a significant number of residents dispersed along the limited road system. In contrast, the Chugach census subarea has very little private land and fewer than 7,000 residents, most of whom are concentrated in Cordova and Valdez. Cordova, Tatitlek, and Chenega are not connected by road to the rest of the state, but are served by the state-run ferry system known as the Alaska Marine Highway.

The relatively high median household income in the Chugach census subarea (Prince William Sound region) stems primarily from oil industry employment at the Valdez terminal of the Trans-Alaska Pipeline. Despite this concentration of high-wage private sector jobs, the Prince William Sound region is much more dependent on fishing and local government for employment than the other two regions. There is one actively fished limited entry permit for every 10 employed residents in the Sound, compared to one per 20 employed in the Kenai Peninsula and three per thousand in Anchorage.

Table 1-1—Economic and demographic characteristics illustrating significant differences in the social and economic environment across three portions of the assessment area

Feature	Municipality of Anchorage	Kenai Peninsula Borough	Chugach census subarea
Population and housing:			
Population on July 1, 2014	300,549	57,212	6,707
Population on July 1, 2011	295,920	56,623	6,733
Average annual growth 2011–2014 (percent)	0.5	0.3	-0.1
Occupied housing units in 2010	107,332	22,161	2,676
Employment and income:			
Residents employed in 2013	130,673	23,909	3,152
Private sector (percent)	85	80	74
Local government (percent)	8	14	20
State government (percent)	7	6	6
Median household income (dollars)	77,454	61,793	91,338
Fishing and subsistence:			
Number of limited entry permit holders who fished	388	1,097	334
Estimated ex-vessel value of fish harvested (dollars)	46,630,382	136,807,046	62,137,013
Federal rural subsistence priority?	No	Yes	Yes, except Valdez

Sources: ADCCED 2015 and ADLWD 2015.

Subsistence is an important component of household consumption and well-being for many people, particularly in the Kenai and Prince William Sound portions of the assessment area. Harvest and use of wild native species represent a significant component of the culture across all three regions, but occur within different social, economic and cultural contexts. Fay et al. (2005) summarized the results of a major subsistence study covering Prince William Sound communities affected by the Exxon Valdez oil spill:

The study found strong evidence of the continuing importance of subsistence harvests and uses of fish and wildlife resources in the study communities. Virtually every household in each community used subsistence resources and the vast majority engaged in harvest activities and was involved in sharing. Harvest quantities in the 1997–1998 study year as estimated in usable pounds were substantial, ranging from 179 pounds per person in Cordova to 577 pounds per person in Chenega Bay. Tatitlek's annual harvest was 406 pounds per person, though in 1988–1989 the per-person annual harvest was 644 pounds. Harvests were also diverse, with the average household using 15 or more different kinds of resources in the study communities (Fay et al. 2005: 73).

Personal-use fish harvests—harvests by Alaska residents for personal use and not for sale or barter (Fall et al. 2014, Utermohle 1999)— also are significant to many households throughout and beyond the study region.[5] In 2012, total personal-use salmon harvests in the Chugach-Kenai region were 781,132 fish, 69 percent of which came from the Kenai River dip net fishery and 18 percent from the Chitina Subdistrict dip net fishery (Fall et al. 2014) (table 1-2). Anchorage and Kenai Borough residents harvested about two-thirds of the total, with an average harvest of 1.4 fish per person. The personal-use and subsistence activities connect individuals, families, family groups, and communities to specific landscapes, often resulting in an intimate understanding of natural resources and important connections to place. The annual calendar for many residents is organized around the timing of natural events (e.g., salmon returns) and longstanding traditions associated with the timing, methods, location, processing, and use of native plants and animals.

Personal-use and subsistence activities connect individuals, families, family groups, and communities to specific landscapes, often resulting in an intimate understanding of natural resources and important connections to place.

Table 1-2— Salmon harvest from Chugach-Kenai region personal-use fisheries, 2012

	Sockeye salmon	Other salmon	Total salmon
Lower Cook Inlet	137	1,757	1,894
Upper Cook Inlet:			
Kenai River dip net	526,992	8,243	535,235
Kasilof River dip net	73,419	2,229	75,648
Other Upper Cook Inlet	29,195	695	29,890
Upper Cook Inlet subtotal	629,606	11,167	640,773
Cook Inlet total	629,743	12,924	642,667
Chitina Subdistrict dip net	136,441	2,024	138,465
Total Chugach-Kenai region	766,184	14,948	781,132

Tourism and recreation are important to the economies of all three regions (Colt et al. 2002, Crone et al. 2002, Fay et al. 2005).[6] An estimated 500,000 people recreate on the Chugach National Forest each year; much of this use occurs in the summer, but snow-based winter recreation is becoming increasingly popular as well (USDA FS 2014). A total of 145 commercial recreation special-use permits

[5] From a legal and management perspective, "personal use" fisheries differ from "subsistence" fisheries depending on determinations by the Alaska Board of Fish. According to the Alaska Department of Fish and Game, "Subsistence uses of wild resources are defined as 'noncommercial, customary and traditional uses' for a variety of purposes." http://www.adfg.alaska.gov/index.cfm?adfg=fishingsubsistence.main.

[6] Because tourism is not a defined industry for statistical reporting purposes, it is not possible with current data to determine tourism employment or income for specific regions in Alaska.

have been issued for 2016 on the Chugach, of which 134 are for outfitting and guiding services (CNF 2016). Recreation on the Chugach is supported by a system of facilities, roads, and trails across the eastern Kenai Peninsula, Prince William Sound, and the Copper River Delta region. This infrastructure includes more than 100 recreation sites, about 840 km of trails, and just over 145 km of roads. Many facilities are most popular during a specific time of year when conditions are best for fishing, hunting, boating, mountain biking, snowmachining (snowmobiling), or backcountry skiing, to name a few activities. More information on recreation settings, opportunities, and use levels can be found in the Forest Plan Revision Assessment (USDA FS 2014: chapter 3).

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Frank Kovalchek



Lost Lake, near Seward, Alaska.

Chapter 2: Climate Change Scenarios

Nancy Fresco[1] *and Angelica Floyd*[2]

Summary

- Downscaled climate projections developed by the Scenarios Network for Alaska and Arctic Planning (SNAP) are useful for examining potential changes in a range of climate variables, and have been used to develop quantitative and qualitative stories regarding climates that may be experienced across the assessment area in the future.
- In this chapter, we examine basic SNAP projections, including mean and extreme monthly temperature and precipitation for July and January; the timing of thaw and freeze; and the expected monthly proportions of snow versus rain ("snow-day fraction").
- Overall, the assessment area is expected to become warmer in the middle of this century, with earlier springs, later autumn, a longer growing season, and shorter, less-severe winters.
- Some increases in precipitation are likely, but overall snowfall will decrease owing to higher temperatures, particularly in the late autumn (October to November), and at lower elevations. The snowline will move higher in elevation and farther from the coast. This change in snow dominance will also be explored in other chapters of this report.

Introduction

Alaska's climate has undergone rapid changes. Substantial warming has occurred at high northern latitudes over the last half century. Most climate models predict that high latitudes will experience a much larger rise in temperature than the rest of the globe through the 21st century; however, the geographic location of the assessment area, in a coastal region with complex weather patterns and tortuous topography, results in patterns of change dissimilar to arctic Alaska (SNAP 2015). To understand the impacts of climate change in the Chugach National Forest/Kenai Peninsula region, these changes must be examined in the context of the dynamic nature of the region.

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Development of Climate Scenarios

Much of the climate modeling for this project uses datasets downscaled or derived by the Scenarios Network for Alaska and Arctic Planning (SNAP) (http://www/snap.uaf.edu), a program within the University of Alaska. The SNAP program is a collaborative network that includes the University of Alaska; state, federal, and local agencies; nongovernmental organizations; and industry partners. SNAP provides access to scenarios of future conditions in Alaska and other Arctic regions for planning by communities, industry, and land managers. For this effort, we chose a set of models that perform particularly well in south-central Alaska. For additional detail, including discussion of model uncertainty, see app. 2 and http://www.snap.uaf.edu.

SNAP climate projections are based on downscaled outputs from five global climate models (GCMs) that were selected, based on regional accuracy, from the 15 GCMs used by the Intergovernmental Panel on Climate Change (IPCC) when preparing its fourth assessment report, which was released in 2007 (IPCC 2007, Walsh et al. 2008). SNAP scaled down these coarse GCM outputs to 771 m resolution, using baseline climatology grids (1971–2000) from PRISM (parameter-elevation regressions on independent slopes model). This effort employed CMIP3 models because those were the most recent available at the onset of the project. These results focus on the A2 greenhouse gas emissions scenario as defined by the IPCC. Although the IPCC's most recent report, the fifth assessment report (AR5) (IPCC 2013) refers to four Representative Concentration Pathways (RCPs) rather than the scenarios described in the Special Report on Emissions Scenarios (SRES) published in 2000, the slightly older model outputs used in this analysis are still relevant within the new framework (Fussel 2009). The A2 scenario outputs fall between those of RCP 6 (a mid-range pathway in which emissions peak around 2080, then decline) and RCP 8.5, the most extreme pathway, in which emissions continue to rise throughout the 21st century (Rogelj et al. 2012). For the purposes of comparison, some results from the slightly more optimistic A1B scenario are also shown in appendix 2.

Temperature and precipitation values are expressed as monthly means for decadal time periods (current, 2020s, 2040s, and 2060s). This averaging helps smooth the data and reduce the effects of model uncertainty so that a clear trend emerges, facilitating comparison among decades. However, some uncertainty does occur across broader timeframes, owing in part to the influence of the Pacific Decadal Oscillation (PDO) and other long-term, broad-scale climate patterns (Bieniek et al. 2014, Walsh et al. 2011). Uncertainty is discussed further in appendix 2.

January and July data were selected to highlight changes in the most extreme months of winter and summer. Changes in shoulder season characteristics and timing are also biologically and culturally important, and are captured via assessment of freeze and thaw dates.

Changes in Temperature

Modeled data for the current decade show that temperatures in the coldest month of the year (January) range from a mean decadal average of approximately -20 °C in the mountains to slightly above freezing along the coastline south of Cordova and Valdez. In the hottest month, July, the mean decadal average temperatures (15 °C) are found in low-lying inland areas, while the coolest temperatures are again found at the mountain peaks, where averages are well below freezing (-7 °C).

These temperature profiles are expected to change over time, with all areas warming by about 3 °C in the next 50 years. Areas with July temperatures below freezing are unlikely to undergo significant glacial melting, although it should be noted that daily highs will exceed mean values, and that direct solar radiation can drive effective temperatures above recorded air temperature.

Winter temperature change is expected to be even more extreme (fig. 2-1). Average temperatures in the coldest month of the year are predicted to rise from only slightly above freezing in the warmest coastal areas to well above freezing, or approximately 4.5 °C. Moreover, these warm temperatures will spread inland toward Cordova, Valdez, and Seward, with above-freezing Januaries dominating across all coastal regions of the Chugach, and some areas as much as twenty miles inland. Many rivers shift from a below-freezing to above-freezing temperature regime. Across the region, winter warming is expected to be approximately 3 to 3.5 °C. Although the greatest impact of summer warming may be in the coldest regions of the Chugach, where snow and glaciers will be most influenced, the greatest winter impacts may be in the warmest coastal and near-coastal regions, where a shift is underway between winters with seasonal mean temperatures below freezing to winters in which the mean temperature across December, January, and February is above freezing. Although this shift does not preclude significant frost and snowfall, it does imply a change in the duration and prevalence of snowpack and ice.

Areas with mean January temperatures above freezing may still experience days or even weeks of freezing temperatures, and daily lows are likely to be significantly cooler than mean values. However, it is unlikely that significant ice formation would occur in such areas, particularly given the fact that sea water freezes at approximately -2 °C rather than at 0 °C. For brackish water, intermediate freezing temperatures are the norm.

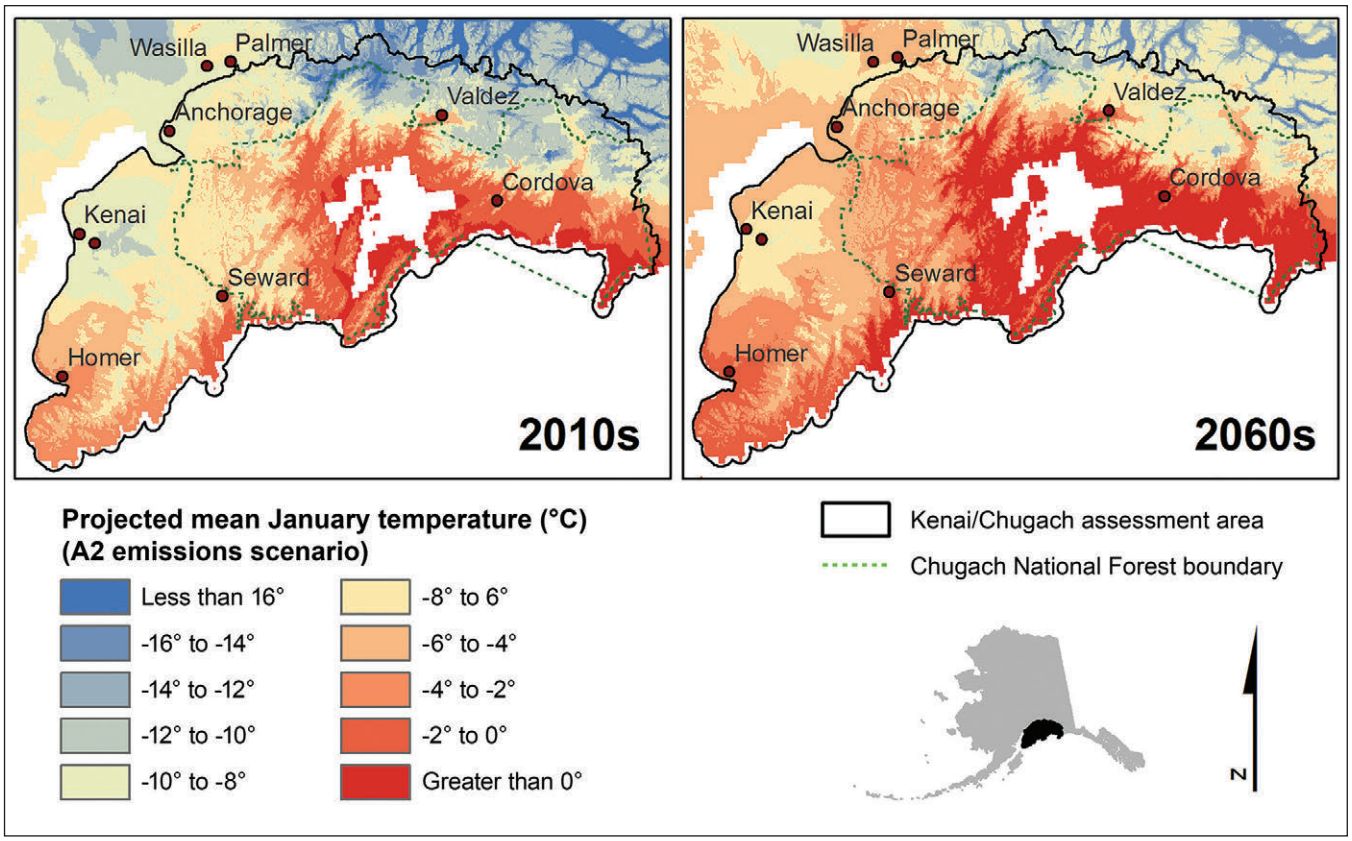


Figure 2-1—January temperatures for the 2010s, 2020s, 2040s, and 2060s for the A2 emissions scenario.

Changes in Precipitation

The projected decadal trend is toward greater precipitation in both January and July. However, model predictions for precipitation are less robust than those for temperature, in part because precipitation is intrinsically more geographically variable. In addition, although precipitation is predicted to increase, inferring the hydrologic status of soils, rivers, or wetlands based on this greater influx of water is problematic. Increases in temperature (and associated evapotranspiration) may more than offset increases in precipitation, yielding a drying effect. Changes in seasonality and water storage capacity can also affect the hydrologic balance. Furthermore, a shift in the percentage of precipitation falling as snow can drastically alter the annual hydrologic profile.

Although current SNAP models do not directly address storm frequency, the literature suggests that climate-change-driven increases may be occurring in the frequency and severity of storm events in the Gulf of Alaska and Bering Sea (Graham and Diaz 2001, Terenzi et al. 2014).

Model results: freeze, thaw, and warm season length—
SNAP interpolates monthly temperature and precipitation projections to estimate the dates at which the freezing point will be crossed in spring and fall. The intervening time period is defined as "summer season length." It should be noted that these dates do not necessarily correspond with other commonly used measures of "thaw," "freeze-up," and "summer season." Some lag time is to be expected between mean temperatures and ice conditions on lakes or in soils. Different plant species begin their seasonal growth or leaf-out at different temperatures. However, analyzing projected changes in these measures over time can serve as a useful proxy for other season-length metrics.

Across the assessment region, date of thaw in spring is expected to come earlier. Large areas of coastal and near-coastal land are projected to shift from early spring thaw to the "rarely freezes" category. This is likely to correspond with lack of winter snowpack and an altered hydrologic cycle. Primarily frozen areas are expected to shrink significantly. Elsewhere, changes are projected to occur as a shift of 3 to 10 days, on average. For example, the A2 scenario shows spring thaw occurring in Soldotna and Kenai around April 4 in the current decade, but in late March by the 2060s.

Autumnal changes are, overall, projected to be slightly greater than those seen in spring, with the date at which the running mean temperature crosses the freezing point shifting noticeably later in just a single decade. Major changes in warm-season length include incursion of the "rarely freezes" zone as far as 20 miles inland; an increase from about 200 days to about 230 days for Palmer, Anchorage, Wasilla, and Kenai; and an even more drastic increase for Seward, Valdez, and Cordova.

Future snow response to climate change—
SNAP data, based on downscaled GCM outputs, do not directly model snowfall as a separate quantity from overall precipitation, measured as rainfall equivalent. However, for the purposes of this project, SNAP researchers used algorithms derived by Legates and Bogart (2009) to estimate snowline and create contour maps depicting the probability of snow versus rain during winter months. The implications of this modeling—as well as other applications of SNAP data to snow and ice conditions—are explored in other chapters. However, a summary of snow-day-fraction outputs is provided here.

A rapid change in snowline is expected over time.

A rapid change in snowline is expected over time. This change is illustrated in figure 2-2 by the change in geographic locations at which an estimated 90 percent of winter precipitation will fall as snow (fig. 2-2). Although inter-year variability in snowline is expected to be high in the next 10 to 20 years, the modeled snowline shifts well inland from Valdez. By 2040, many areas are predicted to receive less

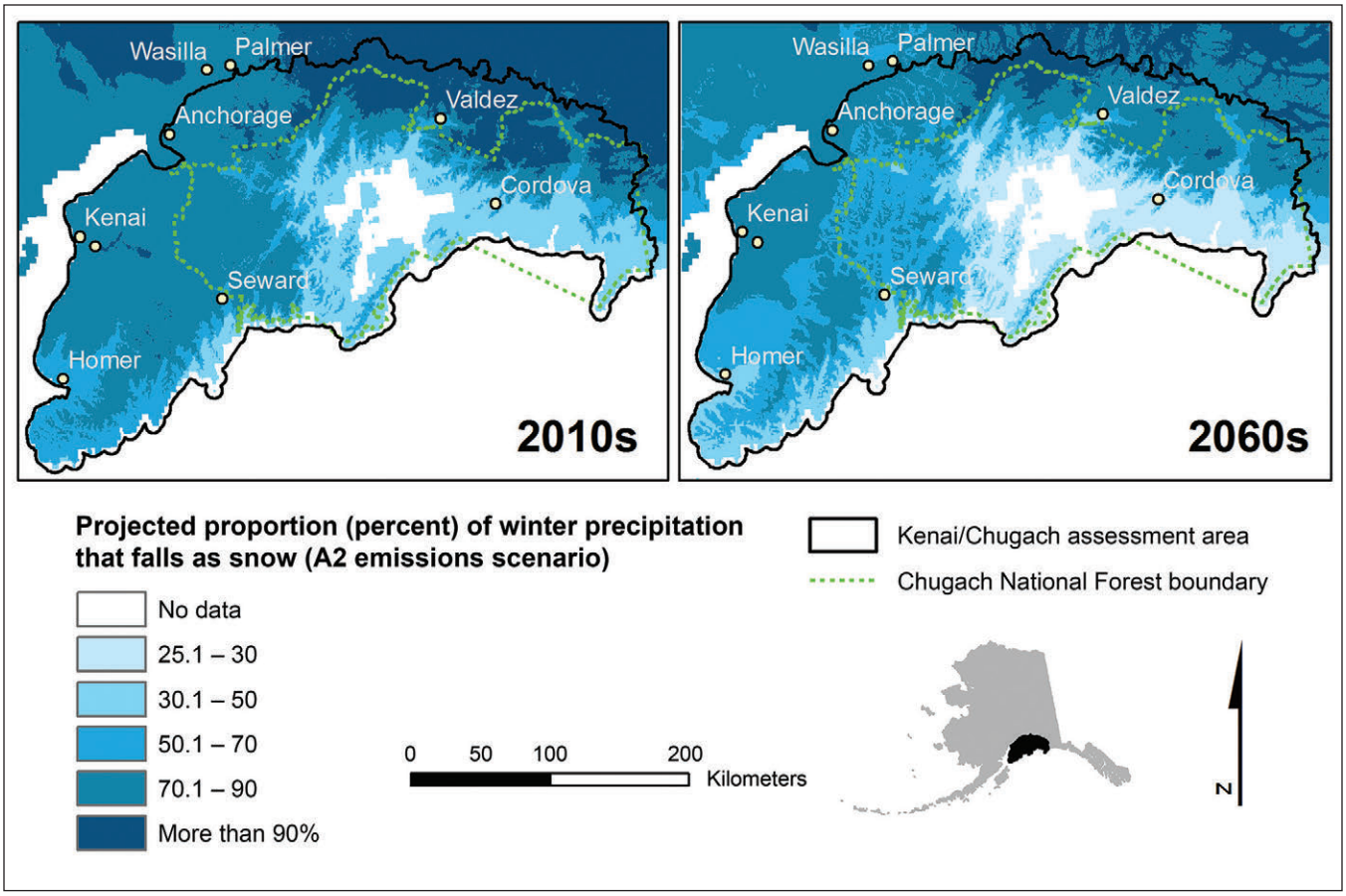


Figure 2-2—Projected snowline for the A2 emissions scenario for the current decade and a 50-year outlook.

than 30 percent of winter precipitation as snow, and by the 2060s the snowline (as defined by the 90 percent contour) is predicted to shift to the highest peaks.

To assess the snowline during the coldest season, as opposed to the winter as a whole, we also examined the projected snowline for the month of January alone. Results show that for many areas that typically experience almost all January precipitation as snow, this pattern may shift in coming decades. By the 2060s, Anchorage, Kenai, Soldotna, Wasilla, and Palmer may have only intermittent snow cover, even in the coldest month of the year.

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U.S. Fish and Wildlife Service



Skilak Glacier, Kenai National Wildlife Refuge, Alaska.

Chapter 3: Snow and Ice

Snow: *Jeremy S. Littell*[1] *and Stephanie McAfee*[1]
Glaciers: *Shad O'Neel,*[1] *Louis Sass,*[1] *and Evan Burgess*[1]
Economic service evaluation: *Steve Colt*[2]
Recreation evaluation: *Paul Clark*[3]

Summary

- Temperature and precipitation are key determinants of snowpack levels. Therefore, climate change is likely to affect the role of snow and ice in the landscapes and hydrology of the Chugach National Forest region.
- Downscaled climate projections developed by Scenarios Network for Alaska and Arctic Planning (SNAP) are useful for examining projected changes in snow at relatively fine resolution using a variable called "snow-day fraction (SDF)," the percentage of days with precipitation falling as snow.
- We summarized SNAP monthly SDF from five different global climate models for the Chugach region by 500 m elevation bands, and compared historical (1971–2000) and future (2030–2059) SDF. We found that:
  - Snow-day fraction and snow-water equivalent (SWE) are projected to decline most in late autumn (October to November) and at lower elevations.
  - Snow-day fraction is projected to decrease 23 percent (averaged across five climate models) from October to March, between sea level and 500 m. Between sea level and 1000 m, SDF is projected to decrease by 17 percent between October and March.
  - Snow-water equivalent is projected to decrease most in autumn (October and November) and at lower elevations (below 1500 m), an average of -26 percent for the 2030–2059 period compared to 1971–2000. Averaged across the cool season and the entire domain, SWE is

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projected to decrease at elevations below 1000 m because of increased temperature, but increase at higher elevations because of increased precipitation.

- Compared to 1971–2000, the percentage of the landscape that is snow-dominant in 2030–2059 is projected to decrease, and the percentage in which rain and snow are co-dominant (transient hydrology) is projected to increase from 27 to 37 percent. Most of this change is at lower elevations.
- Glaciers on the Chugach National Forest are currently losing about 6 km^3 of ice per year; half of this loss comes from Columbia Glacier (Berthier et al. 2010).
- Over the past decade, almost all glaciers surveyed within the Chugach have lost mass (with one exception), including glaciers that have advancing termini (Larsen et al. 2015).
- Glaciers that are not calving into the ocean are typically thinning by 3 m/year at their termini (Larsen et al. 2015).
- In the future, glaciers not calving into the ocean will retreat and shrink at rates equivalent to or higher than current rates of ice loss (Larsen et al. 2015).
- Columbia Glacier will likely retreat another 15 km and break into multiple tributaries over the next 20 years before stabilizing.
- Other tidewater glaciers have uncertain futures, but likely will not advance significantly in coming decades.
- These impacts will likely affect recreation and tourism through changes in reliable snowpack and access to recreation and viewsheds.

Introduction

Climate change can be expected to affect where, when, and how much snow and ice occur on the terrestrial landscape. Changes in temperature and precipitation alter the fundamental physical processes that govern the buildup and melt of snowpacks, the growth or decline of glaciers, and the timing and quantity of important hydrologic processes such as streamflow. However, the impact of climate change on snow and ice depends on what time frame is considered; how local weather and climate respond to hemispheric or global changes in temperature and precipitation; and, at finer scales, how these changes play out over the complex and rugged topography of the region. Some of these changes are intuitive, but the complex interaction between topography, elevation, and broad-scale weather patterns may lead to some unexpected dynamics for both snow and glaciers.

In this chapter, we discuss the mechanisms by which climate affects snow and ice in the Chugach National Forest and surrounding region. We also synthesize available scientific literature and data to characterize plausible impacts of climate change on snow and ice in the future.

Climate Change and Its Effects on Snow and Ice

Climate—the statistics of weather over time (usually 30 years or more)—is determined by the combination of temperature, precipitation, wind, the nature of storms, atmospheric pressure, and other factors characteristic of a place. Climate also includes the interannual to decadal (and longer) variability in those characteristics and the regional to global mechanisms that cause it. However, what is "characteristic" is changing rapidly in ways that are explainable only by global climate change, that is, those trends in climate that are significantly influenced by anthropogenic greenhouse-gas emissions. Projecting possible climate impacts on snow and ice processes requires understanding the mechanisms by which weather and climate affect snowpack and glaciers.

Snowpack—

In places where snow and ice were historically common, changes in climate can be expected to affect snowpack development, distribution, and melting as temperature increases, as well as the timing and quantity of precipitation change. Increasing temperature affects snowpack directly by affecting both the seasonal timing of snowmelt and the period of the year that is cool enough to promote snowpack accumulation. First, as temperature during fall, winter, and spring increases, there is increased likelihood that storms will coincide with above-freezing temperatures, and the proportion of precipitation that falls as rain instead of snow increases. Second, as spring temperatures increase, the timing of spring melt is pushed earlier in the year. In places where storms historically occurred at temperatures near freezing, a small increase in temperature can result in relatively large decreases in snowfall as the form of precipitation changes to rain. In contrast, in places where storms historically occurred at temperatures well below freezing, the impact is proportionally less. Rain-on-snow events may also increase with temperature, but are difficult to predict and model. Furthermore, despite increased temperature, increased precipitation may result in substantial increases in snow at high elevations where precipitation was less abundant in the past but future temperatures are rarely expected to be above freezing. Therefore, at colder locations where temperature is consistently below freezing (usually at higher elevations), increased future precipitation could result in increased snowpack.

Glaciers—

Glaciers are the result of a climate that consistently produces more snowfall during winter than can be melted in summer. The surplus of snow accumulates over decades to millennia and eventually compacts into ice. As the ice deepens, the glacier's immense weight causes the ice to flow downhill until the ice reaches lower elevations, which are warmer and receive less snowfall, thus allowing the excess glacial ice to melt. A glacier can maintain a constant size and shape if the net gain of snow in the upper accumulation zone of the glacier perfectly offsets the net amount of ice lost in the lower ablation zone (melt zone). If the amount of melt exceeds the amount of snow accumulation, the mass budget of the glacier becomes negative and the glacier will shrink, adding that water to streamflow, and eventually, the oceans. The size of glaciers is thus inextricably linked to the relative amounts of snowfall and melt—two terms that are expected to change with a changing climate.

Glacierized basins (i.e., ice-covered currently as opposed to glaciated, or historically ice-covered) produce 2 to 10 times more runoff than similarly sized, non-glacierized basins (Mayo 1984). When compared to ice-free basins, basins with only a few percent of basin ice coverage exhibit notable differences in streamflow at all time scales. Given two identical neighboring basins, with the sole exception of one basin having 20 percent ice cover, cumulative annual streamflow will be higher in the glacierized basin, and the annual streamflow will have a longer period of higher flow, owing to continued release of water after basin snow cover is melted. Daily streamflow will exhibit diurnal variations, even in the absence of snow, resulting from melt. Historically, higher glacial coverage in a watershed translates to increased runoff rates, later timing of peak streamflow in late summer, and decreased interannual variability (Fountain and Tangborn, 1985, Jansson et al. 2003, O'Neel et al. 2015). Meanwhile, water clarity, stream temperature, and streambed stability all decrease (Fleming 2005, Hood and Berner 2009, Milner and Petts 1994).

Glaciers in the Chugach region receive an exceptional amount of snow each winter and are also subjected to exceptional amounts of melt in summer. They must flow exceptionally fast to offset the high mass turnover and therefore are relatively quick to respond to climate variability and change.

Glaciers in the Chugach region receive an exceptional amount of snow each winter (estimated at greater than 3000 mm water-equivalent precipitation averaged over the region) and are also subjected to exceptional amounts of melt in summer. They must flow exceptionally fast to offset the high mass turnover and therefore are relatively quick to respond to climate variability and change.

Tidewater glaciers—those that calve icebergs into the ocean—are not only controlled by climate; they are also sensitive to changing ocean temperatures and fjord shape. These controls are powerful enough to affect a glacier's mass balance by promoting additional ice loss through iceberg calving. Subtle changes—perhaps

in climate or glacier shape—can cause the glacier to accelerate, which leads to more iceberg calving and more acceleration, and hence a feedback loop that causes the glacier to lose far more ice than climate would allow alone. This is referred to as a "rapid" retreat (e.g., Meier and Post 1987). On the other hand, a similarly sized change in climate may yield no response at a different stage of the tidewater glacier advance-retreat cycle (Post et al. 2011). Columbia Glacier in the Chugach is typical of this process; it has lost 155 km^3 of ice in the past three decades but less than 10 percent of this loss has been due to climate (O'Neel 2012, Post et al. 2011, Rasmussen et al. 2011). In concept, rapid retreats continue to affect glacier mass balance after a retreat from deep ocean water. The retracted geometry (removal of ablation area) favors positive mass balance, and mass gains are likely even in a climate unsupportive of widespread mass gain/advance for land-terminating glaciers (Post et al. 2011).

Calving dynamics are the reason for the wide range of tidewater glacier behaviors currently occurring in Prince William Sound and will be responsible for a complex future pattern of glacier change in the Chugach (Larsen et al. 2015). Glaciers in the Chugach that do not terminate in the ocean are not subject to these interactions. When one is reviewing current and projecting future changes in Chugach glaciers, it is important to distinguish between tidewater glaciers and all others (Arendt et al. 2002, Larsen et al. 2015). How climate and tidewater dynamics are affecting glaciers now and how they may affect glaciers in the future will be discussed in following sections.

Impacts of Climate Change Effects on Snow and Ice

Streamflow timing and volume—
Collectively, the expected changes in snow and ice will have impacts on the hydrology of systems both within and downstream from mountains and glaciers (O'Neel et al. 2015). These hydrologic changes can in turn have significant impacts on—and be influenced by—terrestrial, riparian, and coastal ecosystems. Geology and geography, along with the physical and ecological changes in watersheds, affect the response of hydrography to climate change, so responses can differ significantly from watershed to watershed within a region. There are also strong ice-ocean-ecosystem linkages and feedbacks, including nutrient delivery and primary productivity, which likely have implications for fish, marine mammal, and bird populations. This illustrates the importance of an interdisciplinary approach and modeling to understand climate change impacts in complex systems.

Neal et al. (2010) and Hill et al. (2015) estimated that 43 percent (370 km^3/year of 870 km^3/year) of the runoff flowing into the Gulf of Alaska is from glaciers

Climate warming eventually influences the net mass balance of land-terminating glaciers and thus the seasonal timing and amount of streamflow in streams dependent on them.

in southeast Alaska, a volume comparable to that of the Mississippi River basin despite being seven times smaller in area. Freshwater delivery to the ocean affects ocean circulation, sea-level change (Larsen et al. 2007), and possibly also hydropower resources. For example, the Alaska coastal current, which flows north from the Gulf of Alaska, delivers more fresh water via marine supply than is supplied to the Arctic Ocean by the two largest rivers in the region (Weingartner et al. 2005.) Climate warming eventually influences the net mass balance of land-terminating glaciers and thus the seasonal timing and amount of streamflow in streams dependent on them (Jansson et al. 2003), but the glacier volume buffers the streamflow response—there is a smooth increase with glacier melt, then a decrease in response to declining volume. Runoff increases until glacier contribution decreases, and then runoff decreases. In much of Alaska, the current status of such river systems is unknown because the relative position of watersheds in the evolution of glacier melt and hydrologic delivery (runoff) is unclear. Changes in runoff depend on complex seasonal evolution that is itself a function of details of glacier structure (firn, piping, water saturation and ponds and channels, and bedrock geometry). These factors affect downstream flows via their influences on the diurnal timing and within-season variability in streamflow. A study of monthly flow for nine rivers in Canada (Fleming 2005) indicates that nonglacial basins have a freshet peak with comparatively long persistence into summer. As little as 2 percent of ice cover in a basin is enough to transfer a hydrograph to glacial basin dynamics. Glacierized basins have a much larger freshet relative to baseflow, and higher flows persist longer. In Alaska, comparison of a continental glacier (Gulkana Glacier) with a coastal, land-terminating glacier (Wolverine Glacier) suggests that a coastal glacier has comparatively high fall flow, and larger peaks the rest of time (O'Neel et al. 2014). Projecting future streamflow in glacierized basins is difficult. Precipitation amount and timing, temperature, and local topography and glacier morphology all affect dynamics of glaciers and thus the streamflow from them. But changes in glacier shape are difficult to predict (Jost et al. 2012). Cumulative mass balance at Gulkana Glacier steadily decreased, (-25 m in area-average thickness since the 1960s), while Wolverine Glacier had an increased rate of mass-balance gain in the 1980s but a rapid decrease since then, thus mass losses have been proportionally less on the coast (-16 m) (O'Neel et al. 2014). Coastal glaciers have fared better historically because they have a different seasonal climate (more precipitation and less summer heat), but the slope of the decrease in mass balance is similar over the last 20 years. Coastal glaciers are probably more vulnerable over the long term because they have a temperature regime closer to 0 °C than do those in the interior.

Role of glaciers in oceanography, marine ecosystems—
Glacier mass balance and effects on streamflow are not the only expected impacts of climate change associated with glaciers. For example, the surfaces of glaciers have been shown to support microbial ecosystems. Atmospheric deposition of nutrients, the resulting primary and heterotrophic production at the glacier surface, microbial activity underneath the glacier ice (Skidmore et al. 2000), and hillslope runoff combine to result in large material contributions to the marine environment. Heterotrophic carbon in glacier runoff (Hood et al. 2009) is nearly that of some boreal forest runoff (glacial dissolved organic carbon [DOC] = 12–18 kg C/ha/year; boreal forest DOC export 22–86 kg C/ha/year). The runoff flux from glaciers to streams or ocean is therefore large, and is bioavailable, including nutrients (phosphorus), micronutrients (iron), and contaminants (mercury and others). However, much as with glacial changes, the flux response is locally variable—biochemistry and turbidity vary widely in streams dominated by glacial runoff (Hood and Berner 2009). Riverine biodiversity increases with basin glacierization (Jacobsen et al. 2012). Despite this variability, it is important to recognize the substantial input of organic nutrients from glaciers, a characteristic that was recognized only recently (Hood et al. 2009).

Glacier runoff also affects near-shore ecology in part because of the input of nutrients including organic matter to the system. Euphausiids and zooplankton can thrive in glacier-dominated fjords (Arimitsu et al. 2012), as do coastally adapted birds (Mehlum and Gabrielsen 1993). Diving seabirds forage on upwelled crustaceans and thus have high fidelity to glacial habitat. Tidewater glaciers provide refuge from predation for seals, and pups born near calving glaciers have short weaning times (Blundell et al. 2011, Herreman et al. 2009, Womble et al. 2010). The effects of glacial turbidity on light penetration affect the vertical migration of fish. In clear water, sunlight penetrates >100 m and moonlight penetrates <50 m, but in sediment-laden water sunlight penetrates less than 50 m. As a consequence, mesopelagic fishes are nearer the surface during daylight hours. Consequently, forage fish plausibly spend more daylight hours at the surface and are therefore possibly more available to birds.

For fjord glaciers, warming and melting result in changes to coastal (baroclinic) current through changes in physical oceanography. These result in effects for the whole circulation pattern in the fjord, which changes the rate of iceberg production, forage-fish survival and productivity, and the timing and structure of currents. Beyond their influence on individual fjords, glaciers play an important role in delivering fresh water to the Gulf of Alaska. Where tidewater (calving) glaciers have a direct connection to the ocean environment, there is a direct interaction,

through melting of ice below sea level. This "submarine melt" has been shown to be capable of melting the majority of ice delivered to the calving front from upstream during summer months. In the Chugach region, the ocean is normally warm enough to melt ice 5 or 6 months a year, and freshwater contribution to the marine environment peaks in autumn. In such environments, there are enormous amounts of submarine melt, as all tidewater glaciers are grounded below sea level in the ocean (Bartholomaus et al. 2013, Motyka et al. 2013).

Global climate models take advantage of modern computing capacity to simulate historical and future climate from "first principles"—knowledge of the physical properties and behavior of the atmosphere, ocean, land surface, and other factors as well as how they interact to affect climate.

Future Snow Response to Climate Change

Strengths and Limitations of Climate Modeling for Snow Impacts

One tool available for assessing the plausible impacts of climate change on snow and ice is future climate modeling. Global climate models (GCMs) take advantage of modern computing capacity to simulate historical and future climate from "first principles"—knowledge of the physical properties and behavior of the atmosphere, ocean, land surface, and other factors as well as how they interact to affect climate. It is worth noting that the climate modeling community has recently transitioned from the CMIP3 group of climate models used in the fourth IPCC assessment (AR4) to the next generation, or CMIP5 group of models, which generally have finer resolution and (slightly) more advanced treatment of the climate system. Knutti and Sedlacek (2013) concluded that CMIP3 and CMIP5 can be considered realizations of the same probability spectrum of plausible climate scenarios, and at the time of this writing, CMIP5 downscaled climate output for Alaska did not exist. Given the mid-century focus of this assessment, the scenarios presented in this chapter should be broadly consistent with CMIP5 models with the higher RCP emissions scenarios (4.5, 6.0, or 8.5) because those do not diverge appreciably from A2 until the 2050s or 2060s. Despite modern computing capability, however, the atmospheric resolution of GCM simulations is commonly performed at about 0.5 to 1.0 degrees latitude (roughly 35 to 70 mi [56 to 113 km]), though some models exceed this resolution. This limits the local processes that can be resolved by these models. For example, rugged topography such as in the Chugach National Forest might result in an elevation difference of 1500 m or more at the scale of one or two cells in a climate model.

To make climate model output more applicable to finer landscape features, a process called "downscaling" can be used (see chapter 2). The many approaches to downscaling differ in complexity. Whether increasing complexity is advantageous depends on the question. For example, understanding future monthly or seasonal changes in temperature and precipitation averaged across several climate models may not require the same level of detail as understanding daily responses

in climatic extremes, which may require complex statistical relationships between historical gridded data and GCM cells. In Alaska, the Scenarios Network for Alaska and Arctic Planning (SNAP) uses an approach called the "delta" method to relate gridded historical climate information (PRISM) to the expected CHANGE for each GCM. That is, the difference between the GCM historical climate and the GCM future climate is calculated, and that change (or "delta") is added to (for temperature) or multiplied by (for precipitation) the historical value.

The delta method, while less complex than some other approaches, has a straightforward and easy-to-understand method for dealing with climate model bias. The bias in a climate model is the degree to which it is too warm or cold (wet or dry) compared to measured climate in the historical record. For example, mountain ranges that are too small to be resolved in the model create real rainshadows that the model cannot "see," resulting in too much modeled precipitation in the rainshadow and not enough in the mountains. Bias correction uses historical data to estimate the correction of such model error. The delta method does not explicitly model the error—instead it takes the simulated historical climate and the simulated future climate from the GCM and uses the difference between the two to estimate the change expected by the model in the future. This is an indirect control of bias, but it is straightforward and effective, and does not result in substantial loss of information for monthly or seasonal questions.

SNAP's future projections come from five different GCMs (CCCMA-CGCM3.1 t47, GFDL-CM2.1, MPI-ECHAM5, MIROC3.2 medres, and UKMOHadCM3) that have been evaluated for their fidelity to Alaskan climate (a "reanalysis," i.e., not directly from weather station data) (Walsh et al. 2008) during the instrumental period (1958–2000). Deltas for each of these GCMs have been computed and applied to gridded, interpolated historical climate (PRISM) at 30-arc-second resolution (similar to 800 m resolution, about 771 m at 60° north latitude). This results in more localized (downscaled) estimates of historical and future temperature and precipitation. However, the consequences of changes in precipitation and temperature for snowpack at a location as fine as 800 m are complex. Snowpack is affected by other factors that are not commonly downscaled to such fine resolution, and without this information, climate models cannot simulate snowpack at local scales. For example, the difference in snow accumulation on one 800-m pixel compared to a neighboring pixel is a product of elevation, orientation to prevailing winds, wind effects on redistribution, vegetation, and the variations in storm track from year to year. Elevation and aspect are fixed—they do not change appreciably over the time frame important for such questions. However, year-to-year differences in wind redistribution of snow and storm tracks can affect

the two neighboring pixels differently. It is also critical to remember that **changes** in temperature and precipitation at the two pixels are effectively the same, though downscaling could result in different absolute values.. Downscaled climate output gives us the ability to examine those changes, but there is considerable local information that climate models do not "see"—they do not resolve the wind differences and topography for the two example pixels. Therefore, "forecasts" of an 800-m snowpack for a given year or even a given decade are beyond the scope of such work. However, the changes from historical snowpack to future snowpack over the duration of the "climatology" (30-year period) average out the factors that result in large year-to-year and pixel-to-pixel differences and focus instead on the trends to be expected given changes in temperature and precipitation.

In the following analyses, we have chosen to focus on the midterm impacts of climate change (SRES Scenario A2) over a 30-year period in the future—2030 to 2059. This is a sufficiently long time span that the averages of temperature and precipitation ("climatology") are comparatively robust to interannual and decadal variation in climate, but sufficiently near in the future that it has bearing on management time horizons considered between now and the 2030s. For this initial analysis, we have chosen to analyze impacts for 500-m elevation bands, which avoids confounding the results too much with local differences. The changes in the projections below should therefore be considered "averages" with some variability to be expected within the elevation bands and the 30-year period resulting from topographic and interannual variability in factors that affect snowpack.

We focus on three aspects of how snow may change in the future: SDF, SWE, and snowpack vulnerability. Snow-day fraction addresses the changes that could reasonably be expected in the proportion of precipitation that falls as rain versus snow now and in the future. Snow-water equivalent addresses the consequences of changes in both precipitation and SDF for snow accumulation on the land surface during the cool season. Finally, snowpack vulnerability addresses the proportion of precipitation entrained in the snowpack during the cool season.

Projected Effects of Climate Change on Snow-Day Fraction in the Chugach National Forest

McAfee et al. (2013) developed models of decadal SDF for all of Alaska at 800 m.[4] Snow-day fraction is the ratio of days with precipitation falling as snow to the total number of precipitation days. For example, an SDF of 30 percent means that of the

[4] Data: http://www.snap.uaf.edu/data.php#dataset=historical_monthly_snow_day_fraction_771m; User's guide: http://www.snap.uaf.edu/files/data/snow_day_fraction/snow_fraction_data_users_guide.pdf.

days with measurable precipitation, on 30 percent of those days the precipitation fell primarily as snow. A projected change of -20 percent SDF would result in a future value of 10 percent SDF, but would represent a decrease of 67 percent of the historical value.

Here, we present a summary of SDF for the Chugach National Forest based on data and projections developed by McAfee et al. (2013). They developed decadal historical data (1900–1909, 1910–1919, etc., to 2009) and future projections (2010–2019, 2020–2029, etc., to 2099) for different future greenhouse-gas emissions scenarios (B1, A1B, and A2 SRES emissions scenarios, e.g., Nakicenovic et al. 2000). Given the 2030–2059 projected future timeline for this assessment, we chose to use the future climates derived from scenario A2, which result in similar temperature changes as A1B until about the middle of the 21st century, after which they result in more warming than A1B. Recent emissions are comparable to the trajectory of both A1B and A2 scenarios, so we elected not to consider B1 scenarios. We used an historical benchmark climatology of 1971–2000, and thus averaged the three decadal 800-m-resolution downscaled estimates of SDF for the 1970s, 1980s, and 1990s. We did the same for the downscaled projected values for the 2030s, 2040s, and 2050s. We subtracted the historical data from the future projections to estimate the change in SDF. All analyses to this point were done for the whole state of Alaska.

By using the project domain for the Chugach National Forest Vulnerability Assessment and the digital elevation model associated with the SNAP products, we developed eight 500-m elevation bands for analysis, from sea level (0 m) to >3000 m (fig. 3-1; table 3-1). We calculated the mean historical (1971–2000) and projected future (2030–2059) SDF for the elevation bands (i.e., over all pixels in each elevation band).

Snow-day fraction changes by elevation band—
The results of this analysis are summarized in table 3-1 and figure 3-2. In the text that follows, the comparisons described are between the historical SDF and the five-model mean future SDF. Individual model projections may be more or less than the five-model average (see fig. 3-2). When the range of model projections includes the historical mean, it is less clear that the projected changes are distinguishable from the historical variability. In no case is the five-model future mean greater than the historical mean; in a few cases, notably in May below 2000 m and July at elevations above 2000 m, the GCM with the highest future SDF exceeds the historical mean.

Projected decreases in snow-day fraction are most pronounced at lower and mid elevations during late autumn and early winter (October through December).

In most months at all elevations, the five-model mean indicates projected decreases in SDF. These decreases are most pronounced at lower and mid elevations

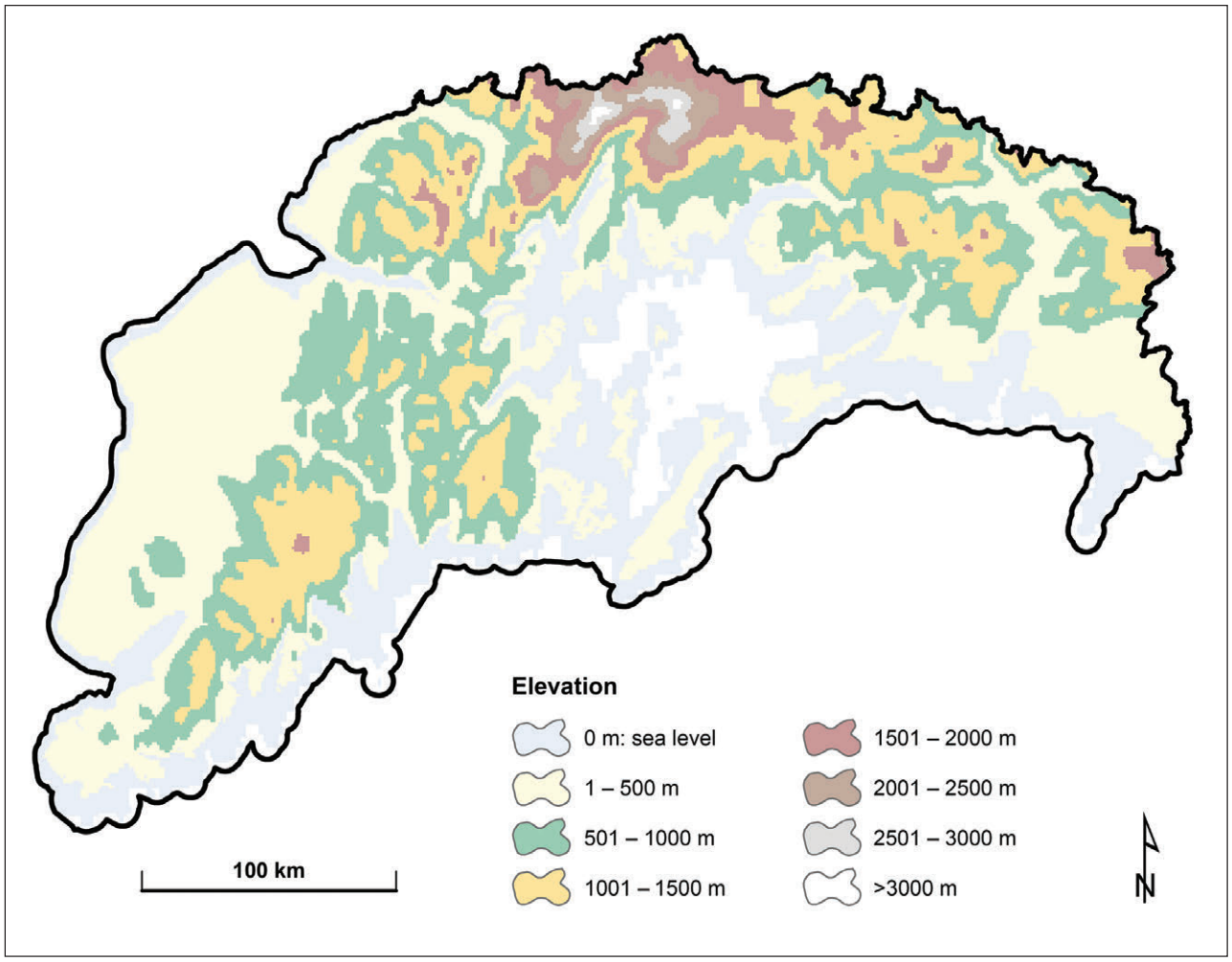


Figure 3-1—Elevation bands used in snow-day fraction analysis for the Chugach National Forest.

Table 3-1—Elevation bands, area, and snow-day fraction for the Chugach National Forest

Elevation band	Pixels	Area	Historical[a] snow-day fraction (October—March)	Projected[b] snow-day fraction (October—March)	Change[c] (October—March)
Meters		*Square kilometers*	- - - - - - - - - - - - - - - *Percent* - - - - - - - - - - - - - - -		
0	14,612	8686			38.1
1–500	22,361	13 292	56.7	29.5	-22.7
501–1000	14,865	8836	71.1	47.6	-16.0
1001–1500	9,725	5781	80.6	62.5	-12.1
1501–2000	2,541	1511	86.4	72.8	-9.7
2001–2500	971	577	91.7	80.2	-7.3
2501–3000	368	219	95.4	87.3	-4.7
>3000	44	26	97.8	92.7	-2.8

[a] 1970–1999 cool season average.
[b] 2030–2059 cool season average, five-GCM mean; GCM = global climate model/general circulation model.
[c] [(Projected—historical)/projected] × 100.

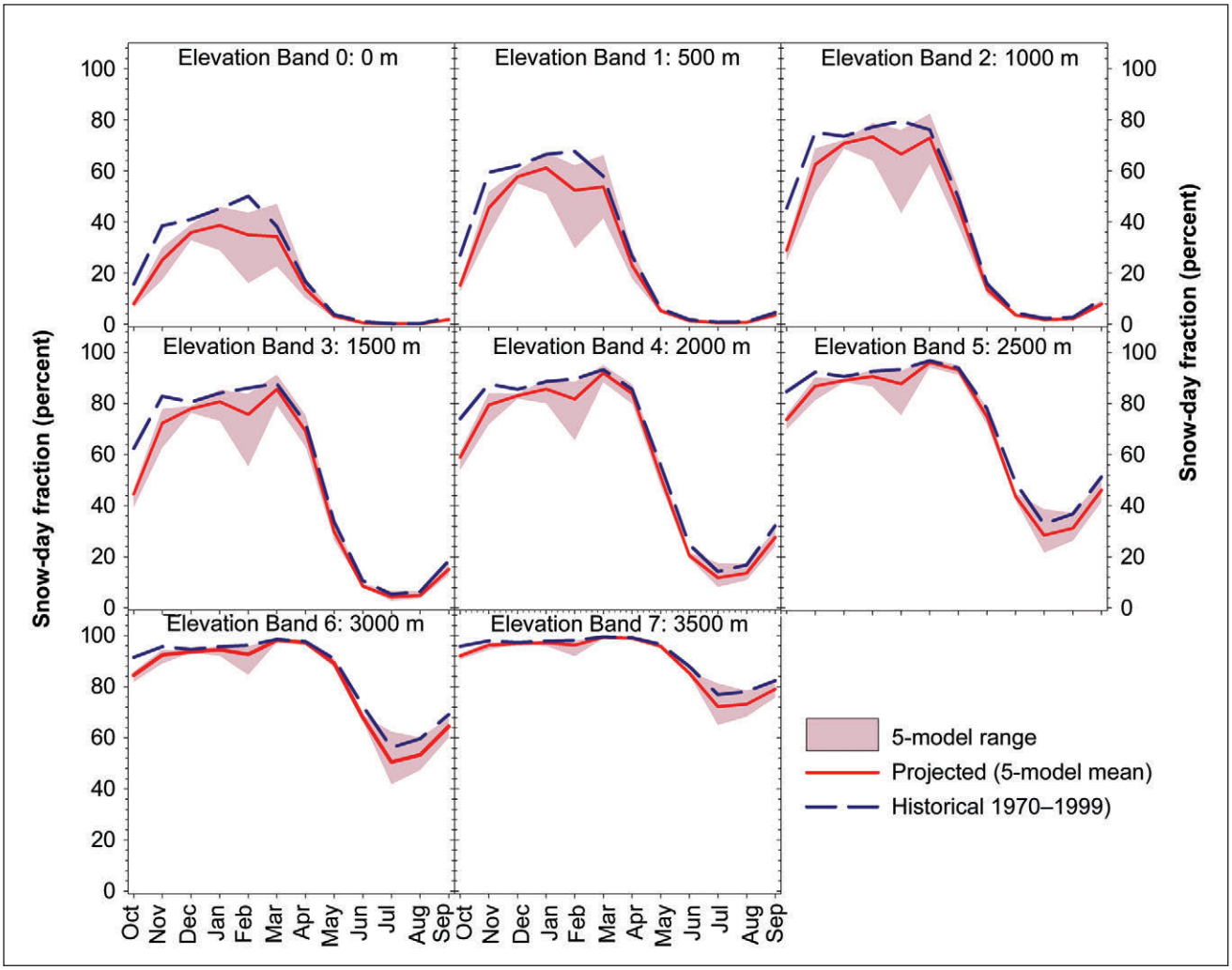


Figure 3-2—Historical (1971–2000) and projected (2030–2059) changes in mean monthly snow-day fraction by elevation band for the domain of the Chugach National Forest Vulnerability Assessment. Months are in "hydrologic year" order, October to September. Blue line indicates the historical average; red line indicates five-model mean future average; pink area represents range of five future climate models.

(2000 m and less) in the late autumn/early winter (October, November, and December). For elevation bands at 2000 m and below, the projected (2030–2059) model with the highest SDF is less than the historical (1971–2000) means for these months. Decreases in these elevations differ with month (fig. 3-3) and elevation (fig. 3-2), but are higher in October (mean -13 percent, model range -6 to -24 percent) and November (mean -12 percent, model range -4 to -25 percent) than in December (mean -4 percent, range -2 to -8 percent). Differences in October are evident at elevation bands above 2000 m, but the projected changes decrease as elevation increases (fig. 3-2). For elevation bands at 1500 m and below, there also appears to be a decline in February SDF (around -13 percent average, model range -36 to -2 percent), although

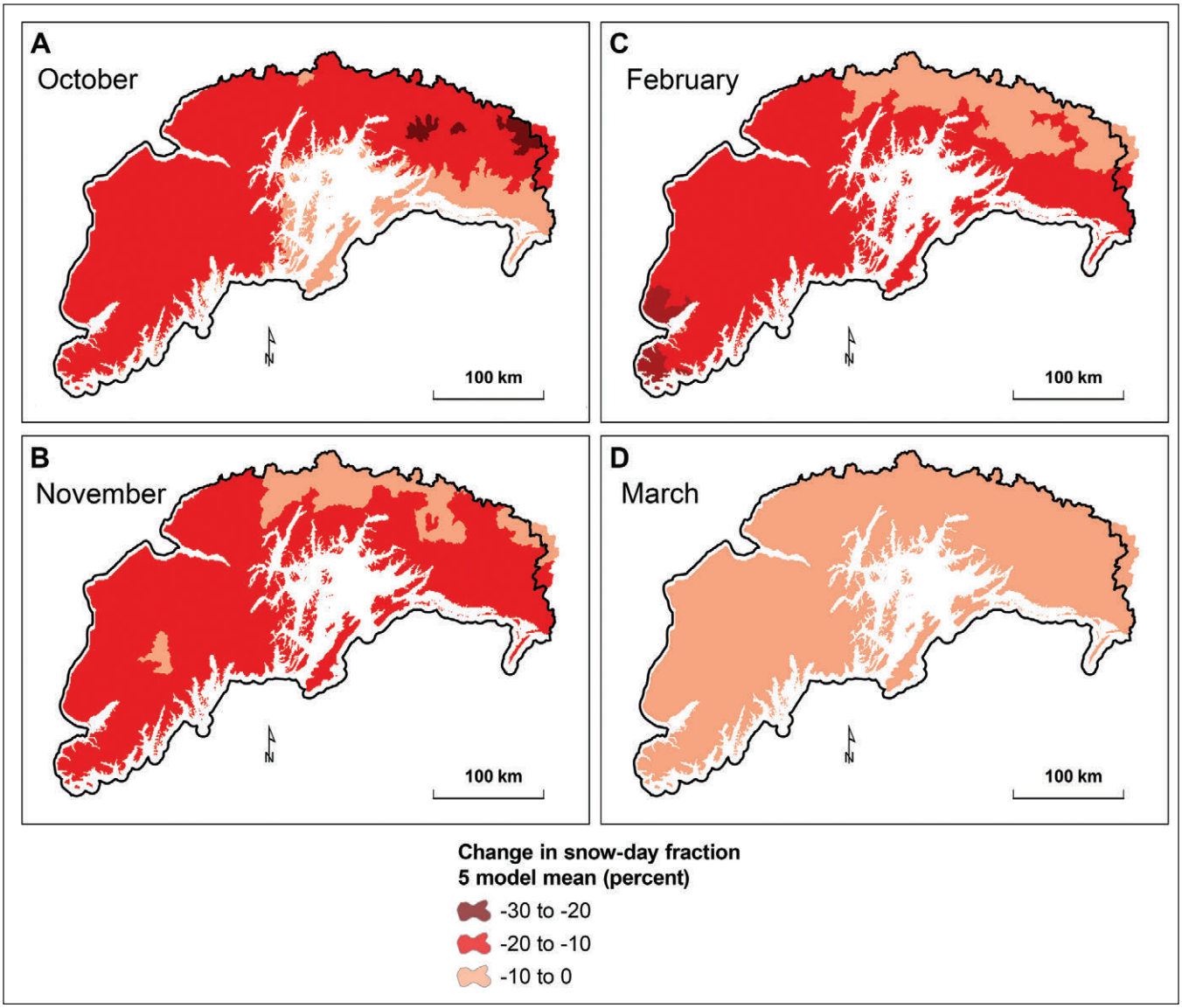


Figure 3-3—2030–2059 changes in HUC-12 level mean snow-day fraction relative to historical (1971–2000) for selected months: (A) October, (B) November, (C) February, and (D) March. The maps are focused on the domain of the Chugach National Forest Vulnerability Assessment; other lands are faded. Note that larger absolute declines at mid elevations from figure 3-1 (between 500 and 2000 m) in (A) October, and at lower elevations (<500 m) in (B) November. Note that the percentage values in the maps are raw declines, not percentages of percentages, such that a decrease from 60 to 30 percent and from 30 to 0 percent would get the same change but result in different absolute values. HUC = hydrologic unit code.

February has one of the largest ranges of projected future responses of any month, particularly at 2500 m and below (fig. 3-2).

The difference between historical and future SDF, as well as the disagreement among climate models, initially decreases with increasing elevation. However, models agree more on warm-season (April to September) changes below 2000 m than they do on cool-season (October to March) changes. At elevations above

2500 m, models agree more on cool-season changes than they do on warm-season changes.

Projected Effects of Climate Change on Snow-Water Equivalent in South-Central Alaska

Snow-water equivalent is the amount of water entrained in a given volume of snowpack. Snowpacks with identical depth but different densities have different water content. Snow-water equivalent is a way of putting snow depths and densities, which differ considerably, on a consistent hydrologic footing.

Using the same scenarios as for SDF, we used historical and future gridded precipitation[5] to estimate precipitation totals and projected changes for the key cool season months October to March. Snowpack obviously can accumulate in south-central Alaska, particularly at the highest elevations, earlier in the autumn and later in spring than these months, but this is a comparatively standard hydrologic season that comprises the bulk of the snowiest months. For each month, we multiplied the SDF by precipitation to estimate total maximum SWE. Local processes, such as wind redistribution, sublimation from the surface or tree canopies, and melt could well affect the actual SWE, so these should be interpreted as estimates of the climatically determined component of SWE.

Snow-water equivalent changes projected using this methodology indicate different responses at different elevations (fig. 3-4) across the cool season and substantial differences across months (table 3-2). Averaged across the cool season, SWE would be projected to decline most in autumn (October and November) and at lower elevations (below 1500 m), an average decrease of 26 percent for the 2030–2059 period compared to 1971–2000, with the largest decreases at lower elevations and in October. In contrast, from December to March at elevations above 1000 m, the five-GCM average SWE is projected to increase by an average of 12 percent, with the largest increases at highest elevations in January and February. Below 500 m, SWE is projected to decrease in all months except January and March, which have model-projected increases (table 3-2). For the cool season as a whole, the five-model GCM average projects decreases in SWE at elevations below 1000 m and increases above 1500 m (fig. 3-5; table 3-3). Agreement across GCM models is reasonably good at the lowest and highest elevations—most of the models agree on decreases in monthly SWE for October through March at the lowest elevations (<1000 m) and increases at the highest elevations (>2500 m). However, at mid elevations, some models project decreases and some increases (table 3-3; fig. 3-6).

[5] Data: http://www.snap.uaf.edu/data.php#dataset=historical_derived_precipitation_771m.

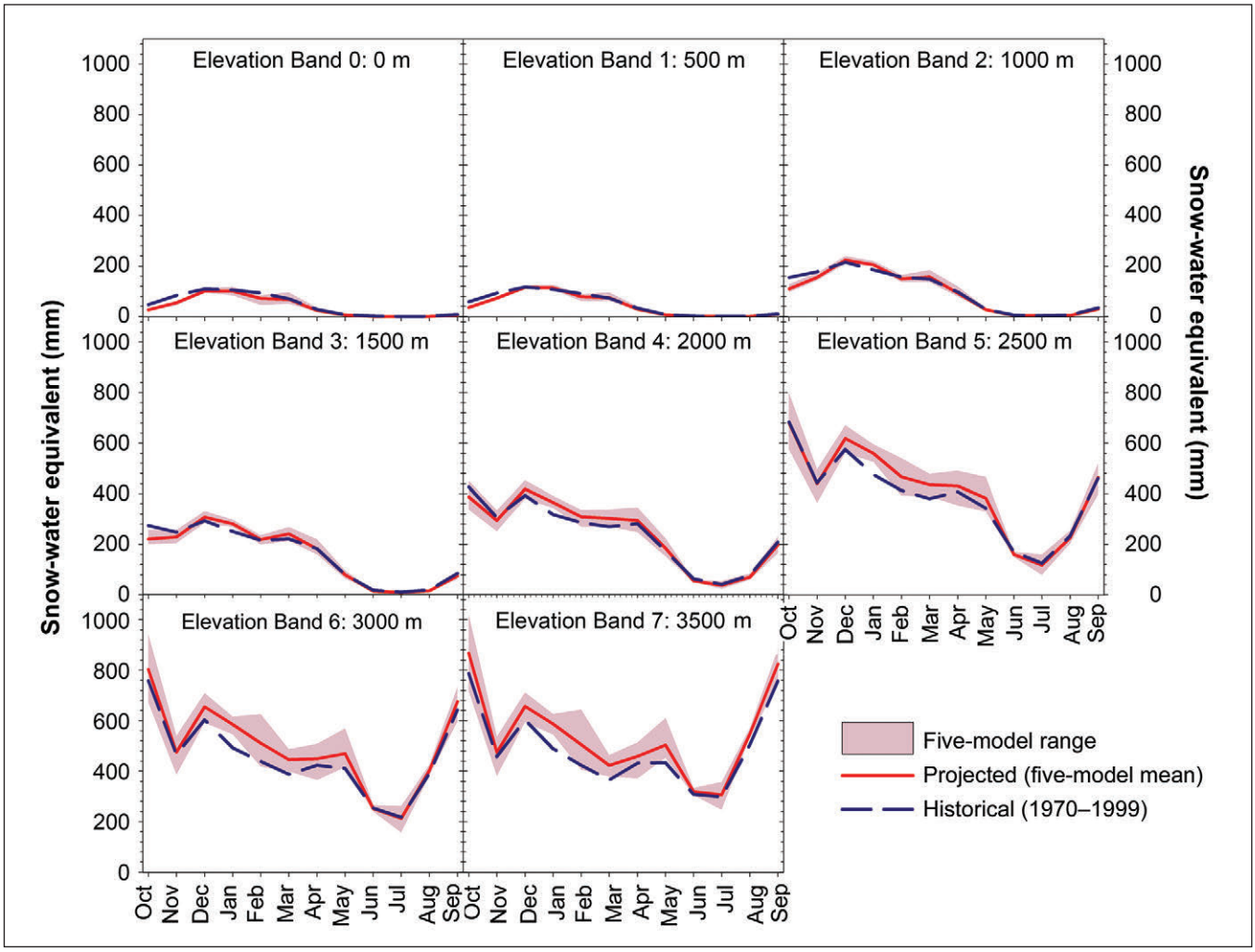


Figure 3-4—Historical (1971–2000) and projected (2030–2059) mean monthly snow-water equivalent (SWE) by elevation band for the domain of the Chugach National Forest Vulnerability Assessment. Months are in "hydrologic year" order, October to September. Blue line indicates the historical average; red line indicates five-model mean future average; pink area represents range of five future climate models. Seasonal decreases in SWE are consistent with snow-day fraction, including decreases in autumn at elevations of 1500 m and below, and possible increases in the winter months at elevations above 1500 m.

Table 3-2—Historical snow-water equivalent (SWE) (1971–2000) and percentage of change (five-GCM average, 2030–2059) by month and elevation band

	Month											
	October		November		December		January		February		March	
Elevation band	Historical SWE	Change	Historical SWE	Change	Historical SWE	Change	Historical SWE	Change	Historical SWE	Change	Historical SWE	Change
Meters	*Millimeters*	*Percent*	*Millimeters*	*Percent*	*Millimeters*	*Percent*	*Millimeters*	*Percent*	*Millimeters*	*Percent*	*Millimeters*	*Percent*
0 (sea level)	47	-45	84	-34	109	-8	105	-4	94	-24	70	-3
1–500	58	-38	93	-22	117	-1	107	7	91	-13	73	3
501–1000	155	-29	177	-13	215	4	184	11	156	-5	148	7
1001–1500	274	-20	247	-8	293	5	250	12	216	1	222	9
1501–2000	426	-9	307	-4	393	6	317	15	285	8	269	12
2001–2500	684	0	443	-1	575	8	475	18	412	13	380	15
2501–3000	758	6	465	2	603	9	492	19	438	17	387	15
>3000	787	10	457	4	603	9	489	20	423	20	365	16

GCM = global climate model/general circulation model.

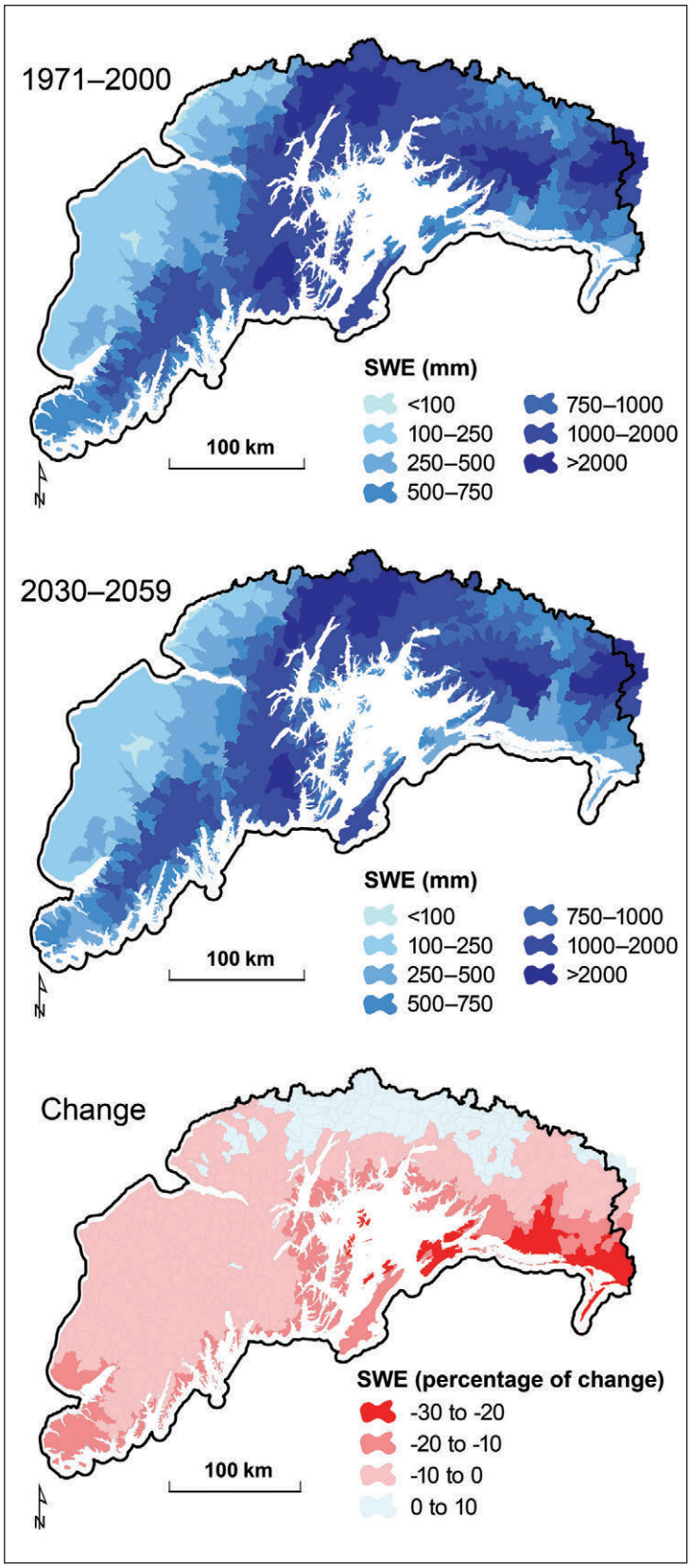


Figure 3-5—Historical (1971–2000, top) and projected future (2030–2059, mean of five GCMs, middle) October through March snow-water equivalent (SWE), with percentage of change (bottom).

Table 3-3—Historical snow-water equivalent (SWE), percentage of change, and five-GCM range for October to March season

	October through March		
Elevation band	**Historical SWE**	**Change**	**Model range**
Meters	*Millimeters*		*Percent*
0 (sea level)	509	-20	-36 to -4
1–500	539	-11	-22 to +1
501–1000	1035	-4	-13 to +7
1001–1500	1502	0	-9 to +10
1501–2000	1998	5	-7 to +16
2001–2500	2968	9	-5 to +21
2501–3000	3143	11	-4 to +25
>3000	3123	13	-3 to +20

GCM = global climate model/general circulation model.

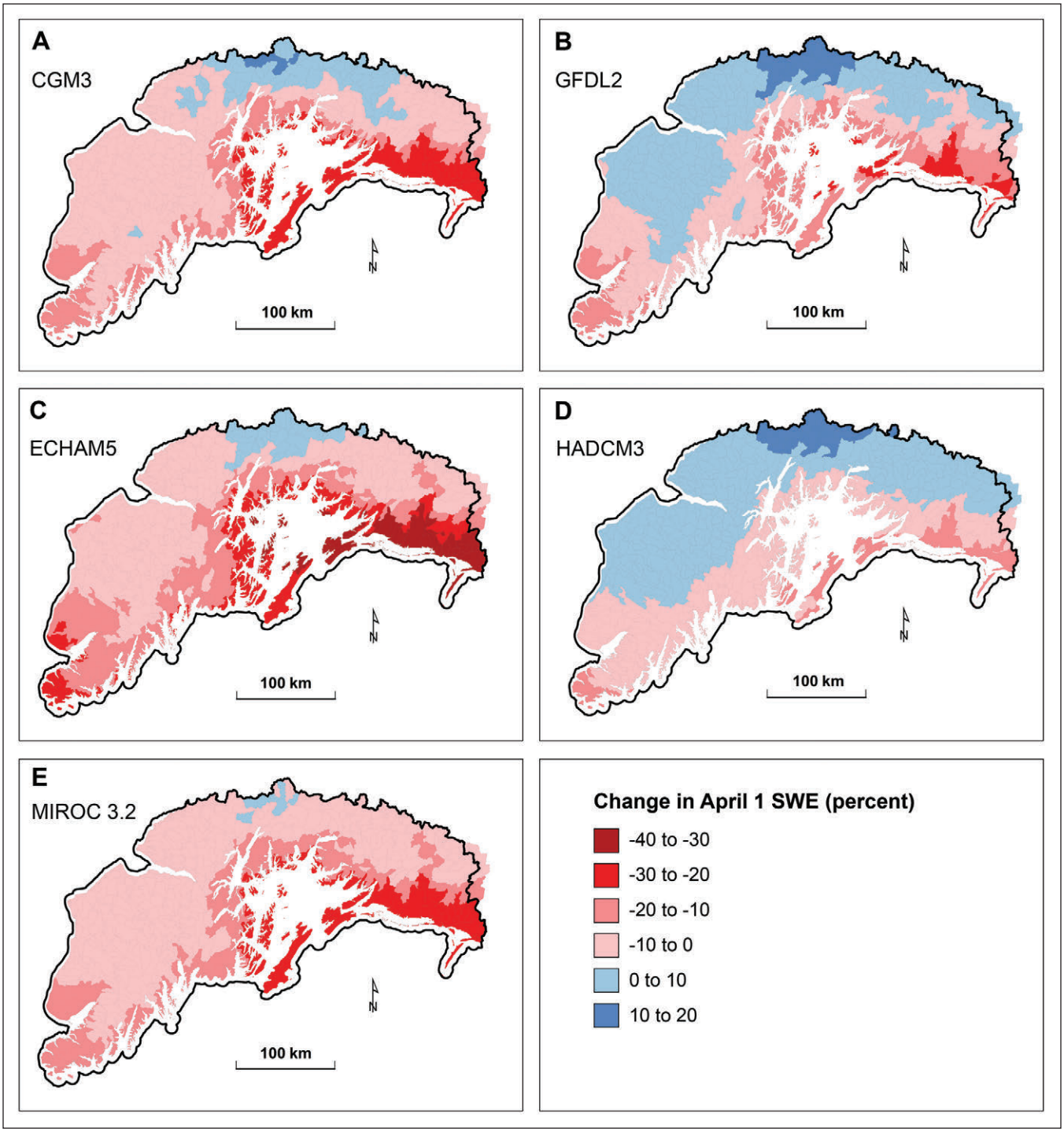


Figure 3-6—Projected changes in April 1 snow-water equivalent (SWE) (1971–2000 to 2030–2059) for five GCMs under the A2 emissions scenario: (A) CGCM 3.1; (B) GFDL CM 2.1; (C) ECHAM 5; (D) HadCM3; and (E) Miroc 3.2 MedRes. Note that the percentage values in the maps are the percentage of change from historical SWE.

Projected Effects of Climate Change on Snowpack Vulnerability in South-Central Alaska

Snow-water equivalent projections used in conjunction with precipitation projections allow calculation of an index of snowpack vulnerability (indicated by changing exposure to melt) to climate change (see Elsner et al. 2010 and Mantua et al. 2010 for details). This index is the ratio of April 1 SWE to the total precipitation between October 1 and March 31. Values of less than 0.1 (that is, 10 percent of the precipitation was entrained in snowpack on April 1) indicate a "rain-dominant" hydrology. Values between 0.1 and 0.4 indicate a "transient" hydrology, in which the annual hydrologic cycle is partially driven by rain and partially by snowpack. Values greater than 0.4 indicate a "snow-dominant" hydrology, in which snowmelt strongly affects the timing of peak flow.

We used two separate datasets to evaluate snowpack vulnerability. First, the University of Washington Climate Impacts Group (UWCIG 2012) developed historical (1950–2000) and future (2030–2059) temperature and precipitation outputs from the same five GCMs as Walsh et al. (2008), downscaled to 0.5° (about 65 km) over a domain of the entire North Pacific, and used them as input to the variable infiltration capacity (VIC) model (e.g., Liang et al. 1994) to estimate SWE. However, they developed these outputs for the SRES A1B emissions scenario, which arguably results in slightly less warming by the middle of the 21st century than scenario A2 used for the SNAP data above. Although the 0.5° products are ultimately too coarse to allow small (e.g., 12-digit hydrologic unit code [HUC]) watershed calculation and comparison, these projections can give a regional perspective on snowpack vulnerability using independent methods.

Second, we calculated the same snowpack vulnerability index for areas within the Chugach Vulnerability Assessment by using the calculations for SWE in the previous section in conjunction with SNAP's precipitation projections to calculate snowpack vulnerability index for the same gridded surfaces in the snow fraction and SWE analyses above, allowing smaller watershed comparisons.

In both cases, we calculated the snow vulnerability index (April 1 SWE/October to March total precipitation) for a 2030–2059 time period. Compared to historical data, the results from the UWCIG (2012) data averaged across all five future models for the Chugach vulnerability assessment domain suggest a decrease in the percentage of the landscape that is snow-dominant and an increase from 8 to 13 percent transient (63-percent increase) and an increase from 0 to 3 percent rain-dominant (table 3-4).

Table 3-4—Changes in landscape fraction of snowpack vulnerability index classes for the Chugach National Forest estimated from coarse (0.5°) downscaled GCMs

	Snow-dominant[a]	Transient[b]	Rain-dominant[c]
		Percent	
Historical	92	8	0
CCCMA-CGCM3.1 t47	76	16	8
MPI-ECHAM5	76	18	5
GFDL-CM2.1	76	18	5
UKMOHadCM3	84	16	0
MIROC3.2 medres	87	8	5
Five-model average	84	13	3

[a] April 1 SWE / ONDJFM PPT > 0.4.
[b] April 1 SWE / ONDJFM PPT between 0.1 and 0.4.
[c] April 1 SWE / ONDJFM PPT < 0.1.
Note: Rows may not add to 100 percent because of rounding.

Figure 3-7 shows the historical and projected future distribution of the index for each climate model using the SNAP data and the SWE calculated here. According to the finer downscaling approach that SNAP used, the historical condition of the HUC 12 watersheds Chugach vulnerability assessment domain was about 73-percent snow-dominated (>40 percent of October to March precipitation entrained in snowpack) and 27-percent transient (between 10 and 40 percent by area, with no rain-dominated watersheds. The five-model average future distribution is projected to be about 63-percent snow-dominated and 37-percent transient, still with no rain-dominated watersheds (table 3-5). The five GCMs vary considerably in their future proportion of the landscape in transient versus snow-dominated watersheds (fig. 3-7; table 3-5), with a lower estimate of snow-dominant watersheds at 55 percent (CCCMA-CGCM3.1 t47) and a higher estimate at 67 percent (UKMOHadCM3).

Of the 551 HUCs in the domain, 4 percent (23) shift from snow-dominated to transient, while none shifts from transient to rain-dominated or from transient to snow-dominated. Among historically transient HUCs, the average change in snowpack vulnerability index is about -0.04, but among the historically snow-dominated HUCs the average change is 0. This value, however, is misleading—the comparatively large increases (+0.4 to +0.8) in the historically most snow-dominated HUCs (at higher elevations and with SVI > 0.55; see fig. 3-8) cancel out the changes in other snow-dominated HUCs. For example, in figure 3-8, lower elevation HUCs become closer to rain-dominant, but below about 1200 m, a large number of HUCs becomes a class away from becoming transient.

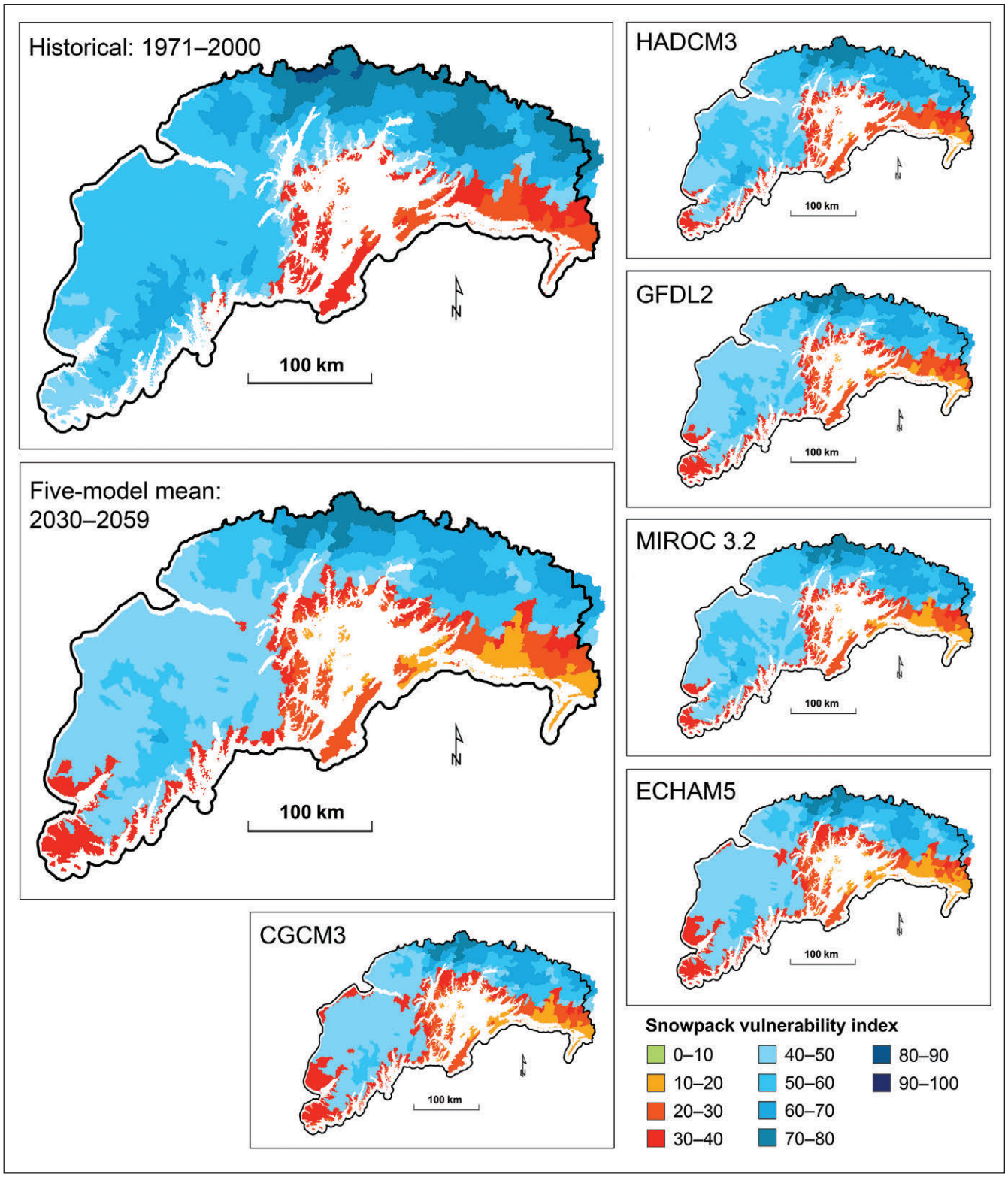


Figure 3-7—Projected changes in snowpack vulnerability index from SNAP historical (1971–2000) to 2030–2059) for five GCMs. Top left: historical; bottom left: five-model composite future; right, from top: HadCM3, GFDL CM 2.1, Miroc 3-2—MedRes, ECHAM 5, CGCM 3.1. Note that "red" is transitional, in which precipitation is a mix of rain and snow during the cool season, and orange indicates that precipitation is moving toward being rain-dominant.

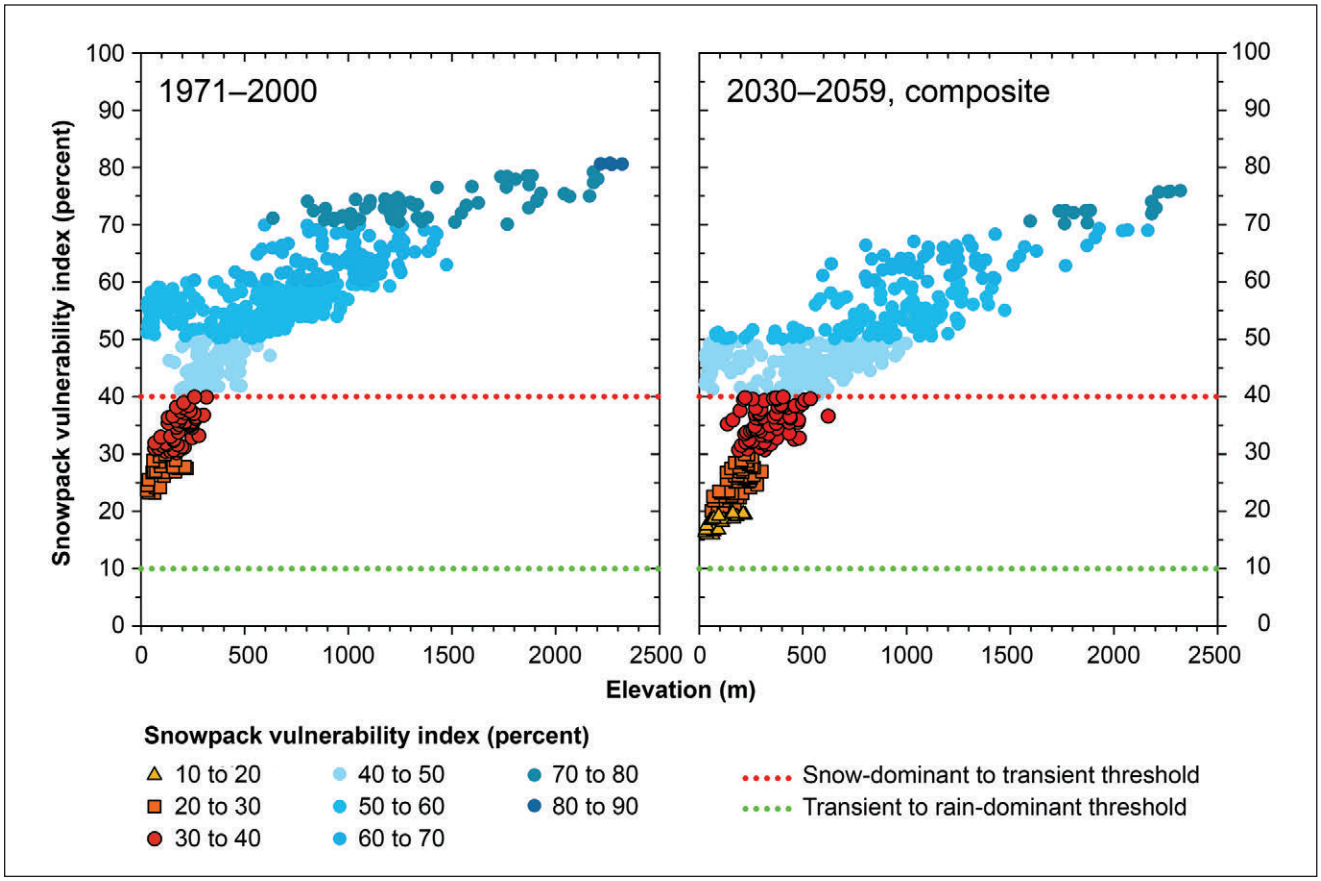


Figure 3-8—Snowpack vulnerability index for each Chugach National Forest domain hydrologic unit code by elevation for historical and projected future periods.

Table 3-5—Changes in landscape fraction of snowpack vulnerability index classes for the Chugach National Forest estimated from fine (800 m) downscaled GCMs

	Snow-dominant[a]	Transient[b]	Rain-dominant[c]
		Percent	
Historical	73	27	0
CCCMA-CGCM3.1 t47	55	45	0
MPI-ECHAM5	58	42	0
GFDL-CM2.1	64	36	0
UKMOHadCM3	67	33	0
MIROC3.2 medres	65	35	0
Five-model average[d]	63	37	0

[a] April 1 SWE / ONDJFM PPT > 0.4.
[b] April 1 SWE / ONDJFM PPT between 0.1 and 0.4.
[c] April 1 SWE / ONDJFM PPT < 0.1.
[d] Five-model averages are not the average of the rows above, but are calculated for each pixel in the domain, and thus are slightly different than the average of the five-model summaries presented here.

Limitations: Caveats and Uncertainty

Weather stations with long, complete, and well-documented historical climate observations are sparse in Alaska, especially above 500 m in elevation.

There are several important limitations on the future SDF, SWE, and snow vulnerability index projections. First and foremost, weather stations with long, complete, and well-documented historical climate observations are sparse in Alaska, especially above 500 m in elevation. The equations developed by McAfee et al. (2013) to estimate SDF from temperature data and the hydrologic modeling done by UWCIG (2012) were constructed almost exclusively from observations below 500 m because this is the only information available. In addition, the historical observations underlying them are sparser than a comparable area in more populated parts of North America. For example, for SDF, this translates to less certainty in the relationship between observed temperature and the probability of snow at higher elevations, particularly under conditions near freezing (0 °C). However, given that these higher elevations are areas with less projected absolute change in this analysis and are historically colder, this limitation probably does not affect interpretation of the results very much. If anything, the projections are likely to be conservative because the actual lapse rate in coastal areas is likely to be, at least when annually averaged, shallower than the gridded climatology-assumed environmental average lapse rate of 6.5 °C. Given the topography of the region and the lack of weather station data applicable to understanding the interactions between topography and storms, the spatial variability of the projections is also undetermined. The aggregation of the pixel values to watersheds and over multiple decades is a partial hedge on this uncertainty.

Second, near-term decadal-to-interdecadal climate variability is not well predicted, even though the climate models of the AR4 generation often simulate realistic variability at those time scales. In fact, decadal prediction is cutting-edge science in the most recent generation of climate models and is an active area of research. But it is likely that temperature trends projected for a future decade could be above or below the future observations because of natural climate variability. We have used a 30-year climatology in both analyses that should, given current knowledge, be relatively robust to such variations. In addition, the fact that the projection window (2030–2059) is before uncertainty regarding future emissions begins to exceed that of models or variability increases our confidence in these projections.

Third, the elevation bands used for the analyses are relatively broad. Under average environmental conditions, the temperature difference across 500 m of elevation is often around 3.3 °C and sometimes considerably more in drier climates or in some seasons. These elevation bands are used as averages across the study domain, and conditions at a location within an elevation band could be quite different from the average depending on local factors associated with topography, sea

ice, etc., and broad-scale factors such as the pixel or HUC's position east or west of Prince William Sound.

Finally, this analysis is not based on an exhaustive approach to future climate scenarios—these are plausible scenarios based on global climate models that have reasonable skill in simulating historical observed climate in Alaska at relatively broad scales. The process of downscaling them provides more physically tailored responses, but it does not resolve some local features and processes that are known to be important in the development and melting of snowpack. The strength of the projections is therefore at coarser spatial scales—watershed to regional, rather than pixel-by-pixel.

For these reasons, the projections presented here should not be viewed as predictions, but rather scenarios of the best available projected future conditions given current knowledge, capability, and resources.

Current and Future Ice and Glacier Response to Climate Change

Since 1950, Alaska has warmed 2 °C in winter and 1 °C in summer (Arendt et al. 2009). Although decadal climate variability explains some of this change, an increase in temperature is certain, is occurring throughout Alaska's weather station network, and is expected to continue with climate change (Stewart et al. 2013). Increases in temperatures have likely led to increased melt but have also led to higher elevation freezing levels and hence conversion of precipitation to rain from what historically would have been snow. Precipitation overall (rain and snow) is expected to increase slightly in the future, though it is not clear if this is happening currently. Only 17 percent of meteorological stations show an increase in precipitation; all others show no change (Arendt et al. 2009).

These changes in climate have contributed to a widespread loss of ice from glaciers throughout Alaska. Statewide, Alaska glaciers are losing 65 km^3 of ice per year on average, meaning that glaciers are losing far more mass to melt than they are able to gain though snowfall (Arendt et al. 2013, Larsen et al. 2015). This volume of ice lost annually is equivalent to more than a year of discharge on the Copper River. The rate of mass loss from year to year is not steady, however; variations in summertime temperatures led to annual losses of up to 125 km^3 in 2004 and even a mass gain of 15 km^3 in 2008 (Arendt et al. 2013).

Statewide, Alaska glaciers are losing 65 km^3 of ice per year on average, meaning that glaciers are losing far more mass to melt than they are able to gain though snowfall. This volume of ice lost annually is equivalent to more than a year of discharge on the Copper River.

Chugach National Forest glaciers are currently losing about 6 km^3 of ice per year, which is equivalent to melting a uniform 60 cm of ice across all glaciers in the Chugach (Berthier et al. 2010). However, these changes are not uniform (fig. 3-9). All non-calving glaciers within the Chugach are losing mass. Most of these glaciers are also retreating, and typically thinning at glacier termini by about 3 m/year

(fig. 3-9) (Larsen et al. 2015). These changes are consequence of warming summer temperatures (Larsen et al. 2015).

Changes in tidewater terminus positions are more complex. Since the 1950s, 10 glaciers have retreated more than 0.5 km, only Harvard Glacier has advanced more than 0.5 km, and the rest have displayed relatively little change (McNabb and Hock 2014). The length and pace of these retreats far outweighs the advances. In the last decade, Harvard, Yale, and McCarty Glaciers have gradually advanced despite losing mass overall (Larsen et al. 2015, McNabb et al. 2014). Most other glaciers have recently stabilized at retreated positions (McNabb and Hock 2014), but some fully retreated tidewater glaciers have continued to retreat up onto bedrock (therefore ceasing to function as tidewater glaciers), while others have begun a re-advance. Because most of these retreated glaciers still appear to be losing mass, it is more likely that they will remain close to their stabilized positions or retreat in the near future (warming climate) and less likely that these glaciers would re-advance.

Because Columbia Glacier is responsible for half of the Chugach glacial ice loss, its future evolution must be considered separately. The volume of Columbia Glacier has declined by approximately 50 percent in the past 35 years, in one of the largest scale calving retreats ever observed. Future iceberg calving is likely to remain significantly lower than peak levels (O'Neel et al. 2013) because of a large-scale reduction in ice thickness across the entire glacier. The glacier is bedded below sea level 15 km or more upstream of the current terminus, and best projections suggest about 20 years of continued retreat (Pfeffer et al. 2015).

O'Neel et al. (2014) analyzed mass balance and streamflow data from Gulkana and Wolverine Glaciers to show that both are losing mass as a result of stronger summer ablation. In the continental climate (Gulkana Glacier), positive streamflow anomalies arise primarily from negative annual mass balance anomalies. In the more complex maritime climate (Wolverine Glacier), streamflow has multiple drivers, including melt, and highly variable rainfall and snow accumulation. Although it is common to assume that discharge varies proportionally to annual mass balance for heavily glacierized basins, our data show that, in maritime climates, discharge is less coupled to annual mass balance than the delivery of mass balance to outlet streams as summer streamflow.

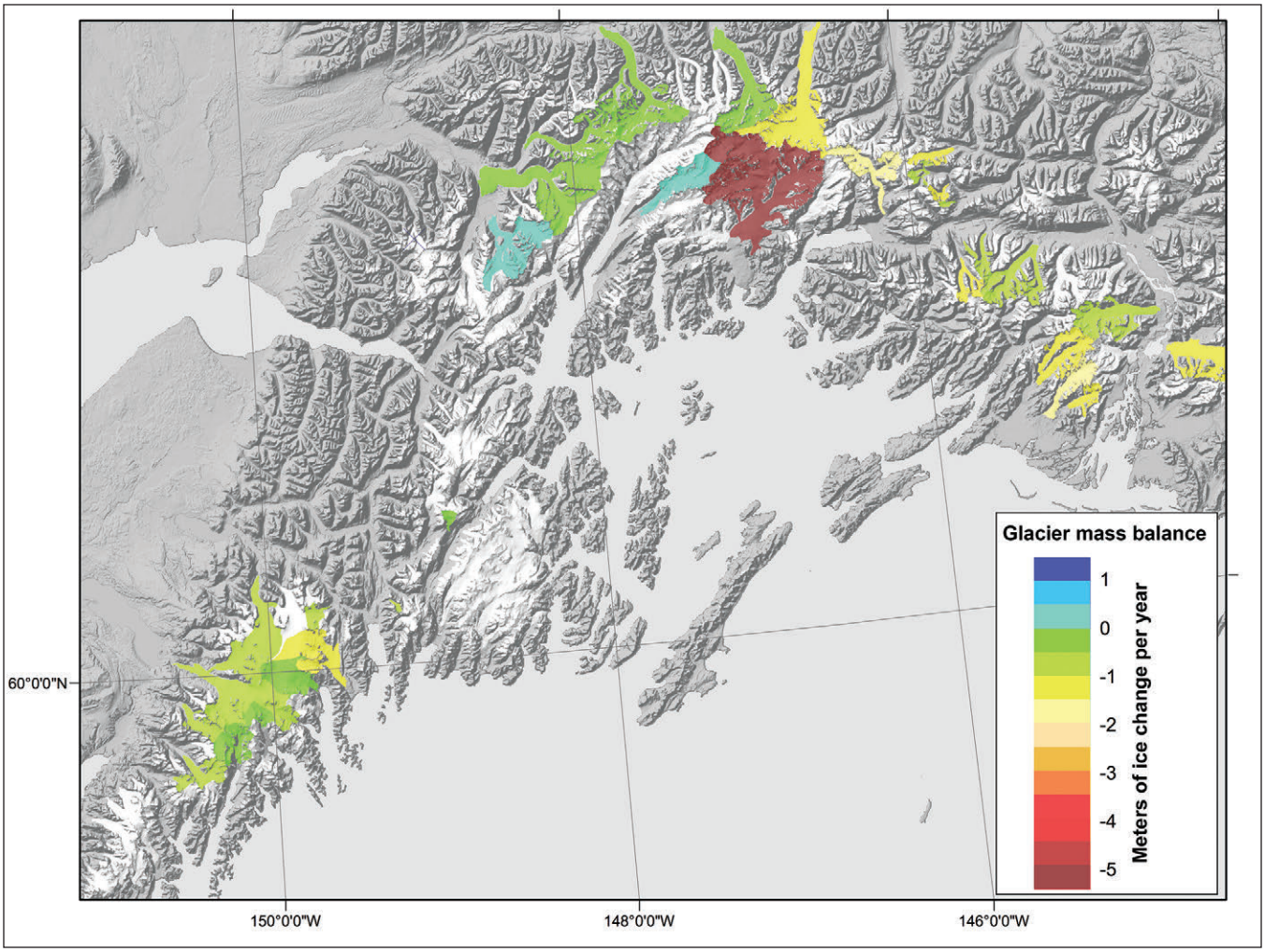


Figure 3-9—Volume of ice lost from glaciers in the Chugach National Forest. Surveyed glaciers are colored; unsurveyed glaciers are shown in white. Brick to green color indicates mass loss; blue indicates mass gain. Note that short survey time frames (2009–2012) do not yet capture trends for some of these glaciers (Larsen et al. 2015).

Case Study: Monitoring the Retreat of Exit Glacier

Deborah Kurtz, resource management specialist, National Park Service, Kenai Fjords National Park

Glaciers are a sensitive indicator of climate change. As temperatures warm or precipitation decreases, a threshold can be reached in which glacial ice is lost faster than it is replenished. This phenomenon results in a reduction of the ice mass; the surface elevation decreases as ice thins and the area diminishes as the ice margins melt or calve off. For many who observe glaciers, this is most apparent in the retreat of a glacier, resulting in an overall decrease in its length. During the Little Ice Age, a period (circa 1550 to 1850) of cool conditions in the Northern Hemisphere, many glaciers reached their recent maximum extent, and most have retreated since then. General trends in historical retreat rates can be reconstructed through physical clues in the landscape and analysis of historical photography. Past terminus positions can be determined based on recessional moraines, landscape features that were deposited during temporary stationary periods amidst an overall period of retreat.

Researchers at Kenai Fjords National Park have used a combination of these techniques to document the retreat and changes in the geometry of Exit Glacier.[6] Past terminus positions evident from recessional moraines were identified by Ahlstrand (1983), Wiles (1992), and Cusick (2001) using a combination of photogrammetry and field techniques such as tree-core analysis and radiocarbon dating. These recessional moraines date back to Exit Glacier's 1815 Little Ice Age maximum position. A series of aerial photography and satellite imagery beginning in 1950 provides additional documentation of the glacier's position. Until the mid-1900s, Exit Glacier was a piedmont glacier, meaning that its ice extended beyond the valley walls and spilled out into the relatively flat and unconfined valley floor. From photo documentation, we know that the glacier's shape changed dramatically from 1950 when it was a piedmont glacier to 1974 when the thinner, more pointed shape that is characteristic of a valley glacier was first documented.

In 1980, Kenai Fjords National Park was established, and park staff began direct observation of changes to the terminus (fig. 3-10). Photographic evidence reveals that, from 1983 to 1993, Exit Glacier experienced an advance and the glacier lengthened by 75 m (see footnote 6). A recessional moraine

[6] **Tetreau, M. 2005.** Exit Glacier recent history in simple terms. Unpublished report. On file with: Kenai Fjords National Park, 411 Washington Street, Seward, AK 99664.

resulting from the decade-long advance is visible on the outwash plain today. The glacier began retreating again in 1995. In 2006, park staff began documenting annual terminus positions with a global positioning system (GPS) and calculating annual rates of retreat. These data documented a recent shift in seasonal glacier movement as well. Although there was net annual retreat for these years, Exit Glacier advanced slightly during the winters 2005–2006 through 2008–2009. Beginning in winter 2009–2010, Exit Glacier has been retreating year-round.

Exit Glacier's overall trend of retreat is consistent with the retreat of glaciers around the world (WGMS 2008). Changes to glacier lengths, documented at Exit Glacier by the change in terminus position, appear in response to past climate conditions and mass-balance changes with a response time on the order of decades. Climate is not the only factor influencing terminus positions. Geometry, basal topography, slope, aspect, and microclimates also contribute to changes. The intermittent advance that was documented at Exit Glacier in the 1980s is not unusual among glaciers. ■

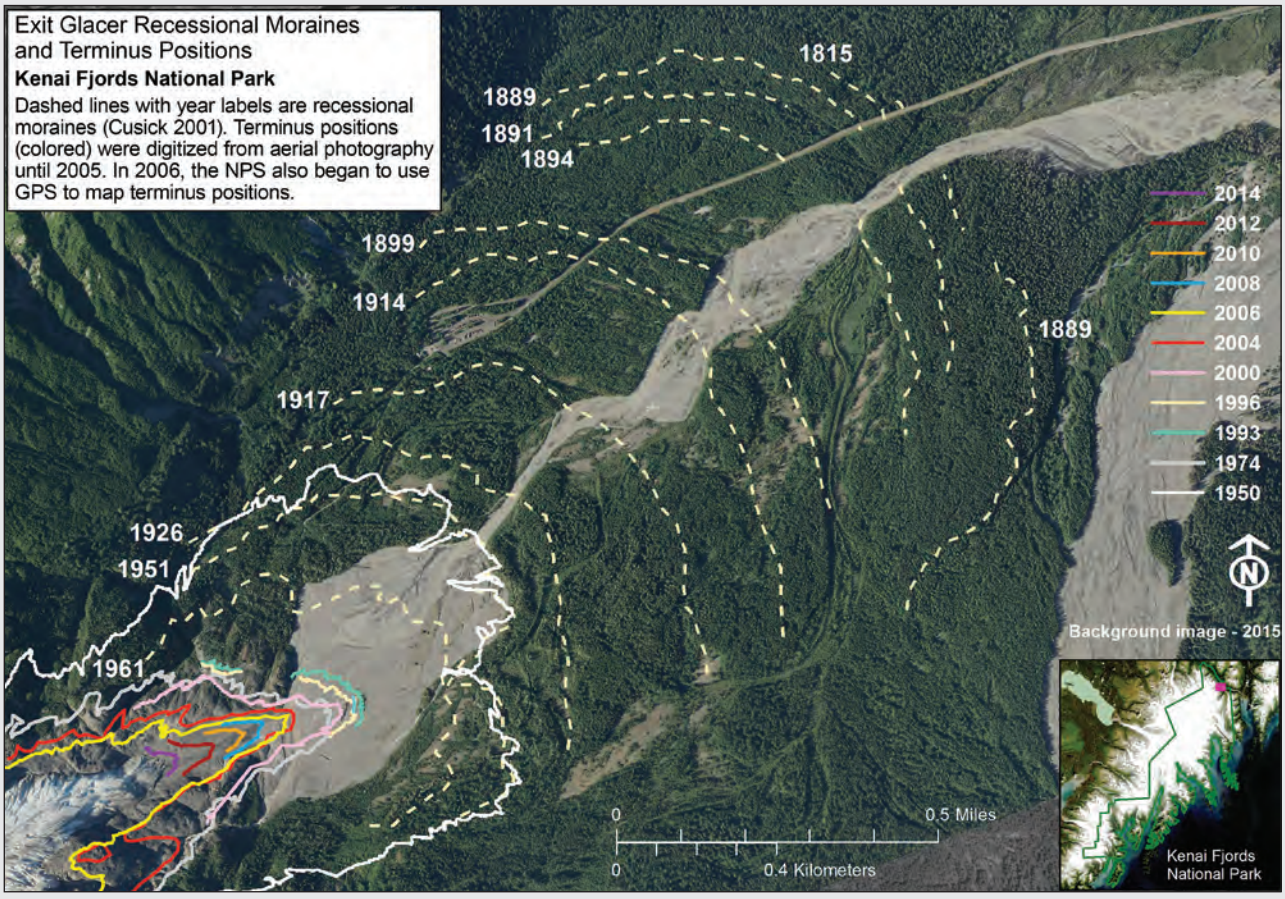


Figure 3-10—Pattern of glacier recession at Exit Glacier, Kenai Fjords National Park, from 1815 to 2009.

Case Study: Evaluating Glacier Change By Using Remote Historical and Current Remote-Sensing Tools

Linda Kelly, GIS specialist, USDA Forest Service, Chugach National Forest

Landscape photographs taken by early explorers and historical aerial photography provide records to evaluate multi-decade to century-long change in the surface area of individual glaciers. However, evaluating change in glacial cover for an entire region such as south-central Alaska over this same historical period represents a significant challenge. I explored existing maps, aerial photography, and geographic information system (GIS) tools to examine changes in surface area occupied by glaciers across the assessment area. After thorough evaluation, I found that existing information precluded estimating change with reasonable certainty at this broad spatial extent. Here I document my investigation to assist further investigation of glacier change.

The Randolph Glacier Inventory (RGI) (Pfeffer et al. 2014) version 3.0, released in 2013, represents a reliable source for estimating the current extent of glaciers in the assessment area (http://www.glims.org/RGI/). This GIS product is a global inventory of glacier outlines, supplemental to the Global Land Ice Measurements From Space (GLIMS) initiative. Glacier outlines were developed using satellite imagery. Uncertainty is estimated about ±5 percent based on comparisons with alternative inventories. To estimate glacier expansion or decline, I sought a source, or combination of source data, to map historical glacier extent for comparison with the RGI. I examined:

- Chugach National Forest timber type mapping which includes cover of icefields and snowfields (source data: 1:15,840 aerial photography dated from the 1950s–1970s)
- Chugach National Forest Geology GIS layer: source data 1:250,000 paper map, prepared by the U.S. Geological Survey (USGS) Branch of Alaska Geology, 1985.
- Chugach National Forest Landsystems GIS layer: source data 1:63,360 USGS 15-minute quadrangle maps, 1975, 1978, 1982, and 1983.

These three sources were rejected owing to their limited extent of mapping within the assessment area. I also evaluated the National Hydrography Dataset (NHD) (http://nhd.usgs.gov/) a digital vector dataset containing water features, including glaciers, maintained by the USGS for the National Map program. For Alaska, the source data was mapped at 1:63,360 scale. Source date for the NHD depends on the production date of the initial line work and

whether this line work was updated when Digital Line Graph files were created by USGS. Therefore, the vintage of the line work for Alaska varies from the 1950s to the present. Examination of the USGS topographic base maps used to form the NHD layer in the November 2012 product suggested that they result from aerial photographs taken in 1950 and 1957. My evaluation indicated that this GIS layer represented the most promising source to compare with the Randolph product.[7]

Therefore, I used the NHD (November 2012) and RGI (April 2013) to compare the area extent of glaciers and produce a display that illustrates areas of potential glacier change (fig. 3-11). The NHD data were expected to reflect a glacial area extent from an earlier time than the RGI, with a time span assumed to represent 50 to 60 years.

The Chugach National Forest 1950 and 1959 (1:15,840) black-and-white aerial photography set and 2008–2009 4-band orthophotography (60-cm resolution) were used to verify a sample of watersheds representing the greatest degree of change measured between RGI and NHD.

To examine potential sources of error in the comparison, the map in figure 3-11 was used to select areas of glacier change to validate with a backdrop of photography. The analysis suggested potential sources of error leading to unreliable estimates of glacier expansion and loss. The most significant source of error displayed as examples in figures 3-12 and 3-13 represent errors in mapping glacier boundaries in the NHD. The area of glacial extent is less credible in the NHD than in RGI.

In conclusion, using differences in NHD and RGI to detect changes in the extent of glacial boundaries to measure effects of climate change should proceed with caution and careful validation that employs alternative sources such as aerial photographs. Mapping employed in NHD failed to include some glacial features that were large enough to meet standards for the size of features that should have been captured. In addition, the finer detail of other features was simplified, such that the area mapped as glacier was less extensive, leading to potential errors in estimates, particularly of increased glacier cover in NHD/RGI comparisons. The standard of the NHD feature capture was not consistent across the study area. On the other hand, RGI

[7] The NHD data were from a data download from USGS NHD in November 2012. The Randolph Glacier Inventory data have since been used to update glacier features in NHD, replacing the previously mapped areas of glacier polygon features in the Waterbody dataset. Any current NHD downloads would no longer allow this type of comparison.

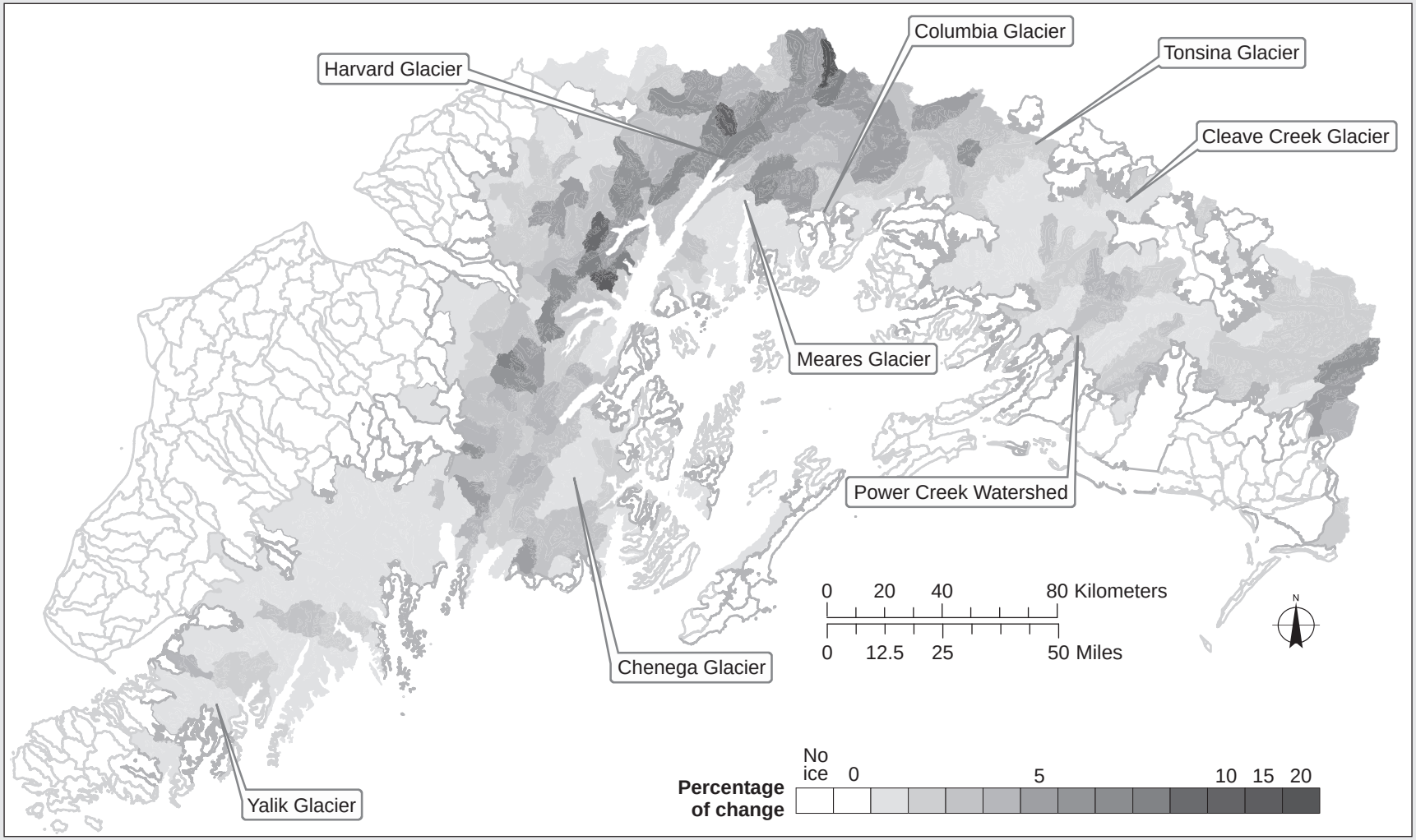


Figure 3-11—Difference in the spatial extent of glaciers mapped using the Randolph Glacier Inventory (RGI) and National Hydrography Dataset (NHD). Here, watersheds are classified by the extent to which RGI indicates that ice is present and NHD indicates that ice is not present. Interpretation of this difference might suggest that glaciers may be advancing, which has been documented for Harvard and Mears Glaciers but is questionable in other places. Map by Linda Kelly, USDA Forest Service.

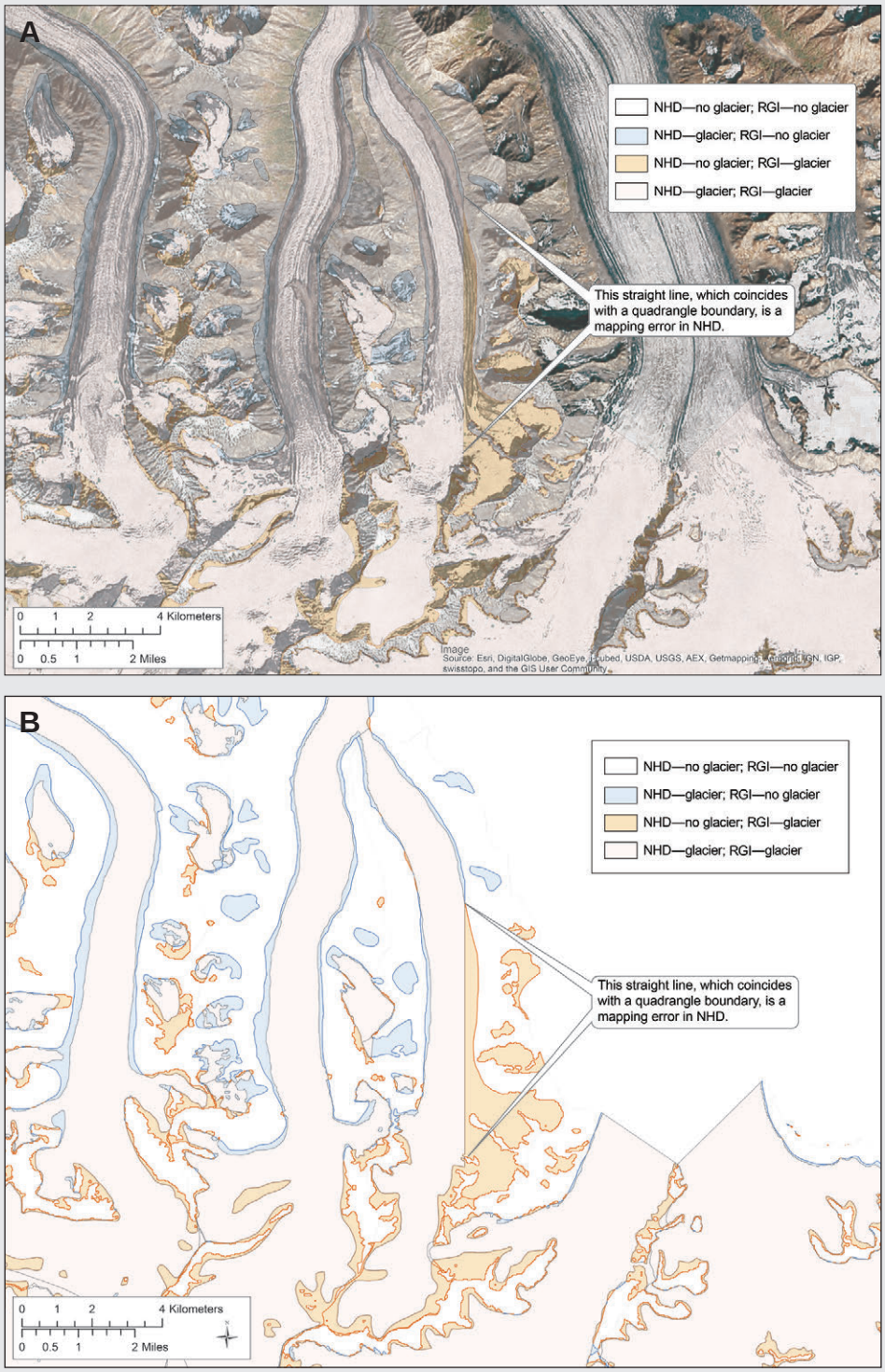


Figure 3-12—Tarr Glacier watershed, illustrating an approach to validating differences in glacial extent, measured using Randolph Glacier Inventory (RGI) and National Hydrography Dataset (NHD) data: (A) overlaying a photography base, and (B) with the data only. The differences between the mapped glacial margins illustrate an occurrence in which a programmatic comparison falsely suggests glacier expansion resulting from mapping errors. Map by Linda Kelly, USDA Forest Service.

more frequently misclassified glacial features along rocky ridges and very steep slopes, particularly shadowed slopes, which NHD tended to correctly interpret as rock in areas where I compared both datasets to photographic sources. My evaluation of NHD and the resulting comparison of NHD with RGI correctly identified the three cases of advancing tidewater glaciers: Harvard and Surprise Glaciers in the College Fjord area and Mears Glacier in north-central Prince William Sound. This suggests some value in cautious use of these tools to examine glacier change. Using NHD and RGI to detect recent ice expansion was mainly useful for selecting areas for further examination. I caution against estimating

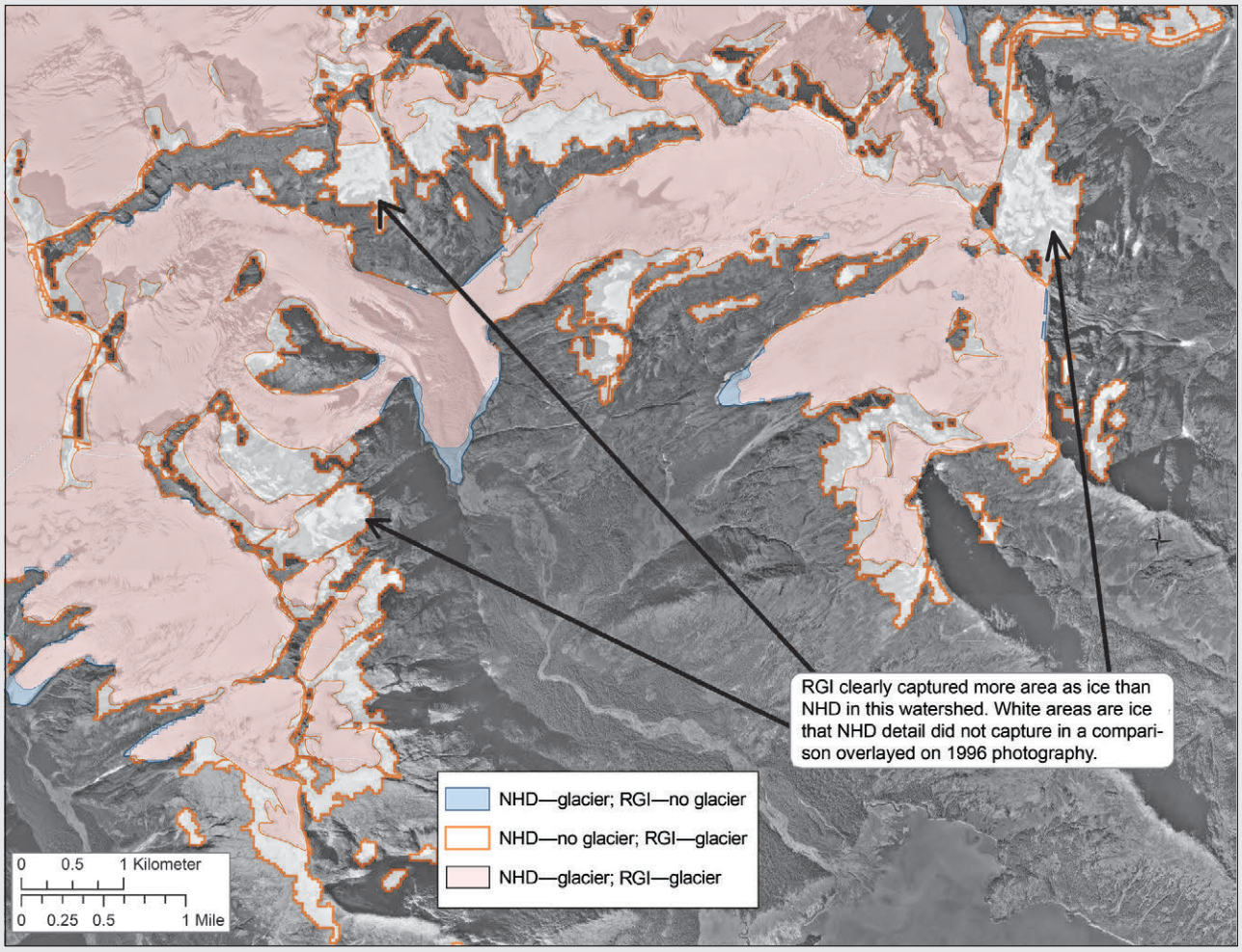


Figure 3-13—Pigot Glacier watershed, illustrating an approach to validating differences in glacier extent measured using Randolph Glacier Inventory (RGI) and National Hydrography Dataset (NHD) maps employing black-and-white photography from 1996. The RGI maps 15 percent more glacial extent than the NHD, but this difference largely results from errors in NHD, in which there was a failure to map some glacial features. Map by Linda Kelly, USDA Forest Service.

differences in the two datasets for broad measures of increase in glacial extent. In conjunction with validation, local areas can be evaluated.

Comparison of NHD and RGI information can adequately detect retreat along the margins and valley edges of glaciers. Based on my broad evaluation of glacial extent from NHD and RGI, the greatest loss of ice surface area in the domain of our assessment was associated with Columbia Glacier, Miles and Allen Glacier in the Copper River system, and Bear Glacier in Kenai Fjords National Park (fig. 3-14). ■

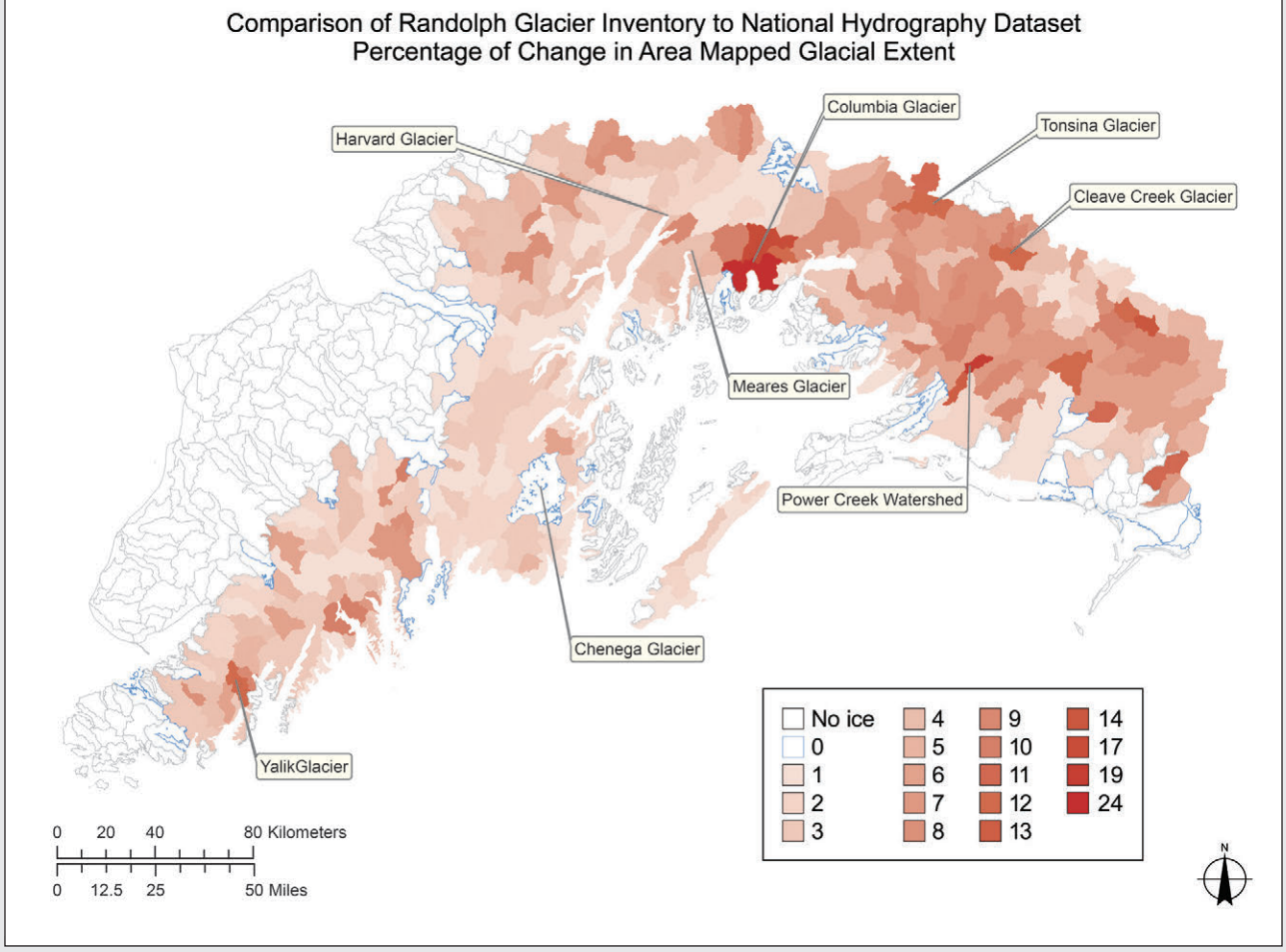


Figure 3-14— Estimation of ice loss resulting from comparison of Randolph Glacier Inventory (RGI) and National Hydrography Dataset (NHD) products at Columbia Glacier and surrounding areas. Verification with photography suggests that the pattern of ice loss illustrated by comparing RGI and NHD in this case is valid.

Snow and Ice: Effects on Ecosystem Services

Introduction and Conceptual Framework

In this section, we consider how the findings discussed above—especially higher elevation average snowlines and fewer average snow days—might affect the ecosystem services related to tourism, recreation, and visitation of the study area.

Our approach is to treat the natural resource interaction with humans in their roles as producers and consumers as a complex social-ecological system (SES). Snow- and ice-dependent tourism and recreation are a subsystem within this SES. So, too, are specific activities such as heli-skiing. This kind of analysis is relatively

new. Previous analyses (notably Haufler et al. 2010) have considered the implications of climate change on broader ecosystem services. However, as one of the few published papers focusing on the human dynamics of the tourism industry notes, "While tourism and the environment has been studied extensively… the concept of resilience as a means to understanding the impact of disturbances or stress on a system has rarely been used…" (Becken 2013).

Although that paper uses resilience rather than vulnerability as the organizing concept, the general point about such analyses being relatively new still applies.

It is challenging to isolate the effects of climate change on the SES and relevant subsystems because they are affected by numerous other shocks, stresses, and forces of change. As Becken (2013) put it, "The emphasis on present and future **climatic disturbances** allows for a focused analysis; however, it is important to note that tourist destinations experience a wide range of **other stress factors** simultaneously" (Becken 2013) (emphases added).

Some of these other stress factors include global and national market forces and prices, changing technology and preferences (e.g., the rise of snow bicycling), and key decisions taken by major industry players (cruise lines, Alaska Railroad) and government agencies.

The stability landscape concept (Walker et al. 2004) provides a useful framework for this discussion. Each subsystem is currently within a relatively stable state known as a basin of attraction. Each basin has a single "low point" toward which the subsystem tends absent any disturbance. The **latitude** (L) of the basin is a measure of how much the subsystem can be disturbed before it leaves the basin. For example, summer boating and sea kayaking in Prince William Sound have very wide latitude with respect to warmer temperatures. The **resistance** (R) of the system is a measure of how sensitive it is to perturbation. For example, if snow at high elevations remains dry despite average temperature increasing by 4 °C, this would be high resistance. Finally, the **precariousness** (Pr) of the subsystem is a measure of how close it is to a tipping point or threshold. For example, a ski area that has had several mediocre seasons because of economic recession might have very low cash reserves, and thus be precariously close to going out of business after a bad snow year.

These concepts make more sense when combined into a summary such as this one: social-ecological systems can be close to, or far away from, important thresholds (Pr). They can be easy or hard to change (R). The range of dynamics that can be accommodated while still retaining basically the same system can be large, or small (L). (Walker 2004: 7)

The disturbances affecting the stability landscape are also usefully characterized as "slow" vs. "fast" changes (Carpenter and Turner 2000). The Alaska economy and its tourism industry are subject to the "fast" influences of crude oil prices, national or global economic recession, and weather. Climate change operating to raise the snowline over 50 years is a "slow" change, as is an aging and growing resident population. Similarly, humans can respond with "fast" adaptations such as postponing a trip or drawing on financial reserves. But over "slow" time scales, regions within Alaska, and Alaska itself, can become significantly less unique or less preferred as a destination by both residents and tourists.

Affected Ecosystem Services

The snow- and ice-related ecosystem services most likely to be affected in ways that influence the recreation and tourism subsystems of the Chugach-Kenai SES are:

- Reliably deep snow
- Reliably dry snow
- Reliably accessible snowpack
- Stable (meaning storm-free) weather.

As a general proposition, there is one general threshold of greatest interest; the change from snow to rain or from sub-freezing to above-freezing temperatures.

The dearth of snow during the 2014–2015 winter season demonstrates that snow levels have significant economic and social consequences for the people and businesses of the Chugach-Kenai region.

Deep snow—

The dearth of snow during the 2014–2015 winter season demonstrates that the presence or absence of snow has significant economic and social consequences for the people and businesses of the Chugach-Kenai SES. Ski areas were shut down (Edge 2014, 2015) and backcountry skiing was limited or nonexistent (Hollander 2014). Dog races were moved (Alaska Dispatch News 2015).

Although it is generally recognized that snowfall is volatile, and most businesses can shrug off an occasional bad snow season, as long-term averages change **or as expectations change**, people may begin to substitute other options for snow-dependent activities in specific places. For example, Hatcher Pass, approximately 50 km north of Anchorage, can be thought of as the place where Anchorage skiers may go when all else fails. It is a good example of economic substitution within a range of specific ecosystem services in specific places. It costs more time and fuel to get there, so only the more ardent skiers make the trip. However, it may be that Hatcher is the "substitute of last resort" for some people; even the fear that it may be dry could cause further substitution out of Alaska altogether.

Dry snow—
Dry snow is the ecosystem service that supports powder skiing and arguably separates Alaska in the marketplace from the Pacific Northwest, and certain other skiing destinations. There is some evidence that heli-skiing is already shifting northward or out of the Kenai Peninsula. The Chugach Powder Guides website (http://www.chugachpowderguides.com/trips) lists only the Girdwood/Alyeska and Seward/Pacific Coast areas as specific skiing zones. Although there is currently no direct evidence to support the proposition, it seems reasonable to speculate that as the study area snowpack becomes wetter on average, it will be less desirable as a destination for both Alaska residents and nonresident visitors.

Access to snow could become a concern as the snowline rises. Existing trailheads could become "stranded" below sufficient snow for recreational access.

Reliable access to snowpack—
This ecosystem service is a function of the elevation of snowline and whether existing trailheads provide access to snow. People can walk to reach skiable terrain (as they famously do in New Hampshire) but snowmachines cannot travel long distances over dry land, and regulations limit snowmachine use when snowpack is shallow. The findings above suggest that access to snow could become a concern as the snowline rises. Existing trailheads could become "stranded" below sufficient snow for snowmachine access. Users would naturally seek out other access points that still connect with snow, resulting in potential crowding and other consequences.

An obvious adaptation response is to extend trailhead access to reach higher snowlines. Although this may be impractical for existing trailheads, new ones could be planned over a 10- to 20-year horizon to accommodate an ascending snowline.

Storms and storm-free weather—
Storm frequency and intensity could also negatively affect visitation. Tour operators must build potential storm-related interruptions into their planning and revenue projections, much as businesses must plan for a certain percentage of bad debts, or concert promoters must plan for cancelled shows. Insurance markets could emerge or expand to address these concerns, with the overall effect being an increase in the cost of supplying "good-weather experiences." There could also be a decrease in demand if customers are forced to bear the risk of cancellation or postponement. Both producers and consumers of recreation and tourism experiences will share the burden of disruptions. Exact allocation will depend on market conditions, but the overall effect of more storms and extreme weather will likely be to reduce the quantity of tourism excursions and experiences, and to increase the prices paid.

Substitution in the face of change—
Within limits, there is substantial scope for substitution of locations and activities within south-central Alaska. In this respect, the latitude (L) of the stability landscape is reasonably wide for winter recreation and tourism as a regional or statewide activity and business sector. Backcountry skiers and snowmachiners can migrate north, seeking drier or more accessible snow. Snowmachiners in particular may simply go higher within existing terrain, assuming they can still gain initial access to the snowpack. Some people will substitute hiking for skiing. However, there will be a loss of quality or recreation value; if not, these shifts would already have happened. Furthermore, some substitution among recreation opportunities may also be negatively influenced by changing climate. For instance, a shift from skiing to rafting may be limited if changes in precipitation reduce streamflow patterns such that the season of rafting is constrained.

If the quality and cost of recreational opportunities in the Chugach-Kenai region shift in ways that favor other winter recreation areas closer to large population centers, then some nonresident tourists are less likely to make the long trip to Alaska and more likely to fly to places like Utah. Similarly, some Alaska residents—referred to by economists as those "at the margin"—may substitute a backcountry ski trip in British Columbia for a ski trip within the Chugach-Kenai region. Although these kinds of substitutions may be relatively rare, each one will have a much larger economic impact than simply shifting recreation locations within south-central Alaska.

Maintaining Ecosystem Services in the Face of Climate Change

Many of the same measures to stabilize infrastructure that are currently used, such as erosion control, will be needed all the more under wetter, warmer scenarios. Therefore, the consequences of climate change further reinforce the rationale for existing management strategies for trail maintenance. However climate change in the form of more rain may overwhelm existing practices; hence one might say that current methods to control erosion may leave the trail system and other infrastructure more vulnerable to damage (an example might be the Resurrection Trail near Exit Glacier).

It is possible that some activities on the forest could be managed more flexibly if the goal was to maximize ecosystem services from snow. For example, the current alternating-year openings of the Resurrection Trail system to snowmachines might be adjusted to reflect snow conditions: if there is a good snow year, there could be a special opening for snowmachines during a nonmotorized year, and vice versa. This kind of regime is already practiced for personal use and commercial fisheries.

Maintaining Recreation and Tourism Subsystems

When specific ecosystem services (snow) cannot be retained because of climate change, it may still be possible for the human activities and the associated economic livelihoods to shift, just as species can potentially move with shifting habitat. There are already mechanisms (e.g., cash reserves) available to accommodate short-term "shocks" to snow-dependent activities. Such mechanisms are mentioned in the tourism literature as being important to operators. For example, Biggs (2011) reported that based on survey data:

- Reef tourism enterprises indicate that financial and marketing support are the most important actions that government can take to support enterprises in the face of a large shock.
- Snowmaking is a longer term reaction to uncertain snowfall, which of course depends on water resources and sufficiently low temperatures. Adding summer-activity infrastructure is another strategy already adopted by many U.S. ski areas. One could perhaps think of the underlying "ecosystem service" as terrain rather than snow.

The tourism industry and resident recreation patterns have changed dramatically in the Chugach-Kenai SES during the past 20 years (Colt et al. 2002). These changes reflect shifting socioeconomic driver variables and an upsurge in entrepreneurial effort directed at providing nature-based tourism as a commercial product. The rapid deployment of people and capital seems to be a hallmark of these activities. Tourism businesses and their employees can and do move in response to changing conditions. Although it is probably outside the management purview of the Forest Service to directly assist with this process as it is carried out by individuals, there may be a scope for easing transitions and accommodating change by focusing more on forest users and tourism businesses and less on the ecosystem services themselves. One example of this approach might be a more flexible fee structure for special-use permits that recognizes the increased economic risk of running a snow-based business in the region.

Almost all the developed recreation facilities are found between sea level and 1500 m of elevation, where projected changes to snow-day fraction, snow-water equivalent, and snowpack vulnerability are the greatest.

Consequences of Potential Change in Snow and Glacier for Recreation Infrastructure

Changes to snow and ice, of all the biophysical changes evaluated in this vulnerability assessment, have the greatest potential to affect the condition of, and demand for, Chugach National Forest recreation infrastructure, particularly changes in snowfall and snowpack. Almost all the developed recreation facilities, which include cabins, campgrounds, day-use sites, trailheads, and the roads and trails

that provide access to them, are found between sea level and 1500 m of elevation, where projected changes to SDF, SWE, and snowpack vulnerability are the greatest. In Prince William Sound and the Copper River Delta, all recreation sites, trails, and roads are located between 0 and 500 m in elevation, with most close to sea level. Currently, recreational use on the Chugach is managed as snow-free (May 1–November 30) and snow-based (December 1–April 30) seasons. Where over-snow motorized vehicles are allowed, there must be adequate snow levels and conditions to prevent damage to vegetation and soils.

Impacts to Facilities

Snow and ice have resulted in damage to facilities in the past, including two cabins that sustained structural damage during heavy snowfalls in the winter of 2011–2012. Scenarios described above suggest that at elevations below 1500 m, snow may put less pressure on structures across the Chugach, especially cabins along the coastline in Prince William Sound and the Copper River Delta. At the same time, a decrease in SDF, especially in October and November, may extend the season of use for snow-free activities on trails that remain snow-free for a longer period of time. Trails popular for hiking, mountain biking, and pack and saddle use may also be vulnerable to ruts, trail widening, and other impacts to trail tread owing to a longer period of muddy conditions if rain replaces snow more often during the year. Where models project a possible change from snow-dominant to transient hydrology, mostly along the coastline in Prince William Sound and in the Copper River Delta area, these changes may effect trail and trail bridge infrastructure depending on how nearby streamflow is affected.

Purpose or Draw to the Facility

Facilities that primarily support snow-based recreation or include glacier viewing would see the biggest change resulting from projected declines in snow days, SWE, and greater snowpack vulnerability, especially early and late in the winter season. The Turnagain Pass facilities are the clearest example, as the two parking areas see more use in the winter as a backcountry skiing and snowmachining destination. Although skiers could still use the site to access higher elevations on foot, snowmachines could not do the same. Approximately 32 km of trails on the Chugach are exclusively snow trails, all below 1500 m in elevation. These trails may see less use, especially where motorized use is currently popular. Also, local volunteers have started to groom Russian River and Trail River campgrounds for Nordic skiing in the winter, an activity that would see a shorter season and more inconsistent conditions throughout the winter.

The Spencer Glacier Whistle Stop in the Kenai Mountains and Childs Glacier Campground along the Copper River were developed primarily for glacier viewing. Looking at projections in glacial retreat and thinning, these sites could face a similar situation as the Begich, Boggs Visitor Center (BBVC), where viewing Portage Glacier from the theater was the main draw. The glacier has been retreating for decades and is no longer visible from the BBVC. Because of this, as well as many other factors, visitation to the BBVC has declined from over 300,000 in the 1990s to around 70,000 in 2013.

Almost all the campgrounds and day-use sites, including picnic areas, campsites, trailheads, and boat ramps, are adjacent to the Seward, Sterling, Portage Glacier, and Copper River Highway. Turnagain Pass, at milepost 68 of the Seward Highway, is the highest point on this road system at an elevation of just over 300 m. Campgrounds and most day-use sites are primarily used in the snow-free season, especially between Memorial Day and Labor Day. Thus, the type and amount of use at these facilities is unlikely to see significant changes, though the shoulder seasons of use could potentially be extended later in the fall.

Access To Facilities

Similar to changing patterns of the use of recreation sites, access to and from sites that depend on adequate snow conditions will be the most adversely affected, though no facilities and only about 32 km of trail are used exclusively for snow-based recreation. On the other hand, where deep snowpack limits access or increases the challenge of using a facility, the season of use may expand. Cabins in Prince William Sound and Copper River Delta areas may be easier to access and could see an increase in use with less snow, though snow is not the only limiting factor for use of these facilities. For instance, it still may not be desirable to be out in Prince William Sound in winter months when weather and seas are unpredictable. The cabins along Resurrection Pass Trail are popular in winter both for skiers and snowmachiners; poor snow conditions make access by these means more difficult or impossible.

Management of most recreation facilities on the Chugach National Forest will be able to adapt to projected changes in snow and ice, because very few are used exclusively for snow-based activities.

Adaptive Capacity

Management of most recreation facilities on the Chugach National Forest will be able to adapt to projected changes in snow and ice, because very few are used exclusively for snow-based activities, and the vast majority of facilities are used more heavily in the snow-free months, especially between May to September. It is difficult to anticipate potential trends of snow-free activities, though, because multiple factors help make facilities popular at a given time during the year, and current

understanding of the behavior of recreationists is insufficient to make reasonable predictions. Thus, just being snow-free may not necessarily increase use. Overall, it is likely that facilities supporting winter, snow-based recreation will see a more significant decline in use than any corresponding increase in the use of infrastructure supporting snow-free recreation.

The least adaptable infrastructure would be motorized snow trails, because these are not used when snowpack is limited or inconsistent. At Spencer Glacier and Childs Glacier, summer recreation may still be popular and the potential to use facilities there does not change, but they may not have the same allure, and visitors may be less likely to spend the money and effort to get to these remote locations.

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Phil Hayward



Picturesque Cove on the west bank of Culross Passage, Prince William Sound, Alaska.

Chapter 4: Seascapes

Andrew Erickson,[1] Claire Colegrove,[1] and Aaron Poe[2]

Summary

- The Chugach National Forest/Kenai Peninsula coastline stretches for 6260 km, including islands and Prince William Sound.
- Coasts and marine environments within the assessment area receive heavy human use from tourism, fishing, and local economic activity. Understanding how coastal environments will be affected by climate change is important for land management planning.
- Important abiotic effects of climate change on the coastal environment include sea-level change, glacial changes, and ocean acidification.
- The current trend for the region shows sea-level decline at rates of up to a fraction of an inch per year, resulting in changes to tidal marshes and barrier islands.
- Prince William Sound receives up to 50 percent of its freshwater discharge from glacial runoff, indicating that changes to the region's tidewater glaciers will have profound effects on the coastal environment.
- Cold ocean temperatures make Alaska's oceans particularly vulnerable to ocean acidification. Cold arctic waters dissolve carbon dioxide (CO_2) readily, which results in acidification. Biotic communities in Prince William Sound, the Copper River Delta, and the Kenai coast may be resilient (over the short term). Systems in this region experience highly variable physical and chemical conditions owing to seasonal freshwater influx.
- Important biotic effects of climate change include harmful algal blooms, changes to eelgrass beds, and effects on shorebirds.
- Warmer waters and glacial melt may exacerbate harmful algal blooms, which pose a threat to shellfisheries in the assessment area.
- Eelgrass beds are abundant within the assessment area and are susceptible to changes in water depth and to human-caused disturbances.
- Prince William Sound and the Copper River Delta, two of the most visited stopover locations for migrating shorebirds, are vulnerable to loss of mudflats caused by sea-level change.

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Introduction

The assessment area is predominantly a coastal landscape. Its 6260-km shoreline encompasses Prince William Sound and numerous islands, connecting the upland forest ecosystem to the Pacific Ocean through rocky beaches, marsh tidelands, eelgrass beds, and tidewater glaciers. As an important part of the Chugach/Kenai landscape, the coastal ecosystem deserves significant attention from the region's scientists and policymakers.

Although this dynamic coastal landscape (Harwell et al. 2010) is accustomed to extremes in physical conditions—it frequently experiences powerful storms, extremely variable wave action, seasonal changes in weather, and many other stressors—climate change presents the potential continuing directional change in the ecosystem (Haufler et al. 2010). Climate-induced abiotic changes (including ocean acidification, increased air and ocean temperatures, altered precipitation patterns, and dynamic sea-level conditions) are likely to affect coastal environments (Ainsworth et al. 2011, Melack et al. 1997). As outlined elsewhere in this assessment (see chapter 3), snow-and glacier-covered portions of the assessment area are currently experiencing altered temperature and precipitation patterns, resulting in changes to seasonal snow cover and glacial extent. The directional changes in abiotic factors are likely to affect biotic characteristics of the Chugach coastal ecosystem, including species diversity and distribution, and introduction of pioneering or exotic species into climate-disturbed areas (Haufler et al. 2010).

This chapter provides a primer on the issues and environmental conditions affecting the coastal ecosystems of the assessment area. We examine an array of climate-induced changes in ocean and coastal conditions, including abiotic and biotic effects of climate change. This discussion is predicated on the understanding that human use of the assessment area, notably Prince William Sound and the eastern Kenai Peninsula, primarily occurs within the marine environment. The coast serves as the primary attraction to visitors to the region and supports those who make a living from the marine environment. Given the importance of the coast and its varied environments to tourists, fishermen, and the biota of both land and sea, examining potential influences of climate change is critical to the larger assessment. However, the chapter's scope is limited by the rapidly developing scientific understanding of the coastal ecosystem and our capacity to distill the complex biological, physical, and chemical processes into a useful tool for land managers. Our intent is not to comprehensively examine the broad array of environmental processes affecting the Chugach coast. Instead, we aim to draw attention to several changes of which land managers and the public should be aware, and to identify issues for which more comprehensive and rigorous evaluation could be beneficial.

Chugach Seascapes

The coasts are among the most accessible and visited parts of the Chugach National Forest.

The coasts are among the most accessible and visited parts of the Chugach National Forest. Since its creation in 1907, a central focus of the Chugach has been to provide visitors with the opportunity to experience unrivaled landscapes, wildlife encounters, and recreational opportunities (USDA FS 2011). But because the high mountain ranges and inaccessible terrain constrain land transportation throughout the forest, the traditional point of access has been along the coast. Ferries, cruise ships, smaller private vessels, and aircraft provide access throughout the assessment area for residents and visitors (Poe and Greenwood 2010). Tourism, fishing, and recreation are the dominant uses of public lands in the assessment area (Poe et al. 2010b), and a majority of this use, particularly when sightseeing from cruise ships is included, stems from the marine environment.

To conceptualize changes occurring over such a vast and diverse coast, we divide the coastal ecosystem into three geographical areas, which we call "seascapes" (fig. 4-1). A seascape consists of more than just the beach—it is the capillary zone where upland forests transition to the ocean. The spatial extent of a seascape varies, but typically it is considered to be a large area in which conditions in the ocean and conditions on upland habitats affect each other. Each of the three seascapes has unique physical and biological characteristics, ecological processes, and human environments (LCCN 2014). The aesthetic quality of seascapes, and their enjoyment by visitors in ocean craft, result from characteristics of seascapes extending far inland (e.g., upland glaciers, forested mountainsides).

The western seascape consists of the upper Kenai Peninsula, beginning in the high alpine peaks of the Chugach Mountains and extending 240 km southwest. The Kenai Peninsula is separated from the mainland of Alaska by Cook Inlet to the west and Prince William Sound to the east. The Kenai is widely recognized for its stunning scenery, world-class fishing, wildlife viewing, and outdoor recreation (USDA FS 2002).

The central seascape consists of the western, northern, and eastern coasts of Prince William Sound, including the many islands within the Sound. This seascape is characterized by shallow straits, long fjords, protected bays, diverse tidal zones, and forested shores. The area is home to a diverse biological community that includes seabirds, shorebirds, fish (including all five Pacific species of salmon), sea otters, harbor seals, Stellar sea lions, orcas, and gray and humpback whales. Cruise ships of all sizes travel through the Sound, offering tourists the chance to see glaciers and wildlife. Commercial, sport, and subsistence fishing are all significant economic drivers of the Prince William Sound human environment (Harwell et al. 2010, Jewett and Duffy 2007).

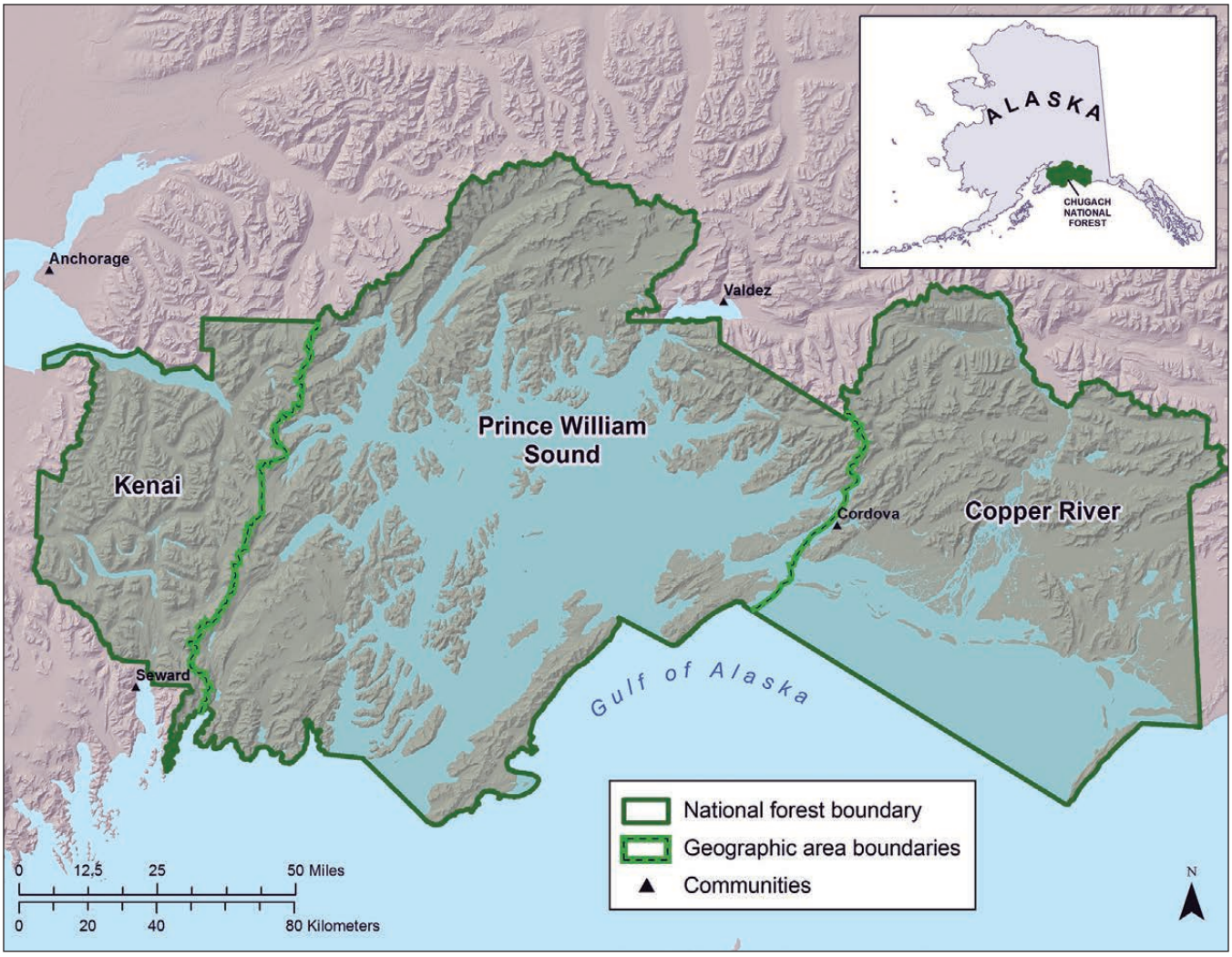


Figure 4-1—Geographic areas of south-central Alaska used to organize discussion of seascapes in the Chugach National Forest/ Kenai Peninsula assessment area.

The northwestern portion of the Prince William Sound seascape sees the highest degree of human use on the Chugach itself, with most of the access via small, privately owned motorized boat. There is also commercial outfitter and guide activity that accesses forest land in this region by small motorized boat and kayak. This activity is authorized by the forest under special-use permit; in comparison to overall vessel use, these users represent only about 10 percent of the total small boat traffic in the region (Poe at al. 2010b). Subsistence harvest, primarily of fish and marine species, occurs throughout this region, but occurs most frequently in the vicinity of the communities of Cordova, Chenega Bay, Tatitlek, and Whittier (Poe et al. 2010a). Downloadable map galleries and datasets are available at http://www.fs.usda.gov/detail/chugach/landmanagement/planning/?cid=stelprdb5139741.

The eastern seascape consists of the Copper River Delta, which stretches across 283 280 ha and drains an area of 68 635 km^2. The delta is extremely large and one of the most significant wetland complexes on North America's Pacific Coast. The delta seascape's most distinct ecological features are its barrier islands, which create shallows that support large populations of marine invertebrates and provide a haul-out and nesting ground for marine mammals and birds. In spring, the delta is a globally significant staging ground for 16 to 20 million migratory birds (USDA FS 2014). Nearly the entire Pacific Coast population of dunlins and western sandpipers rely on the delta for habitat (Bishop et al. 2000). Other important bird species in the delta seascape include knots, Canada geese, and swans (Isleib and Kessel 1973).

In the following sections, we highlight some of the broad abiotic and biotic effects of climate change that are likely to alter the Chugach's seascapes.

Abiotic Effects of Climate Change

As outlined earlier in this assessment (chapters 2 and 3), the climate of south-central Alaska has warmed and is expected to continue warming during the next 20 to 40 years, leading to higher winter and summer temperatures, reductions in snowpack at lower elevations; reductions in glacial mass, volume, and spatial extent; and a longer growing season (Haufler et al. 2010, Keyser et al. 2000, Larsen et al. 2007). As a result of the changing climate, abiotic conditions within the Chugach's seascapes are expected to change, which in turn will affect seascape biological communities and human uses (Haufler et al. 2010). We focus on three important abiotic effects: sea-level change, glacial changes, and ocean acidification.

Sea-Level Change

Alaska has more than 71 000 km of shoreline, more than twice that of the lower 48 states combined (Glick et al. 2010). With such a large coast, Alaska as a whole is exposed to the potential consequences of long-term sea-level rise. But unlike coastal regions in much of the rest of the country, the coasts across the assessment area are unlikely to experience large sea-level rises (Clark et al. 1978, Dean 2009, Haufler et al. 2010).

Despite the global trend of rising seas, the sea level in this region has been falling at rates of up to a fraction of an inch per year.

Despite the global trend of rising seas, the sea level in this region has been falling at rates of up to a fraction of an inch per year. The decreasing sea levels in the assessment area are largely the result of long-term patterns of isostatic rebound and geologic activity. The decrease is also caused, in part, by ocean circulation shifts in response to changes in wind stress at the eastern boundary of the North Pacific.

Isostatic rebound occurs when the melting of glaciers decreases the pressure exerted by ice on the land, triggering uplift in the land (Larsen et al. 2005). In the

assessment area, glaciers that dominate the seascapes have been diminishing in extent and mass for thousands of years (Heusser 1983, Jones et al. 2009), resulting in long-term uplift of the underlying land. Studies conducted on the Kenai Peninsula show regional isostatic rebound rates of 1.0 cm/year, and peak uplift rates for southeast Alaska exceed 3.0 cm/year. The rate of isostatic rebound for the Kenai Peninsula is three times faster than global average sea-level rise; throughout southeast Alaska, isostatic rebound is occurring ten times faster than sea-level rise.

Geologic activity and resulting tectonic movement is also a major contributor to local changes in sea level in the region. South-central Alaska experienced dramatic tectonic movement associated with the historic 9.2-magnitude earthquake in 1964 (Haufler et al. 2010). As a result, some areas of the coast sank while others experienced significant uplift. Because the Chugach/Kenai region contains both areas of uplift and subsidence, local changes in sea level are likely to vary along the coastline. For example, the Copper River Delta is subsiding at approximately 1.2 mm/year (Garrett et al. 2014).

Although isostatic rebound and geologic activity have mitigated the effects of global sea-level rise in the Gulf of Alaska since the mid-1970s (Bromirski et al. 2011), the trend toward stable or falling sea level may not continue in the extreme long term. Isostatic rebound slows once glaciers have melted substantially, tectonic uplift can be reversed by another major earthquake, and it is likely for the Northeast Pacific circulation to change again, all of which would result in a period of sea-level rise substantially faster than the global average (Bromirski et al. 2011).

The potential consequences of changing sea level are especially apparent in the Copper River Delta. The delta seascape contains a large percentage of all the tidal marshes in south-central Alaska. Tidal marshes can occur wherever there is flat land at sea level (Frohne 1953). Three elements are required for tidal marsh formation: (1) the input of tidal waters, (2) sediment deposition, and (3) protection from ocean wave and ocean-current erosion (Boggs et al. 2008). Tidal marshes and the adjoining mudflats are one of Alaska's most important habitats as staging areas for millions of migrating shorebirds, geese, and swans. The marshes and mudflats also support species like dusky Canada goose (*Branta canadensis occidentalis*), Western sandpiper (*Calidris mauri*), and dunlin (*Calidris alpina*), whose conservation status is of concern.

Changes in relative sea level have a dramatic effect on tidal marshes and other coastal ecosystems. Along a subsiding coastline, tidal marshes may migrate inland, inundating formerly nontidal sites such as forests or peatlands. At the same time, tidal communities along an outer marsh may erode or drown completely. Tidal

marshes where coastal areas are stable or subsiding appear to be some of the most vulnerable habitats to sea-level rise in the Chugach National Forest.

Barrier islands within the assessment area may also be vulnerable to the effects of sea-level change. In other parts of Alaska, these islands are also threatened by coastal erosion and inundation as a result of changes in frequency and intensity of coastal storms (Meehan et al. 2012). Barrier islands are sandy coastal islands separated from the mainland by an estuary or bay (fig. 4-2). They are uncommon in southern Alaska and typically occur near large river deltas, such as the Copper River Delta (Boggs 2000, DeVelice and Juday 2007, Hayes and Ruby 1994). Although barrier islands are created by processes similar to those that created spits, they are unique in that barrier island separation from the mainland reduces access to their shorelines by predators such as brown bears and wolves. Consequently, barrier islands provide protected haul-outs for harbor seals, stopover feeding grounds for migrating shorebirds, and habitat for a variety of bird species, including the glaucous-winged gull (*Larus glaucesens*) and dusky Canada goose (Sowls et al. 1978).



M.Bishop

Figure 4-2—Coastal dunes on Egg Island, Copper River Delta, Alaska, illustrating vegetation stabilizing the dune structure.

The barrier islands of the Copper River Delta range up to 2 km in width and 13 km in length and typically rise less than 9 m above sea level (Thilenius 1990) (fig. 4-3). Sand and silt are delivered to the coast by the Copper River, where the sediment is transferred to the marine environment and deposited on the deltas. Longshore currents, which generate waves that strike beaches obliquely, move sediment parallel to these currents. Waves redistribute sediment across the beach profile, and wind erodes depositional features and transports the sand downwind. High-wave-energy environments suspend silt and transport it to lower energy depositional environments. Consequently, sand forms beaches and dunes along the high-energy seaward side of islands, and silt forms tidal marshes and tide flats along the leeward, low-energy estuary side of islands (fig. 4-4).

During storms, portions of barrier islands and spits are often inundated and subjected to wave action known as overwash. Sand is transported from the beach and deposited further inland on the island or spit. Depending on the severity of the storm, overwash may affect the front portion of the landform or completely breach low portions. In the latter case, sediment is deposited on the back side of the landform as a washover fan (Ritter 1986).

Distinct landform and vegetation patterns are common among barrier islands. Low-gradient beaches emerge from the ocean and transition to sparsely vegetated dunes, taller back dunes dominated by herbaceous vegetation, and wetlands in the low areas between the dunes. On the landward side of the tall back dunes, elevation tapers toward the estuary, where vegetation grades to uplifted tidal marshes, tidal marshes, and tide flats. Pioneer species such as American dunegrass (*Leymus mollis*) stabilize the sand with roots that penetrate more than 1 m to the water table (Boggs 2000, DeVelice and Juday 2007). Species and plant association diversity increases with dune stability. Herbaceous associations include fireweed (*Chamerion angustifolium*), beach strawberry (*Fragaria chiloensis*), American dune grass/boreal yarrow (*Leymus mollis*/*Achillea borealis*), and Nootka lupin (*Lupinus nootkatensis*).

Loss of barrier island habitat from climate-induced sea-level change is difficult to predict; projections must account for local trends of tectonic uplift and subsidence, the potential for seismic repositioning of the shoreline, and glacial rebound. In general, barrier islands represent dynamic habitats capable of repositioning, growing, and shrinking in response to changing conditions.

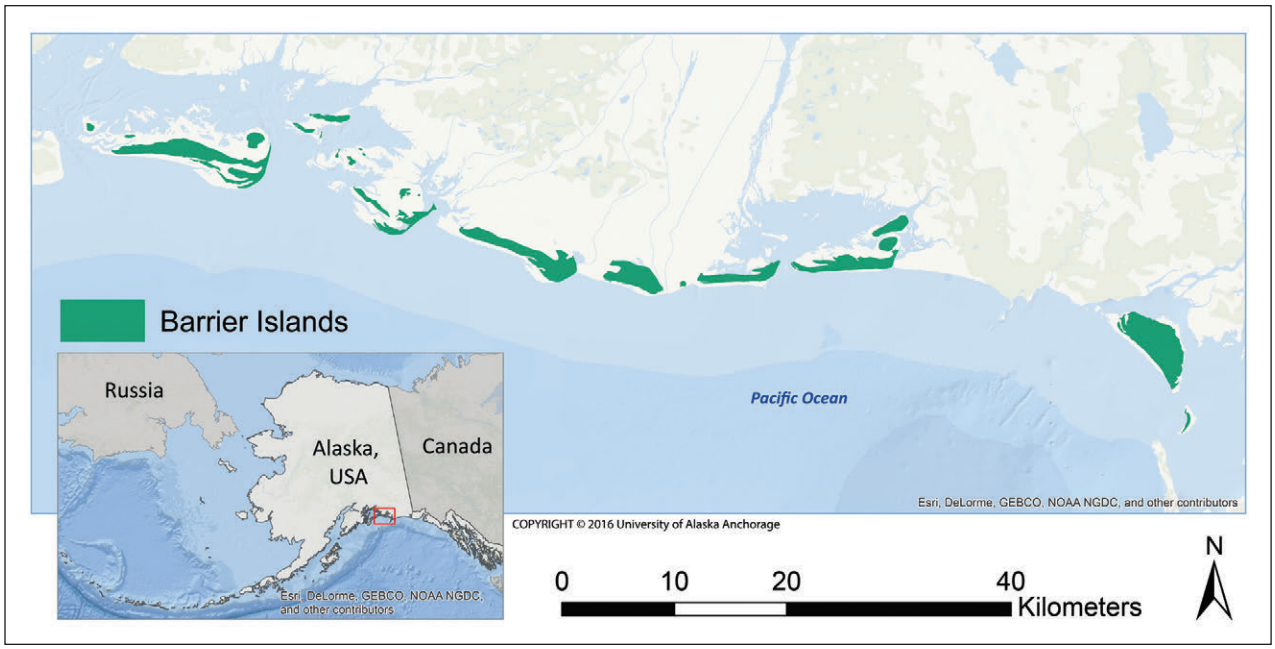


Figure 4-3—Distribution of barrier islands along the Copper River Delta, Alaska.

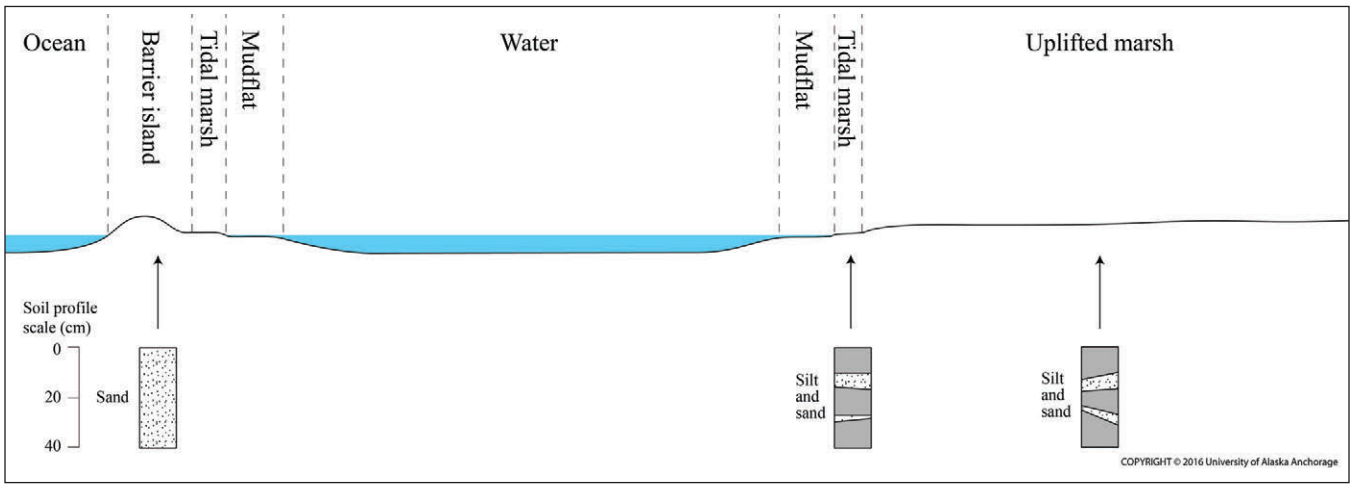


Figure 4-4—Schematic physiography and vegetation profile of a barrier island on the Copper River Delta, Alaska.

Glacial Changes

The second major abiotic effect of climate change in the Chugach seascape is glacial change. Alaska's glaciers are one of the main attractions for tourists in Alaska. Cruise ships and charter boats bring thousands of visitors to view tidewater glaciers each year. Glaciers provide remote recreational opportunities, including world-class ice and alpine climbing, skiing, and glacier trekking, while also serving an important ecological function in the Chugach seascape (Timm et al. 2014) (see chapter 3).

Melting glaciers drive the Alaska coastal current, bring nutrients to the ocean, and control the hydrology of many river ecosystems.

Melting glaciers drive the Alaska coastal current, bring nutrients to the ocean, and control the hydrology of many river ecosystems (Astrom et al. 2014).

Although a small number of Alaska's glaciers are growing (their termini are extending), taken as a whole, the state's glaciers are experiencing a loss of between 40 and 70 Gt/year (Kaser et al. 2006). The first statewide survey of glacier volume change completed in 2002 estimated an ice loss of 21 km/year from the 1950s to the mid-1990s, and a rate of volume loss that is expected to double in the next 5 years (Markon et al. 2012).

The most dynamic glaciers are the low-lying tidewater glaciers (Larsen et al. 2007). The coastal ecosystems created by the interface of glacier runoff and marine environment located at the terminus of tidewater glaciers result in highly productive, heterotrophic systems (Hood and Scott 2008). Changes in climate affect glaciers in complex ways. Melting of ice or accumulation of snow in either the accumulation zone or the terminus result in mass balance changes that influence most interactions of the glacier with the physical and biotic environment (O'Neel et al 2015). In the past, the pattern of glacier growth and decline, or modulation, appears to have occurred primarily at temporal scales of many decades to centuries for most glaciers, superimposed upon the millennium-scale dynamics of glacial and interglacial periods. Human-induced climate change affects this balance, and modeling (see chapters 2 and 3) shows the zone of accumulation pushed to higher elevations. At the highest elevations, precipitation increases substantially and temperatures stay below freezing for much of the year, thus it is possible for glaciers to increase in mass balance as a consequence of high accumulation of snow at upper elevations. The ultimate status of each glacier depends on the long-term outcome of the balance between accumulation at high elevations and loss at lower elevations.

The Prince William Sound coastal region is particularly influenced by climate change because such a significant portion of its freshwater discharge, about 50 percent, is derived from glacial runoff (Neal et al. 2010). The iron supplied by the glacial dust suspended in this freshwater discharge is critical to phytoplankton production in this region. Changes in the dynamics of this ecosystem have implications for nutrient delivery that affects primary productivity and subsequent fish, shellfish, and marine bird and mammal populations. Currently, krill and plankton thrive in glacier-dominated fjords; this productivity stems from the nutrient content of the sediment loads derived from upstream glacial action. Seabirds and harbor seals feeding at tidewater glacier termini show a high fidelity to glacial habitat because of the availability of food and sea-ice haul-outs to protect themselves from predators.

These same areas are also a focal point for marine recreation and tourism, particularly with respect to tidewater glaciers (Poe at al. 2010b), where higher levels of human use overlap with some species of conservation concern (Suring and Poe 2010). Decreases in the biological productivity of these systems as they become less influenced by the presence of glacier ice will have significant implications for species and likely also for their desirability as recreation and tourism destinations (O'Neel et al. 2015). However, as glaciers retreat, they also open up new beaches and recently denuded terrain as new potential recreation locations; this has been observed in the vicinity of Columbia Glacier.

In south-central Alaska, in contrast to areas that support continental glaciers, understanding the affect of climate change on glaciers is complicated by the fact that glaciers in different situations respond differently to the same regional changes in climate. Elevation, association with ice fields, and whether a glacier's terminus is in tidewater affect how the glacier will respond to temperature and precipitation changes.

Ocean Acidification

The third major abiotic effect of climate change affecting Chugach seascapes is ocean acidification. The world's oceans play the dominant role in global dynamics of the carbon cycle through the uptake and chemical processing of carbon dioxide (CO_2). Through biological and chemical processes, oceans absorb nearly a third of the CO_2 emitted every year (Wackernagel et al. 2002). Although ocean capture of CO_2 has buffered the terrestrial world from more significant atmospheric warming, CO_2 in the oceans moves into a dynamic system involving both biotic and abiotic pathways, with a small portion being sequestered in sediments as plants or animals sink to the ocean floor and get buried. Most of the CO_2 remains dissolved in the surface seawater, forming carbonic acid. Over the past 250 years, as atmospheric CO_2 has increased, the pH of the ocean has decreased by 0.1 units (from 8.2 to 8.1), corresponding to a 30 percent increase in acidity, with projected increases at a rate of 0.5 to 1.0 percent per year. Changes in acidity have major consequences for marine life by reducing the availability of carbonate ions that many marine organisms use to build shells and external skeletons. The colder temperatures of Alaska's oceans make them particularly vulnerable to ocean acidification. The Arctic Ocean has had high concentrations of CO_2 dissolved in it since historical times. This is due to physical processes such as cooling of the relatively fresh surface water, which causes this surface water to sink below the surface toward the bottom of the ocean. When this colder, denser water sinks, it sequesters atmospheric CO_2 in the Arctic Ocean. This results in the Arctic Ocean having a much lower pH and lower concentrations of carbonate ions compared to other oceans of the world.

Through biological and chemical processes, oceans absorb nearly a third of the carbon dioxide emitted every year.

The assessment area experiences an extremely complex pattern of ocean currents, freshwater input, and tidal movements. As a result, spatial and temporal variation in pH (and other physical and chemical features of the water) is extreme. Consequently, the organisms within Prince William Sound, along the Copper River Delta/marine interface, and along the Kenai coast experience high variability in physical and chemical conditions. It is difficult to predict how this inherent variability will interact with directional changes in pH to influence marine life over the short term. Over the long term, organisms will be exposed to more acidic conditions with resulting changes in food webs.

Consequences to Biotic Communities

The abiotic changes in the assessment area are likely to affect biotic characteristics of the coastal ecosystem. This section highlights some of the effects of climate change on biotic communities within the Chugach seascapes. We focus on three: harmful algal blooms (HABs), which are an emerging threat within the Alaska coastal environment, changes to eelgrass beds, and effects on shorebird populations.

Harmful algal blooms involving toxic phytoplankton have recently emerged as a threat to commercial and subsistence shellfisheries in parts of Alaska.

Harmful Algal Blooms

Harmful algal blooms involving toxic phytoplankton have recently emerged as a threat to commercial and subsistence shellfisheries in parts of Alaska (Anderson et al. 2000). In addition to the potential influence of climate change, non-climate drivers like point and non-point pollution influence harmful algal blooms.

There are several mechanisms by which climate changes could increase the threat of harmful algal blooms in the coastal areas of the assessment area. Warmer coastal waters, rapid melting of glaciers (resulting in iron-rich dust blowing into ocean waters that provides a critical micronutrient for algae), and ocean acidification may favor organisms that do not have calcium carbonate shells, including dinoflagellates and diatoms, over more beneficial types of plankton (Gao and Campbell 2013).

Beyond the public health threat of HABs, health problems associated with phytoplankton have also occurred in humpback and right whales and a number of bird species, including northern fulmar, great cormorant, herring gull, common tern, common murre, Pacific loon, and sooty shearwater. Also associated with algal blooms is mortality of sea lions, seals, sea otters, dolphins, sperm whales, minke whales, and large numbers of birds, including grebes, gulls, cormorants, American avocets, loons, and sooty shearwaters.

Eelgrass Beds

Eelgrass (*Zostera marina*) appears in abundant meadows and beds throughout Alaska where sand and mud substrates occur in sheltered estuarine environments (fig. 4-5). Mundy (2005) described eelgrass as one of the primary sources of food in the northern Gulf of Alaska along with phytoplankton, macroalgae, and detritus. Macroalgae and eelgrass are the primary groups providing biomass to the nearshore zone, followed closely by shallow and deep infauna, deep epibenthos, and herbivorous zooplankton. The rich and varied eelgrass environment provides significant primary production and stability for sediments as well as varied substrate, cover, and food for invertebrates and vertebrates (Cowardin et al. 1979; Dean et al. 1998, 2000; McRoy 1970). Within Prince William Sound—described by Harwell et al. (2010) as "a semi-enclosed fjord estuary on the southern coast of Alaska—eelgrass beds are an important component of the nearshore ecosystem (Dean et al. 1998). The diverse biota supported by the extensive vegetation and associated detritus are comprised of microfaunal species (foraminifera, ciliates, and other protozoans) (Mundy 2005) and meiofauna (nematodes, harpacticoid copepods, and turbellarians) (Feder and Paul 1980a, 1980b). Some of the more recognizable macroinvertebrates include gastropods, bivalves, polychaetes, and amphipods living in and among the dense rhizome masses, and on and among the leaves (Jewett et al.



David Ward, U.S. Geological Survey

Figure 4-5—Sea stars feeding on mussels in bed of eelgrass (*Zoster* sp.).

1999). Dean et al. (1998) reviewed the literature documenting the rich assemblage of invertebrates, fish, and birds that use eelgrass beds for food and shelter, including economically important species of crabs and fish. Hughes et al. (2014) provided an extensive list of the fish and key invertebrates that use eelgrass beds as nursery grounds at critical life stages. Johnson et al. (2003) considered eelgrass beds to be essential fish habitat that serves as nursery grounds both for salmon and key species of groundfish.

Many shorebirds, sea ducks, and seabirds make use of the nutrition contained in eelgrass beds during different seasons. Perhaps the best-documented example is from the Izembek Lagoon located at Cold Bay on the Alaska Peninsula, where nearly the entire world's population of Pacific brant and Taverner's Canada geese (Ward et al. 1997) use the lagoon's eelgrass meadows. Use of Prince William Sound eelgrass beds by birds is less documented, but the beds are no doubt used extensively by resident birds and by species making their way north and south on annual migrations. Marine mammals and land mammals also forage in eelgrass beds on abundant prey in certain locations. More specifically, sea otters and harbor seals forage in eelgrass beds (Ward et al. 1997), and, at low tide in the Izembek Lagoon, brown bears have been seen foraging in the exposed eelgrass beds.[3]

Potential consequences of climate change on eelgrass ecosystems may be inferred from past research. Potential stressors include changes in water temperature, salinity, pH, and depth. Studies conducted in Izembek Lagoon (Biebl and McRoy 1971) demonstrated remarkable resilience of eelgrass beds to broad fluctuations in temperature. Sharp declines in photosynthesis were not observed until temperatures of 30 to 35 °C were reached. Biebl and McRoy (1971) distinguished between subtidal and tidepool forms of eelgrass beds, with the tidepool form having a capacity to withstand 35 to 40 °C before photosynthesis declined. The study further indicated that, although eelgrass survived well in freshwater for up to 10 days without visible damage, the plants died in 24 hours when exposed to four times the normal salinity of seawater (Biebl and McRoy 1971). Based on these studies, it appears unlikely that eelgrass beds in Prince William Sound will be severely affected by anticipated climate change effects of increased marine temperature (e.g., Abdul-Aziz et al. 2011) and changing salinities.

It appears unlikely that eelgrass beds in Prince William Sound will be severely affected by anticipated climate change effects of increased marine temperature and changing salinities.

Eelgrass favors the soft sediments of shallow, protected lagoons and is excluded from large river deltas and glacial fjords (Hall 1988). Changes in salinity resulting from either freshwater intrusion from melting glaciers or increasing salinity

[3] **Ward, D.H. 2015.** Personal communication. Research wildlife biologist, U.S. Department of the Interior, Geological Survey, Alaska Science Center, 4210 University Dr., Anchorage, AK 99508.

in areas that may be isolated and affected by rising temperatures may have little effect, owing to the high tolerance of the eelgrass to changes in both decreased and increased salinity.

Less is known about the response of eelgrass to changes in pH. Changing pH will influence the broader eelgrass system; however, it is not yet clear what the effects will be on dominant fauna such as calcareous invertebrates or the soft-bodied invertebrates that inhabit eelgrass beds. The abundant invertebrates that use eelgrass for cover and food, and that are less tolerant to short- and long-term changes in pH, may respond most directly to climate change and indirectly influence eelgrass systems.

Eelgrass is susceptible to changes in water depth. Water clarity affected by turbidity and depth of light attenuation affects the bathymetric distribution of eelgrass. Shaughnessy et al. (2012) reported the eelgrass depth range to be 0.9 to -1.6 m in the sheltered Izembek Lagoon with respect to the mean lower low water (MLLW). In a study conducted near Juneau, Alaska, Harris et al. (2008) found the distribution of eelgrass to be from 2.0 to -2.8 m. relative to MLLW. In Denmark, the historical distribution for eelgrass was 5.6 to 11 m depth, with the recent distribution reduced to between 2.5 and 8 m depth in sheltered and exposed areas, respectively (Baden et al. 2003). However, significant changes in effective sea level are not expected over the next 40 years as a result of climate change (see “Sea-Level Change” on page 83). Should water levels rise or descend substantially in the assessment area, it will most likely be due to tectonic activity. Post-glacial rebound is likely to ameliorate significant relative sea-level rises in Alaska (NOAA Climate Program Office 2012). For the immediate future, submergence of the eelgrass beds to an unfavorable depth because of climate change effects is unlikely.

The most significant and immediate threats to eelgrass beds are from more immediate anthropogenic sources such as dredging, vessel groundings and other disturbances, and pollution (Ward et al. 1997), although at least one example of eelgrass beds polluted by the *Exxon Valdez* oil spill demonstrated rather remarkable resilience and recovered relatively quickly (Dean et al. 1998). However, based on the studies following the oil spill, the species occurring with eelgrass are likely to be more susceptible to pollution within this habitat. It is quite possible that the community could be recolonized by zoochore and hydrochore dispersal of invertebrates and their larvae from within the Sound if the eelgrass beds remain largely intact.

Eelgrass meadows and beds, with their apparent resilience, will likely continue to provide habitat and nourishment for the associated invertebrates, fish, birds, and wildlife that use the resource despite changes in marine conditions anticipated over the next 40 years.

Shorebirds

Shorebirds are a dominant ecological taxonomic group associated with the Chugach/Kenai seascapes, and they provide significant ecosystem services to people. The coastline of Prince William Sound, and particularly the Copper River Delta, is one of the most visited stopover locations for birds migrating to northern breeding grounds in spring. The Chugach/Kenai coastline is separated from the valleys of interior Alaska by sheer slopes of the Chugach and Kenai mountain ranges, and that restrictive topography combined with climate and biogeography make it an ideal place for shorebirds to feed and rest, owing to abundant food and feeding habitat at a critical location along the Pacific flyway migratory route. An estimated 5 million shorebirds visit the Copper River Delta each spring, the largest concentration in the Western Hemisphere (Alaska Shorebird Group 2008). More than 73 different species of shorebirds—about a third of the world's shorebird species—have been documented in Alaska, and most move through the Chugach/Kenai region.

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Globally, shorebird populations have declined significantly since 2000 (Alaska Shorebird Group 2008). In Alaska, shorebirds face potential threats as well as positive changes to their habitats. These include sea-level change, glacial retreat, and associated changes in hydrology; uplifted marshes; increased storm activity; potential changes in food availability resulting from changes in ocean temperature; ocean acidification; and phenological shifts that may decouple food abundance from the arrival of the migratory birds. Key shorebird species of current conservation concern in the region, with further vulnerability compounded by climate change, include black oystercatcher (*Haematopus bachmani*), surfbird (*Calidris virgata*), red-necked phalarope (*Phalaropus lobatus*), western sandpiper (*Calidris mauri*), and red knot (*Calidris canutus roselaari*).

Several anticipated climate-related changes could affect shorebird populations along the Chugach National Forest shoreline. One of the clear concerns for western sandpiper is the potential inundation of intertidal mudflats, which could eliminate both feeding and nesting habitat. Because of their low gradient and location at the transition from ocean to land, intertidal mud flats are susceptible to the slightest shift in sea level. A significant increase in sea level would inundate large areas of current mudflats. The availability of this critical habitat type, therefore, would depend on the rate of mudflat formation in areas currently existing as upland habitat. This interplay between sea-level rise and mudflat status is especially complex in the assessment area. Increased storm surges influence the dynamics of mudflats; large storms can inundate substantial portions of tidal mudflats, potentially reducing the food supply across large proportions of foraging areas.

Bird migration is also likely to be affected by climate change. Changes in ocean and air temperatures can cause phenological changes, prompting birds to arrive in their feeding stopovers when food is least abundant, which can lead to many shorebirds not making the final shift to their breeding grounds. Changes in ocean conditions such as shifts in temperature or acidity can also affect food availability in areas where it has previously been plentiful for shorebirds (Visser and Both 2005).

Fewer than 11,000 black oystercatchers are estimated to remain worldwide and over half are known to nest in Alaska, particularly concentrated around Prince William Sound (Morrison et al. 2006, Tessler et al. 2007). The species is listed as a species of high concern in the Alaskan, U.S., and Canadian shorebird conservation plans (Alaska Shorebird Group 2008, Brown et al. 2001, Donaldson et al. 2000). Black oystercatchers exhibit strong breeding-site fidelity, which makes their reproduction particularly sensitive to environmental changes (Andres 1998) and to potential disturbance of shorelines by human use (Poe et al. 2009). Black oystercatchers nest in a restricted area between the high-tide line and coastal vegetation, or on islets just above high tide. Consequently, nests are vulnerable to surging storm tides. Other potential interactions with climate change include changes in abundance of dominant food species (mollusks and bivalves) that may decline in abundance if marine pH declines significantly.

Following the *Exxon Valdez* oil spill, black oystercatcher populations were examined carefully because they appeared to be one of the species to recover most slowly (Andres 1997, Murphy and Mabee 2000). The life history of black oystercatchers, particularly low recruitment of young, suggests relatively long recovery periods following major mortality events. The long lifespan of the species provides a buffer against the loss of reproduction in particular years, with overall population growth most dependent on adult mortality. This large shorebird demonstrated its resilience to the major ecological disturbance following the *Exxon Valdez* spill. Furthermore, the species demonstrated an ability to disperse into, occupy, and increase in new habitat following the development of open shore habitat on Middleton Island resulting from the 1964 earthquake (Gill et al. 2004).

Several of the many species of shorebirds that use the region for migratory stopover habitat are worth highlighting: these include the surfbird, red-necked phalarope, western sandpiper, and red knot. The surfbird also has a relatively small global population estimated at 70,000 (Senner and McCaffery 1997). More than three-fourths of all surfbirds breed in Alaska, north of the assessment area (Senner and McCaffery 1997). Prince William Sound coastline provides one of the most important staging grounds for surfbirds during spring migration. Migrating

surfbirds depend on herring spawn and mollusks for food during critical stopovers during their long migration along the Pacific coast of North and South America (Brown et al. 2001). Both of these prey types underwent steep declines in availability after the *Exxon Valdez* oil spill (e.g., Jewett et al. 1999, Shigenaka 2014, Thorne and Thomas 2008). Pacific herring spawning around Prince William Sound historically has occurred in mid-April when water temperatures reach around 4 °C (Cooney et al. 2001). The eggs are attached to underwater vegetation near shore. Once deposited, many herring eggs experience immediate mortality from heavy wave action and smothering (Cooney et al. 2001). An increase in large waves from storm surges could increase herring spawn mortality. Studies have shown that the majority of egg deposition in Prince William Sound occurs around northern Montague Island and a few eastern and northern sites (Norcross et al. 2001). In a study completed on northern Montague Island in 1994, scientists found that surfbirds accounted for a large percentage of the birds observed in the herring spawning areas, and their arrival occurred shortly after spawning (Bishop and Green 2001). If the herring spawn earlier, triggered by warmer ocean temperatures, surfbirds and other migratory herring-spawn feeders in this area, like black turnstones (*Arenaria melanocephala*), must adjust their migration timing to take advantage of this food source. The potential phenological mismatch is made especially possible by herring spawn's short incubation period of just 2 to 3 weeks (Norcross et al. 2001). Phenological plasticity in surfbirds and other shorebirds is not well understood, especially as it relates to the timing of migratory stopovers. Potential responses to changes in the timing of stopover food availability include shifts in the timing of migration by entire species, broadening of the range of migration dates within species, and changes in bird abundance resulting from changes in migratory stopover food availability. Any shift or variability in herring spawning dates could lead to variability in the areas used by surfbirds during migratory stopover and in the timing of stopovers, reducing their peak numbers.

Red-necked phalaropes are Holarctic breeders with populations that nest on the Copper River Delta (Brown et al. 2001). The breeding status of these birds makes them stand out among shorebirds in the region. These shorebirds use marine areas during migration and staging, and freshwater ponds of the delta during breeding. There is no clear estimate of the population breeding on the delta, but a majority of ponds have at least one and up to 10 pairs breeding on the pond shores. The birds feed on freshwater invertebrates immediately prior to and during the breeding season. Freshwater invertebrates will be more sensitive to near-term increases in air temperature and changes in precipitation than marine invertebrates. Therefore, red

phalaropes may be more exposed to changes in the phenology of invertebrates than will other shorebirds in the region.

Although Western sandpipers have a large population of an estimated 3.5 million birds, there are concerns that the species is declining (Farmer and Wiens 1999, USSCP 2004). Over a million western sandpipers use the Copper River Delta as a migratory stopover in spring (Bishop et al. 2000). An abundance of food and secure resting habitat is critical to assist western sandpipers in reaching their breeding grounds in western Alaska. Little is known about the distribution of the Alaskan population of red knots; however, it is suspected that the entire population uses the delta during migration. Red knots use the mixed sand/mud areas of the barrier islands of the delta. Although these areas may be susceptible to increases in storm intensity and frequency, it is unclear whether the spatial extent of barrier islands is likely to change substantially over time. In the 1970s, red knot numbers were estimated to be about 40,000 on the Copper River Delta (Isleib and Kessel 1973). Currently the *C. c. roselaari* subspecies of red knot is estimated at below 20,000, which would indicate they are undergoing a significant decline.

Over a million western sandpipers use the Copper River Delta as a migratory stopover in spring.

Conclusions

The coastal ecosystem is an important part of the Chugach/Kenai assessment area, and policymakers and scientists are learning more about the potential effects of global climate change on the seascapes of the region. Abiotic factors, particularly glacial changes and ocean acidification, are likely to affect the assessment area (see chapter 5 for more details). Major biotic effects of climate change, including harmful algal blooms, changes to eelgrass beds, and consequences for shorebirds will change and influence other biota and users of the assessment area. Perhaps the most compelling conclusion from this chapter, one that does not arise directly from the review, is the high uncertainty involved in developing scenarios for seascape futures. In particular, the Chugach/Kenai region—where substantial glacier change (see chapter 3) influences both sea level and isostatic rebound, and influences freshwater hydrology but also marine currents and chemistry—is particularly difficult to imagine into the future. Uncertainty, a ubiquitous partner in any climate assessment (see chapters 1 and 3) is particularly apparent for this dynamic region, where land meets sea and the dearth of understanding of marine ecosystems becomes apparent to managers of terrestrial and freshwater systems.

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Ron Neilbrugge



Sockeye salmon (*Oncorhynchus nerka*), Tern Lake, Kenai Peninsula, Alaska.

Chapter 5: Salmon

Mark Chilcote,[1] Angela Coleman,[1] Steve Colt,[2] Peter Kirchner,[3] Gordie Reeves,[4] Dan Rinella,[5] Eric Rothwell,[6] and Steve Zemke[1]

Summary

- About 15 percent of the world's Pacific salmon (hatchery and wild fish combined), originate in the assessment area.
- Production of wild and hatchery salmon from the south-central Alaska assessment area supports commercial fisheries with a $587 million economic impact and 7,944 jobs to Alaska.
- Of the 2.5 million days of recreational fishing by anglers in Alaska, 72 percent of this effort occurred in south-central Alaska, with salmon being the primary target species.
- Across the south-central Alaska assessment area, 720 watersheds were classified based on two variables, percentage of glacial cover and an index of spring snowpack (i.e., the proportion of October–March precipitation that remains as snowpack on April 1).
- Based on climate scenarios for the next 60 years, the snowpack indices for watersheds at lower elevations are projected to decline because of warmer temperatures. In contrast, snowpack indices in higher elevation watersheds are expected to increase because of increased precipitation.
- Sixty-one of the 720 watersheds (8.5 percent) were classified as being vulnerable to climate change because of projected reductions in snowpack over the next 60 years.
- The productivity for 58 percent of the 234 salmon populations analyzed for recruitment performance increased with warmer air temperatures. For the remaining populations (42 percent), warmer temperatures were associated with the opposite population response, reduced productivity. Overall, pink

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salmon production in Prince William Sound is projected to increase by 26 percent over the next 70 years in association with a warming scenario; however, the projected responses for individual populations were highly variable.

- Results from population dynamic modeling for chum salmon project a decrease in numbers under a warming scenario; however, there was a very high degree of uncertainty associated with this finding.
- An analysis of the number of fish caught in fisheries and counted in streams found that, for seven of the eight groups of salmon evaluated, warmer temperatures in past years were associated with more fish.
- Should apparent linkages between temperature found with fishery catch and total run-size continue into the future, we speculate that warming conditions brought on by climate change would result in more salmon in the study area, at least for the next 50 years.
- For the two resident species examined, Dolly Varden char and rainbow trout from the upper Kenai River, no association was found between air temperature and fish abundance.

Introduction

Salmon are a key feature of the biological, social, and economic landscapes of south-central Alaska, and hence are a defining ecosystem service for this region. For example, from 2009 to 2013, the return of hatchery and wild salmon to study area watersheds has averaged 99.3 million per year based on an analysis of fishery harvest and impact rates estimated by the Alaska Department of Fish and Game (ADFG) (see app. 3). To put this in a Pacific-wide context, we estimate the total production of Pacific salmon to be 654 million hatchery and wild salmon per year based on our analysis of information provided by Ruggerone et al. (2010), thus study-area salmon production represents about 15 percent of the total (appendix 3). As a point of clarification, we use the term “hatchery” salmon to refer to fish that begin life in a hatchery and that are released into the wild after growing for a period of time in that hatchery environment.

The economic impact of commercial salmon fisheries to this region is $587 million annually with an associated 7,944 jobs (appendix 3). Of the 2.5 million days that residents and nonresidents spend sport fishing in Alaska, about 72 percent of this activity occurs within south-central Alaska, much of it devoted to fishing for salmon (Southwick Associates et al. 2008). Bowker (2001) found that Alaskans devoted more trips per capita to fishing as the primary purpose of a trip than to any other outdoor activity. In addition to the recreational and commercial importance of

fishing, the unique existence of subsistence and personal-use fisheries in Alaska are additional evidence that salmon play a fundamental cultural and food supply role for many residents of the state. Salmon are a symbol of regional pride.

In Alaska, salmon are a symbol of regional pride.

In addition to their economic and cultural importance, salmon are an interesting group of fish to evaluate with regard to climate change. Unlike many fish species, salmon are born in freshwater, migrate to the ocean where they grow to adult size, then return to freshwater to spawn and die (fig. 5-1). Given that the effects of climate change are likely different between freshwater and marine environments, a species whose life history exposes them to both environments should be an

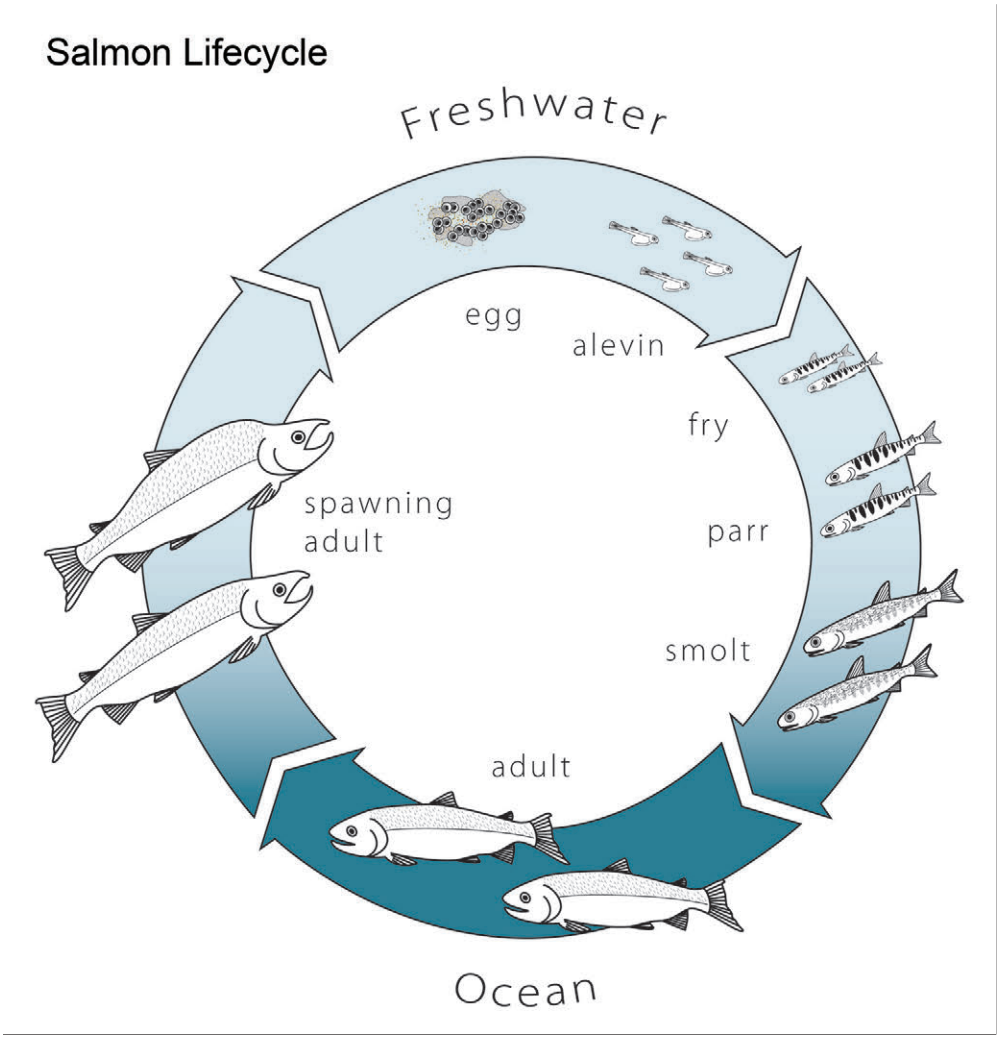


Figure 5-1—The life cycle of salmon is one of two worlds: the first being freshwater streams and lakes where they are born and eventually die, the other being the ocean where they rapidly grow. All five species of salmon found in Alaska follow this basic pattern. However, among these species, there is considerable variability, both in terms of the amount of time spent in the two environments and in terms of how many years it takes to complete their life cycle. (Illustration courtesy of Su Kim, NOAA Fisheries.)

informative indicator of the net impact of climate change across a diverse range of ecological conditions. In addition, there is considerable variation among salmon species with regard to the amount of time needed in freshwater and marine environments to complete their life cycle (fig. 5-2).

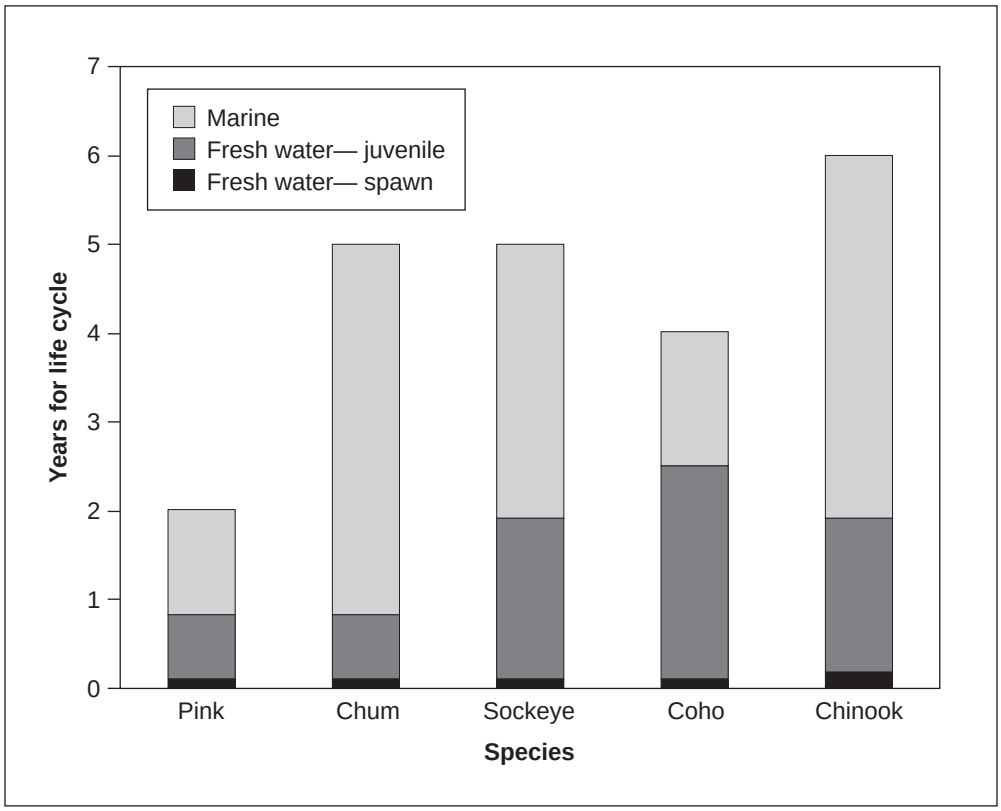


Figure 5-2—Pink salmon have the shortest life history among Pacific salmon; only 2 years occur from egg to spawning adult. The other four species of Pacific salmon require two to three times as long to complete their life cycle. In terms of the relative time spent in fresh water, coho have the greatest freshwater component (62 percent), whereas chum salmon have the least (17 percent). There are significant ecological differences among these species as a result of this life-history diversity.

Overview of Climate Change Impacts on Salmon

Climate change is bringing about changes to both the freshwater and marine environments that sustain salmon. In general, the response of salmon is complexly intertwined with innate capacities for adaptation through the combined mechanisms of phenotypic plasticity and genetic change, which provide resilience (Bryant 2009, Crozier et al. 2008, Ficke et al. 2007). Here we review the important environmental changes resulting from climate change affecting salmon in the assessment area.

Within the freshwater portion of the salmon life cycle, increases in water temperature, which are the result of precipitation falling as rain rather than snow as well as warmer air temperatures, are thought to potentially affect salmon in a

variety of ways. These include earlier hatching of fry because of warmer incubating temperatures (Holtby 1988, Schindler and Rogers 2009); increased growth rate and younger age of smoltification for those species with an extended freshwater-rearing life history (Bryant 2009, Rich et al. 2009, Russell et al. 2012); increased metabolic rates that make survival more difficult during seasonal periods of low food supply (Mangel 1994, Mantua et al. 2010); and earlier downstream migration that may result in a mismatch with optimum initial survival conditions in the marine environment (Crozier et al. 2008). Because the winter-period water temperatures in most of the streams in the study area are only slightly above freezing, even small increases in water temperature will substantially increase the rate of development for incubating eggs. This could result in the timing of hatching and fry emergence being shifted up to a month earlier and possibly being no longer paired with the timing of optimal conditions that affect subsequent survival of young.

Streamflows are expected to increase during the time of year when salmon eggs are incubating in gravel spawning beds (Battin et al. 2007, Shanley and Albert 2014). Such changes may be adverse if physical scouring of gravel and the associated mortality of incubating salmon eggs is proportional to the size and frequency of anticipated high-flow events (Goode et al. 2013, Leppi et al. 2014). However, the magnitude of such impacts on salmon are likely influenced by other factors as well, such as sediment input (Neupane and Yager 2013), geomorphic features of the channel (McKean and Tonina 2013), basin geology, and the structure of the stream network (Tague and Grant 2009, Tague et al. 2008). For example, McKean and Tonina (2013) found that the risk of scour from potentially higher flows was limited because of the geomorphic setting (low gradient and wide valley) areas where salmon spawn. Ice scouring of salmon spawning sites, with the associated loss of incubating eggs and pre-emergent fry, occurs under present conditions in Alaska (Doyle et al. 1993). It is possible with warming conditions and less ice formation during winter months that this impact would be lessened. A shift of stream water supply from snow to rain because of warming would result in less flow during spring and more flow during winter months. This could reduce access to some streams by adult salmon on summer spawning migrations. However, it is possible that increased flows during winter might increase the availability of overwinter habitat and enhance the survival of juvenile salmon during this life-history period.

Studies from the Pacific Northwest predict the loss of snowpack resulting from climate change to increase salmonid growth in streams that are currently cold and to decrease salmonid growth in streams that are currently warm (Beer and Anderson 2011, Crozier and Zabel 2006). In Alaska, given its inherently colder climate and cooler stream temperatures, we would generally expect the growth rate of

juvenile salmon to increase with moderate climate warming. However, simulations for coho salmon in south-central Alaska's Chuitna River demonstrate the complexity inherent in predicting climate change impacts, even for a single species within a single watershed (Leppi et al. 2014). In this study, coho populations within the three subwatersheds evaluated were projected to increase or decrease depending on each subwatershed's habitat conditions and the specifics of the climate change scenarios examined. Similarly, Kovach et al. (2014) found that the observed response of two salmonid species to 31 years of climatic variation was not the same even though they occurred in the same habitat. Kovach et al. (2014) made the point that growing empirical evidence from other studies indicates that climate change can have dramatically different consequences among salmonid populations, even those that are geographically located near each other.

Climate change can have dramatically different consequences among salmonid populations, even those that are geographically located near each other.

Climate change will also affect the marine environment in ways that are expected to affect salmon. However, the assessment of these impacts is complicated by naturally occurring cycles in ocean conditions associated with ocean temperature and atmospheric patterns (Johnstone and Mantua 2014). Periods of relatively warmer sea-surface water temperatures, expressed as positive values for the Pacific Decadal Oscillation (PDO) index, are associated with higher numbers of Alaskan salmon (Mantua et al. 1997). However, this association is not uniform across all populations of northeast Pacific salmon. For example, positive PDO values (warmer conditions) are associated with fewer salmon returning to the watersheds of Washington and Oregon, the reverse of what has occurred for Alaskan stocks (Hare et al. 1999).

Overall, the impacts of climate on the marine environment are thought to have contributed to relative increases in pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon, and to decreases in coho (*Oncorhynchus kisutch*) and Chinook (*Oncorhynchus tshawytscha*) salmon observed in the Pacific Ocean during the past 80 years (Irvine and Fukuwaka 2011). However, these changes are difficult to detect at a local level because of the presence of unrelated natural cycles of low and high production that are typical of most salmon populations and which often occur at decadal or longer time periods (Rogers et al. 2012). Further, these production cycles may be asynchronous among regions, species, and populations (Beamish 2012, Noakes and Beamish 2009).

Against this backdrop of the recent past, climate change is expected to push certain environmental parameters, such as sea surface temperatures in the North Pacific Ocean, above the range of previously observed variability by mid-century if not sooner (Overland and Wang 2007). Although such changes may benefit Alaskan salmon initially, it is difficult to predict the long-term consequences of these

unprecedented ecological conditions. For example, Pierce (2004) modeled the possible changes in zooplankton and phytoplankton dynamics associated with climate change and concluded that, by 2090, some regions of the North Pacific will lose their traditional springtime plankton bloom, to be replaced by even production year-round. This could have an adverse impact on pink and chum salmon smolts, whose transition to the marine environment is timed to capitalize on plankton blooms. Alternatively, this consistent food availability may make the timing of the marine transition less critical, which could benefit salmon if warmer conditions shorten the time needed for growth and development during the freshwater stage.

Another factor relates to changes in spatial extent and location of the conditions preferred by different salmon species in the marine environment. Abdul-Aziz et al. (2011) examined this question by using the A1B (medium) emissions scenario. They projected that high-seas habitat for the five salmon species would decrease by as much as 86 percent for Chinook salmon to as low as 29 percent for chum salmon by 2100. Downscaling these broad scenarios to potential impacts on specific salmon populations is not possible. Results of this modeling do suggest that a northward shift in high-seas distribution of salmon is likely. Adbul-Aziz et al. (2011) also speculated that this shift in thermal conditions may favor the northerly spread of some other species and life histories such as steelhead (anadromous form of rainbow trout [*Oncorhynchus mykiss*]).

In addition to sea temperatures, other factors affected by climate change influence salmon growth and survival in the marine environment. These include changes in salinity, ocean currents, prey quality, interspecific competition, predator-prey relations, and acidity. Of these, the expectation that increased anthropomorphic CO_2 emissions will cause increased ocean acidity is one of the greatest concerns (Mathis et al. 2014). Since preindustrial times, acidification of the world's oceans has increased by 30 percent likely because of anthropomorphic causes (Mathis et al. 2014). As atmospheric CO_2 increases, some of the most dramatic increases in acidity are expected in Arctic and subarctic regions (Steinacher et al. 2009). These changes are anticipated to have an adverse impact on marine ecosystems, particularly for organisms like mollusks and crabs that must form calcareous shells (Mathis et al. 2014). For example, acidic conditions are lethal to some petropods (planktonic mollusks), causing the complete dissolution of their shells in 48 hours (Orr et al. 2005). Petropods are an important food source for juvenile pink salmon, comprising up to 60 percent of their diet in some years (Armstrong et al. 2005). Should petropods be adversely affected by ocean acidification and not be replaced by other suitable prey, their disappearance would likely cause a decrease in the numbers of pink salmon and perhaps other salmon species as well.

Salmon Diversity and Production Cycles

Salmon abundance, and therefore their relationship with people, changes over both short and long time scales. To illustrate this point, over a 50-year period the numbers of wild pink salmon returning to Prince William Sound streams have experienced highs and lows, but without any apparent long-term trend in population size (fig. 5-3). Particularly from 1960 to 1990, this pattern closely tracked values for the PDO. Although associations between PDO and salmon population cycles such as these have been well documented in a variety of other studies (Hare et al. 1999, Mantua et al. 1997), the mechanism behind this association is not well understood, nor are the other interactions involved in regulating salmon production (Rogers et al. 2012). Regardless of the mechanisms driving salmon production cycles, the important message is that such variations in salmon populations are a natural feature of their biology.

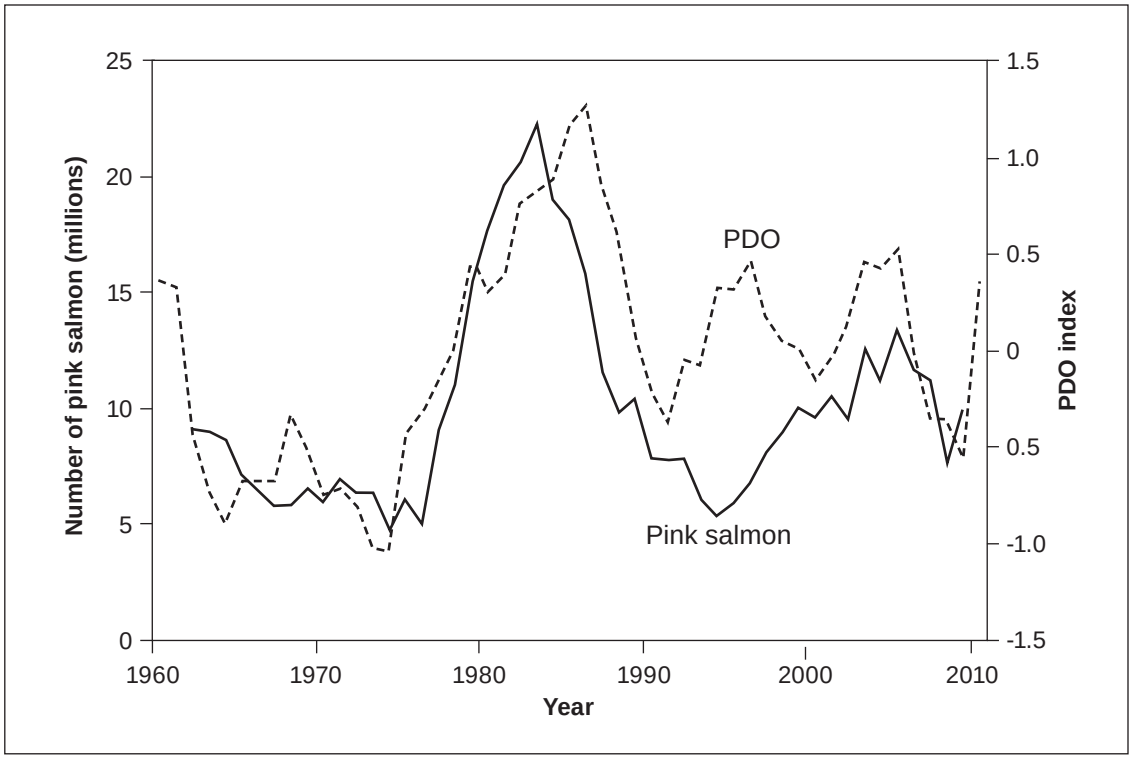


Figure 5-3—Number of wild pink salmon returning to Prince William Sound from 1962 to 2010 (solid line) and the average of monthly values for the Pacific Decadal Oscillation (PDO) from November through March for the years 1960 to 2010 (dashed line); both are expressed as 5-year moving averages.

Although pink and chum salmon have similar life histories, the other three salmon species in this area (chinook, coho, and sockeye [*Oncorhynchus nerka*] salmon) are not only quite distinct from each other, but also quite different from pink and chum salmon. This wide diversity in life histories among salmon species means that variations in abundance will be controlled by different factors (Bryant 2009).

For example, pink salmon migrate directly to the marine environment after they hatch in fresh water. In contrast, coho salmon spend from 1 to 3 years in fresh water, growing to a much larger size, before they migrate to the ocean. Once in the ocean, their pattern is different as well. Pink salmon rear for a little more than 1 year before returning to spawn invariably as 2-year-olds, and coho spend from 1 to 2 years at sea before returning to spawn in mixed age classes. Such differences mean that coho will be more sensitive to year-round habitat quantity and quality in the freshwater environment, which will control how many coho smolts are produced (Bisson et al. 2009). In contrast, because pink salmon enter the marine environment as a very small and vulnerable fish, near-shore abundance of food and predators will be major factors influencing their survival and subsequent adult run-size (Armstrong et al. 2005).

In addition to the diversity that exists among salmon species, considerable variation occurs among populations of each species and among individuals within any population. Relative to other bony fishes, salmon exhibit a large degree of genetic and phenotypic diversity (Crozier et al. 2008, Schindler et al. 2010, Waples 1991) and can adapt to changing conditions rapidly (Healey and Prince 1995, Quinn et al. 2001). This genetic and phenotypic diversity has facilitated persistence of salmon in highly dynamic environments (Waples et al. 2009) and is a key to their persistence in the future (Mangel 1994). Conceptually, climate-related changes will likely intensify the dynamic nature of the environment that salmon occupy, and maintaining adaptive capacity may require an even higher level of within- and among-population diversity. Unfortunately, knowledge of genetic variation and the ability of natural populations to respond adaptively to environmental change is limited, and the rate and extent of climate change is uncertain (Geinapp et al. 2008).

Genetic and phenotypic diversity has facilitated persistence of salmon in highly dynamic environments and is a key to their persistence in the future.

Despite this lack of knowledge, we can say that this region's salmon are probably better prepared to adapt to climate change because they have less exposure to additional stressors of habitat degradation and fragmentation that have contributed to the depletion of many populations to the south (Nehlsen et al. 1991). The region's watersheds have received relatively little impact from such activities as logging, mining, agriculture, stream channelization, water pollution, and damming, and, as

a result, they retain an assortment of complex and accessible spawning and rearing habitats in a relatively intact state. This watershed complexity ranges from small streams and ponds to large rivers and lakes, and is complemented by a diversity of hydrologic and thermal regimes associated with different water supplies (e.g., glacial, snow-dominated, transitional, spring-fed).

This habitat diversity, in turn, supports a high level of population and life-history diversity that contributes to the resilience of a region's salmon and the fisheries that rely on them (Schindler et al. 2010). For example, sockeye salmon in the Bristol Bay region have adapted to a similar range of habitats by optimizing behavioral and physiological traits like timing of spawning, egg size, and the size and shape of spawning adults, resulting in a stock complex comprised of hundreds of distinct spawning populations, each adapted to its own spawning and rearing environment (Hilborn et al. 2003). Superimposed on this localized adaptation is variation within each spawning population, such as differences in the number of years spent rearing in fresh water and at sea, resulting in a high degree of biological complexity (Hilborn et al. 2003, Schindler et al. 2010). These layers of biocomplexity lead to asynchronous patterns of productivity among the various stocks because differences in habitat and life history lead to different population responses despite exposure to the same prevailing environmental conditions (Rogers and Schindler 2008). For example, a year with low streamflows might negatively affect populations that spawn in small streams but not nearby populations that spawn in lakes (Hilborn et al. 2003).

The resilience afforded by biocomplexity can break down when habitats are degraded or when the genetic diversity that allows salmon to use the full complement of available habitats is diminished. The loss of habitat diversity and associated loss of population diversity has contributed to declines of once-prolific salmon fisheries, including those in the Sacramento (Lindley et al. 2009) and Columbia Rivers (Bottom et al. 2005, Moore et al. 2010). Although there are specific areas of human impact on salmon habitat within the assessment area, they are minor compared to the much larger area in which the habitat has not been altered.

The influence of hatchery-produced salmon, particularly pink salmon, on the resilience of local populations is unknown. Hatchery fish mixing with wild populations, as has been noted by Brenner et al. (2012) for certain pink and chum salmon populations within Prince William Sound, could homogenize and disrupt the adaptive genetic character of natural salmon populations. How much such an impact could affect the capacity of these populations to respond to climate change is unknown.

Components of Salmon Vulnerability Assessment

In this chapter, we present three analyses that examine the character and scale of environmental changes on salmon. The findings from these analyses expand existing understanding of the impact of climate change on salmon populations in south-central Alaska. Collectively, this information provides an informed perspective, or scenario, regarding the potential ecological future for salmon in this region to guide development of adaptation and management strategies. The evaluations presented here were developed by a group of managers and scientists (hereafter identified as the Salmon Team).

The three analyses presented here—watershed vulnerabililty, salmon population dynamics, and fish runs and fisheries—are not a comprehensive assessment of the impact of future climate conditions on salmon, but are intended to supplement existing and future information. They present tangible findings from three analytical approaches that to our knowledge represent the first applications of such methodologies to the study area and to associated physical and biological datasets.

Watershed vulnerability identified vulnerable watersheds based on potential changes in hydrology such as streamflow and water quality (i.e., temperatures and turbidity) resulting from climate change as tied to dominant water delivery processes (snow, rain, glaciers). Based on patterns of snowfall from a projected climate scenario, the Salmon Team identified watersheds in the region that would have the greatest chance of experiencing significant change in hydrology and associated processes. In particular, the expectation was that some watersheds would have higher winter flows and a diminished snowpack because of more winter precipitation falling as rain vs. snow. Further, associated spring runoff was expected to start earlier and be lower in volume as snowpack levels are reduced. Water temperatures would be expected to increase to varying degrees year-round. Hydrologic changes along these lines have already been documented in snowmelt-dominated watersheds across western North America, including coastal Alaska, where the timing of snowmelt-derived streamflow has advanced by up to a month during the latter half of the 20th century (Stewart et al. 2005).

Based on patterns of snowfall from a projected climate scenario, the Salmon Team identified watersheds in the region that would have the greatest chance of experiencing significant change in hydrology and associated processes.

To assess **salmon population dynamics**, the team examined existing data on salmon population abundance to develop insights into potential responses of salmon to climate change over the next 50 years. This analysis examined 30 years of salmon return records to determine if a relationship existed between annual air temperature and annual salmon production. After the team found evidence for such a relationship, air temperatures expected under global warming were used to develop a scenario for salmon production in the future.

The third analysis, **fish runs and fisheries**, was an outgrowth of the second. This analysis responded to the lack of detailed population-by-population data for many salmon species across much of the evaluation area. Although the spawner and recruit abundance data needed to apply the salmon population dynamics methodology (the second analysis) were available for pink and chum salmon populations of Prince William Sound, comparable recruitment data for coho, chinook, and sockeye salmon were extremely limited, and, for Dolly Varden char (*Salvelinus malma*) and rainbow trout, virtually nonexistent.

Although pink and chum salmon represent a large portion of the region's fisheries resource, contributions from the other species are also important. Therefore, to inform our evaluation for coho, chinook, and sockeye, we examined annual estimated catch or total run-sizes from a broader geographic area. Unlike the case for recruitment data, a time series of catch and run-size estimates are available for many of the recreational and commercial fish species in the study area. The shortcoming of these data is the large statistical area (e.g., Prince William Sound) sampled and therefore the limited geographic resolution for annual production. Each analysis covers many different populations. As a result, biologically important variability among individual populations cannot be measured.

For this third analysis, we performed a retrospective evaluation to determine whether annual variations in fish numbers corresponded with past variations in climatic indices related to air temperature. Our objective was to determine if there was a relationship between numbers of fish and conditions associated with warmer temperatures, and whether this relation, if found, was positive or negative. Our intent was to use the results as a basis to develop future scenarios of trends in salmon abundance.

Watershed Vulnerability

Temperature and flow regimes are important attributes of salmon habitat, and both are expected to change in response to climate change. As a framework for evaluating climate-related changes in salmon habitat across the Kenai/Chugach region, we developed a spatially specific watershed classification system based on the dominant source of water in a given watershed. We used sixth-level watersheds (hydrologic unit code [HUC] 12) as our unit of classification. The sixth-level watershed boundaries are based on the Watershed Boundary Dataset. This system is tied to key watershed factors in a manner that facilitates the evaluation of changes in air temperature and the amount and timing of precipitation under various climate change scenarios.

The watershed classification system we devised was based on two variables: (1) the proportion of the HUC that is covered by glaciers, and (2) a snowpack index, expressed as the proportion of total precipitation falling from October through March that is entrained in snowpack on April 1. The proportion of the watershed covered by glacial ice was selected as an indicator of the relative impact of glaciers on a watershed. Although the impact of glaciers on the hydrology of a watershed is most directly influenced by glacier volume relative to watershed size, estimating glacier volume is very difficult. For example, Synder (1993) found that 50 percent of the runoff in the Tanana watershed is produced by glaciers, which themselves occupy only 5 percent of the watershed area. For our analysis, we used glacial area because of the challenge of measuring volume, and assumed that glacial area served as a proxy for the functionally more accurate metric of glacial volume. We classified watersheds into three categories based on glacial cover: **glacial** when greater than 10 percent of the watershed area is functionally glacier-covered, **transitional glacial** when 1 to 10 percent of the watershed area is glacier-covered, and **clearwater** when less than 1 percent of the watershed area is covered by glaciers. As described by Pelto (2008), watersheds with greater than 10 percent of their area covered by glaciers function in a similar fashion and are largely driven by glacial processes. Transitional glacial watersheds are less dominated by glaciers and also represent watersheds susceptible to change in the near term from climate change. Clearwater systems are effectively free from glacial influence.

For the snowpack index, three classes were defined similar to those described by Mantua et al. (2010) and also used by the Alaska Climate Science Center vulnerability assessment for snow and ice (see chapter 3). **Snow-dominant** watersheds were defined as those with 40 percent or more of the October through March precipitation entrained as snow on 1 April. **Transitional snow** watersheds were those in which the snowpack on April 1 contained more from 10 to 40 percent of the winter's precipitation. Those watersheds with less than 10 percent of the winter's precipitation remaining as snowpack on April 1 were assigned to the **rain-dominant** classification.

We identified nine watershed categories based on a matrix of all possible combinations of the three watershed classes and three snowpack index classes, as shown in table 5-1. The hydrological dynamics of these watershed categories are distinctive. Probably the best understood are those that are free of glacial influence (i.e., clearwater: all three entries in the first column of table 5-1).

Table 5-1—Nine watershed categories defined for the assessment region based on a matrix of glacial cover and snowpack index classes (see chapter 3)

	Glaciers		
Snowpack index	**Clearwater**	**Transitional glacial**	**Glacial**
Snow-dominant	CS	TS	GS
Transitional snow	CT	TT	GT
Rain-dominant	CR	TR	GR

Clearwater/snow-dominant (CS) watersheds contain streams that drain high-elevation watersheds with robust snowpack levels that provide water throughout summer. Discharge fluctuates with air temperature throughout summer, and water temperatures are relatively cold. Peak flows occur in early summer (June/early July); however, some of the watersheds will also have high flows (a second but lesser peak) associated with autumn rainfall. Some of these streams will shift toward transitional in coming decades.

Clearwater streams in transitional-snow (CT) watersheds more frequently occur at moderate elevations, where peak flows occur in May and June, which is generally earlier than for snow-dominant systems. These watersheds characteristically have a second rainfall peak flow in autumn, which in some cases may be greater than the peak flow in May–June. Both summer and winter water temperatures are generally warmer than those of snow-dominant systems. Some of these watersheds will shift toward rain-dominant in upcoming decades. The peak flows in spring, fed by melting snow, will diminish, and the timing of maximum discharge will shift to autumn.

Clearwater/rain-dominant (CR) watersheds contain streams that drain low elevations with little or no snow accumulation during winter months. Precipitation enters streams soon after it falls, and discharge spikes with periods of rain throughout the year. Year-round, water temperatures are expected to be warmer than in snow-dominant systems.

Watersheds in the **transitional glacial** group (TS, TT, and TR) represent a group with uncertain future dynamics, because it is not clear how modest glacial influence might hydrologically ameliorate snowpack losses. Glacial systems in general are characterized by later peak flows (July and August) corresponding to the highest air temperatures. During summer melt, there is often a strong diurnal pattern of flow, in which discharge peaks after the warmest part of the day, then falls during the night to a minimum in the morning. The greater the contribution of glaciers to watershed flow, the more this diurnal flow pattern will be observed. The presence of glacial cover results in a longer period of cooler water and extended

flows during summer months, particularly in the snow-transitional and rain-dominant watersheds (TT and TR).

Finally, watersheds that fall within the **glacial** class (GS, GT, and GR) are believed to function similarly in that they are largely controlled by annual and longer term cycles of glacial processes, with peak flows in July and August and diurnal flow variation during summer months.

In addition to the glacial and snowpack variables, the presence of lakes in the drainage and the occurrence of groundwater both affect the temperature and flow characteristics of streams (Webb et al. 2008). Lakes, especially if they are large relative to the stream system, can buffer extremes in water temperature and flow, trap sediment, and buffer the intensity of flood events. A substantial number of watersheds in the study area have lakes; however; they differ in size and number, which makes it very difficult to develop a formulated approach to evaluating their impact.

A similar issue exists with regard to the effect of groundwater on watershed character. Groundwater is known to have a strong influence on stream temperature and other characteristics (Webb and Nobilis 2007). Groundwater flow occurs primarily as localized flow controlled by the permeability of aquifer materials and surface topography. Alluvium in river valleys, glaciofluvial deposits, and the coastal lowlands make up the most productive aquifers within the study area (e.g., Carmen River, Williwaw Creek, parts of Copper River Delta).

Groundwater systems are thought to be inherently more resistant to future, climate-change-induced shifts in water temperature and flow. As a result, significant groundwater input will buffer potential change in hydrology as a result of climate-induced changes in snowpack. The relative importance of this cushion for salmon production and survival will vary among watersheds and across regions, but the difficulty of estimating groundwater input confound attempts to estimate the effect.

Groundwater systems are thought to be inherently more resistant to future, climate-change-induced shifts in water temperature and flow.

Case Study: Monitoring Lake Ice

Chuck Lindsay, physical scientist, and Peter Kirchner, physical scientist, U.S. Department of the Interior, National Park Service, Southwest Alaska Inventory and Monitoring Network, Anchorage, AK 99501

Trends observed in historical records from across the Northern Hemisphere over the last 150 years show that duration of lake ice cover has become shorter by an average of 12 days per century during 1846–1995.

Lake ice cover is a key component of cold-region ecosystems, influencing lacustrine physical and chemical systems (e.g., temperature profile, dissolved gas concentration), biological productivity (e.g., zooplankton abundance), and human well-being (e.g., ice-jam flooding, subsistence, and recreational opportunities). Trends observed in historical records from across the Northern Hemisphere over the last 150 years show that duration of lake ice cover has become shorter by an average of 12 days per century during 1846–1995 (Magnuson et al. 2000). Projections of continued warming in the northern high latitudes indicate later ice cover formation and earlier break-up (Prowse et al. 2011).

In this study, we use remotely sensed data to track the timing of ice formation and break-up on large lakes in the western portion of the study area (fig. 5-4). Moderate spatial resolution (250 m) and high temporal frequency (1 day) provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) allow frequent observation of our region, which is characterized by prolonged cloud cover and little infrastructure. We use imagery from the MODIS Aqua and Terra satellites to monitor lake ice dynamics across the national parks and wildlife refuges in southwest Alaska (Reed et al. 2009).[7] The lakes studied on the Kenai Peninsula include two of the largest lakes on the peninsula, Skilak and Tustumena Lakes, and a cluster of small lakes near the Swanson River/Swanson Lakes area, referred to as the northern Kenai lakes (fig. 5-4).

Typically, the lakes in this study did not completely freeze (>90-percent ice cover) until mid-November (northern Kenai lakes) to mid-January (Skilak and Tustumena Lakes), and in some years, Skilak (in 2003) and Tustumena (in 2003, 2013, and 2014) did not completely freeze. Mean freeze start dates (>10-percent ice cover) range from early November (northern Kenai Lakes) to mid-December (Skilak and Tustumena Lakes) and show an interannual variability of up to 105 days (1 standard deviation [SD] = 10 to 29 days; fig. 5-4).

[7] **Kirchner, P.; Lindsay, C.; Shepard, T. [N.d.].** Lake ice freeze and break-up dates for southwest Alaska, 2001–2016. Manuscript in preparation. Natural Resource Report. Fort Collins, CO: U.S. Department of the Interior, National Park Service.

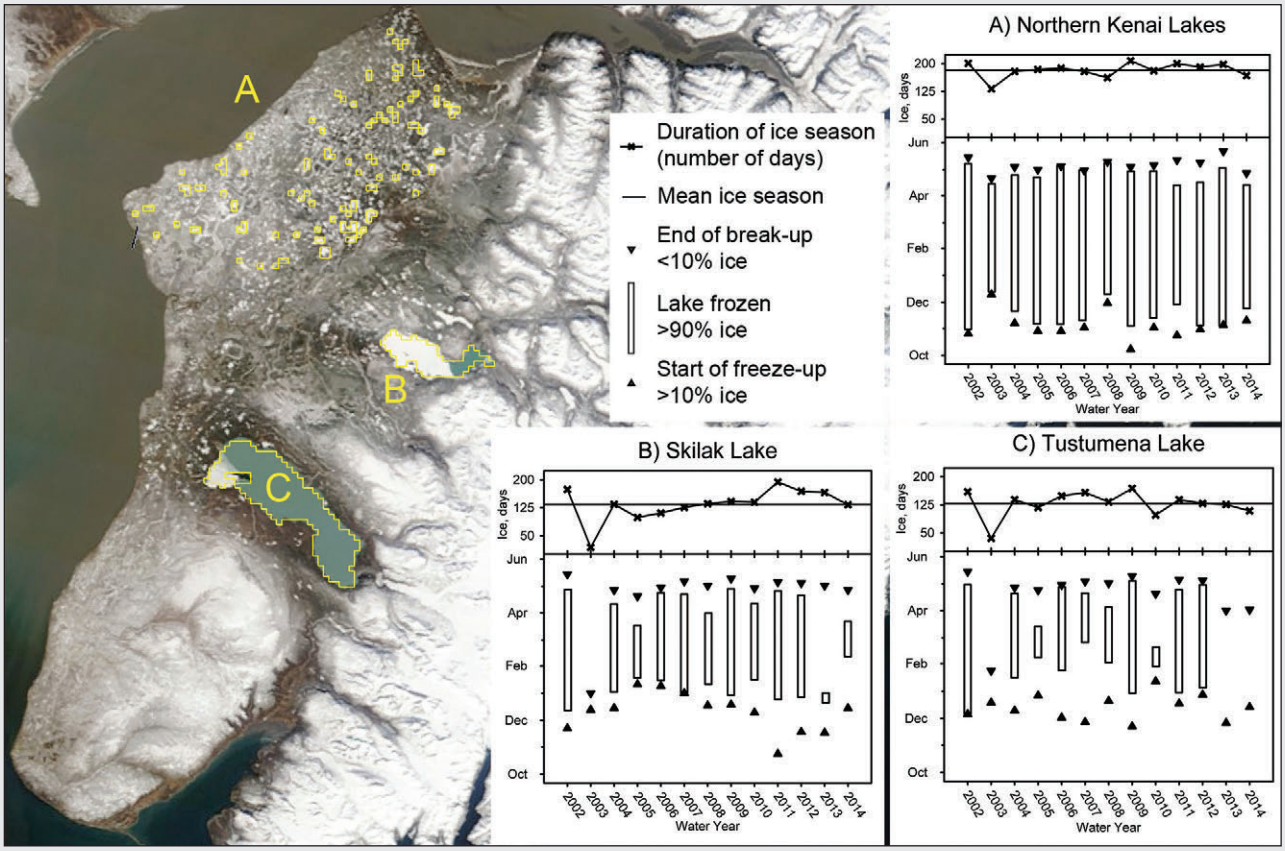


Figure 5-4—Lake ice image and time series of freeze and break-up dates for selected lakes on the Kenai Peninsula. Background image shows location and stages of break-up on April 10, 2014: (A) northern Kenai lakes, completely frozen (92-percent ice); (B) Skilak Lake, undergoing break-up (79-percent ice); and (C) Tustumena Lake, completed break-up (8-percent ice). Line graphs show the number of days per winter that each location had more than 10-percent ice cover, and bar charts show periods of complete ice cover with triangles to indicate freeze and break-up.

This interannual variability in freeze-up start dates likely reflects the dynamic climate of the southwest Alaska region during fall and early winter, which oscillates between warm and cold temperatures over several weeks.

In contrast, break-up occurs more rapidly than freeze-up, and the timing of break-up end dates (<10-percent ice cover) does not differ as greatly with an interannual variability of up to 31 days (1 SD = 7 to 8 days for lakes that completely froze; fig. 5-1). The mean final break-up dates range from late April (Skilak and Tustumena Lakes) to early May (northern Kenai lakes). Adrian et al. (2009) suggested that individual lake properties influence freeze-up more than thawing. Thus, changes in the timing of break-up are better indicators of broad-scale climate patterns than are changes in the timing of freeze-up. The relatively stationary nature of break-up dates observed on lakes on the Kenai Peninsula supports this concept.

In contrast to the shortened duration of lake ice cover across the Northern Hemisphere over the last 150 years, the 13-year pattern of freeze-up and break-up dates in this study does not show an obvious trend. One pattern that is evident is that lake ice cover is closely related to air temperature. During the four years with the highest locally recorded mean annual air temperatures (2003, 2005, 2013, and 2014), Skilak and Tustumena Lakes did not completely freeze (>90 percent ice cover) or froze for only a short period (fig. 5-4). This pattern is less noticeable but is still evident in the duration of ice season at the northern Kenai Lakes. The winters of 2002–2003 and 2004–2005 were significantly warmer than average (>2 SD) and coincided with El Niño events. Benson et al. (2000) and Robertson et al. (2000) also recognized that large-scale atmospheric and oceanic conditions like the El Niño–Southern Oscillation and the Pacific Decadal Oscillation (associated with higher winter and spring temperatures since the late 1970s) have significant impacts on the timing of lake ice formation and break-up.

There have only been a few detailed studies that describe future changes in the timing of lake ice cover. Dibke et al. (2011) simulated lake ice response to future climate in 2040–2079 using a global climate model (CGCM3) and an upper level emission scenario (SRES A2). Their results propose that freeze-up will be later by 5 to 20 days and break-up will be earlier by 10 to 30 days. Lakes in Pacific coastal areas of North America saw the largest projected changes, while lakes in the Alaskan interior were less affected.

Future reductions in the duration of lake ice cover on the Kenai Peninsula would likely be associated with thinner ice, reduced albedo, warmer lake-water temperatures, increased turbidity, increased light input, and decreased opportunities for winter recreation, ice fishing, and trapping. ■

Watershed Vulnerability—Findings

Using available geographic information system (GIS) data and information on snowpack from the analysis outlined in chapter 3, we categorized each HUC based on current (1971–2000) glacial cover and precipitation class (snow/rain). The distribution of watersheds across the two gradients of glacial extent and snowpack indicates that, within the Kenai/Chugach assessment area, the clearwater/snow-dominant (CS) watershed category was the most common (260 watersheds), closely followed by glacial-dominant/snow-dominant (GS), with 251 watersheds assigned

to this category (table 5-2). No watersheds were identified for the rain-dominant categories (CR, TR, and CR). Therefore, only six of the possible nine watershed categories occur under present conditions (fig 5-5).

Table 5-2—Classification of 720 watersheds in the assessment region based on glacial cover and snowpack for current conditions (1971–2000) and glacial coverage and snowpack projected from a climate scenario for the period 2030–2059

Snowpack index	Time period	Glaciers		
		Clearwater	Transitional glacial	Glacial
Snow-dominant	Current	260	74	251
	Future	212	65	247
Transitional snow	Current	113	17	5
	Future	161	26	9
Rain-dominant	Current	0	0	0
	Future	0	0	0

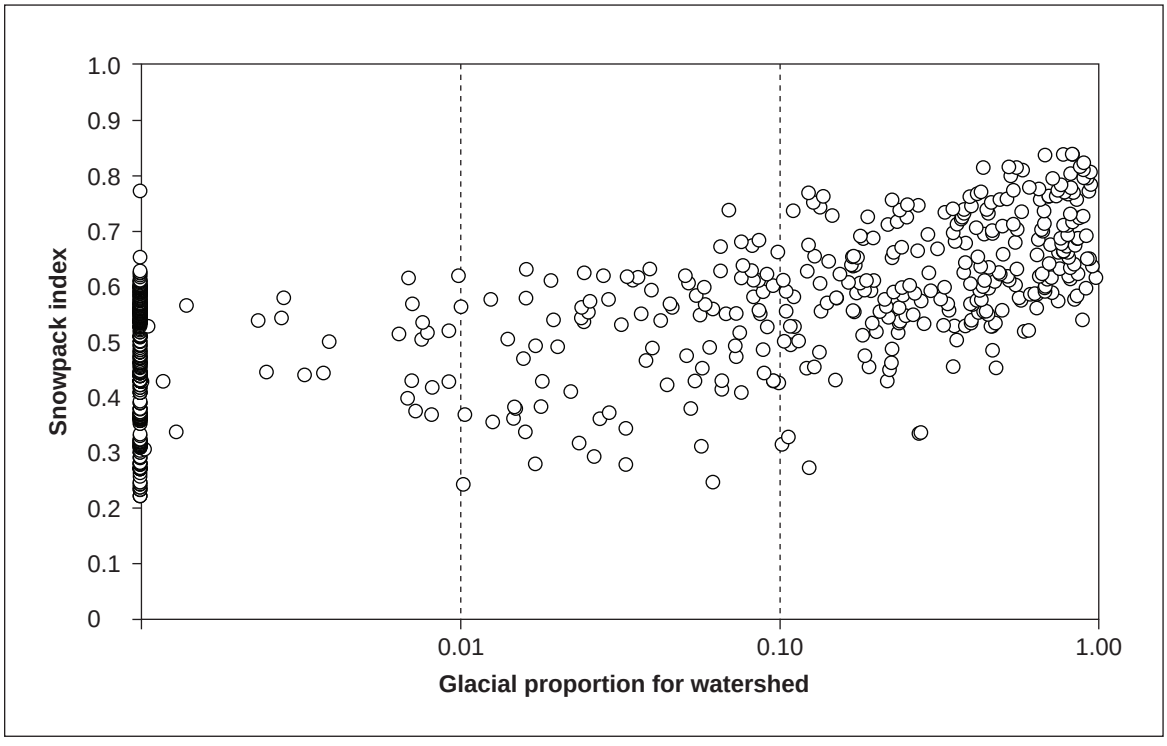


Figure 5-5—Association between proportion of glacier coverage and snowpack for 720 watersheds (6th-level HUCs) in the Chugach/Kenai assessment area for recent time period (1971–2000). Snowpack indices greater than 0.40 indicate a snow-dominant watershed; values between 0.40 to 0.10 indicate a transitional snow-rain watershed; and those less than 0.10 are rain-dominant watersheds. These snow-rain watershed classifications intersect with three possible glacier categories in which glacial proportions greater than 0.10 indicate a glacier-dominant system; glacier proportions from 0.10 to 0.01 indicate a glacial transition watershed; and those with less than 0.01 glaciers indicate a clearwater system.

There was a strong spatial pattern in the distribution of watershed categories across the assessment area. Clearwater/snow-dominant watersheds (CS) were confined to the northwestern portion of the region (fig. 5-6). Glacial/snow-dominant watersheds (GS) occur throughout the mountainous portions of the assessment area. Watersheds assigned to the transitional snow categories are most frequent along southern coastline and especially common for watersheds that ring Prince William Sound.

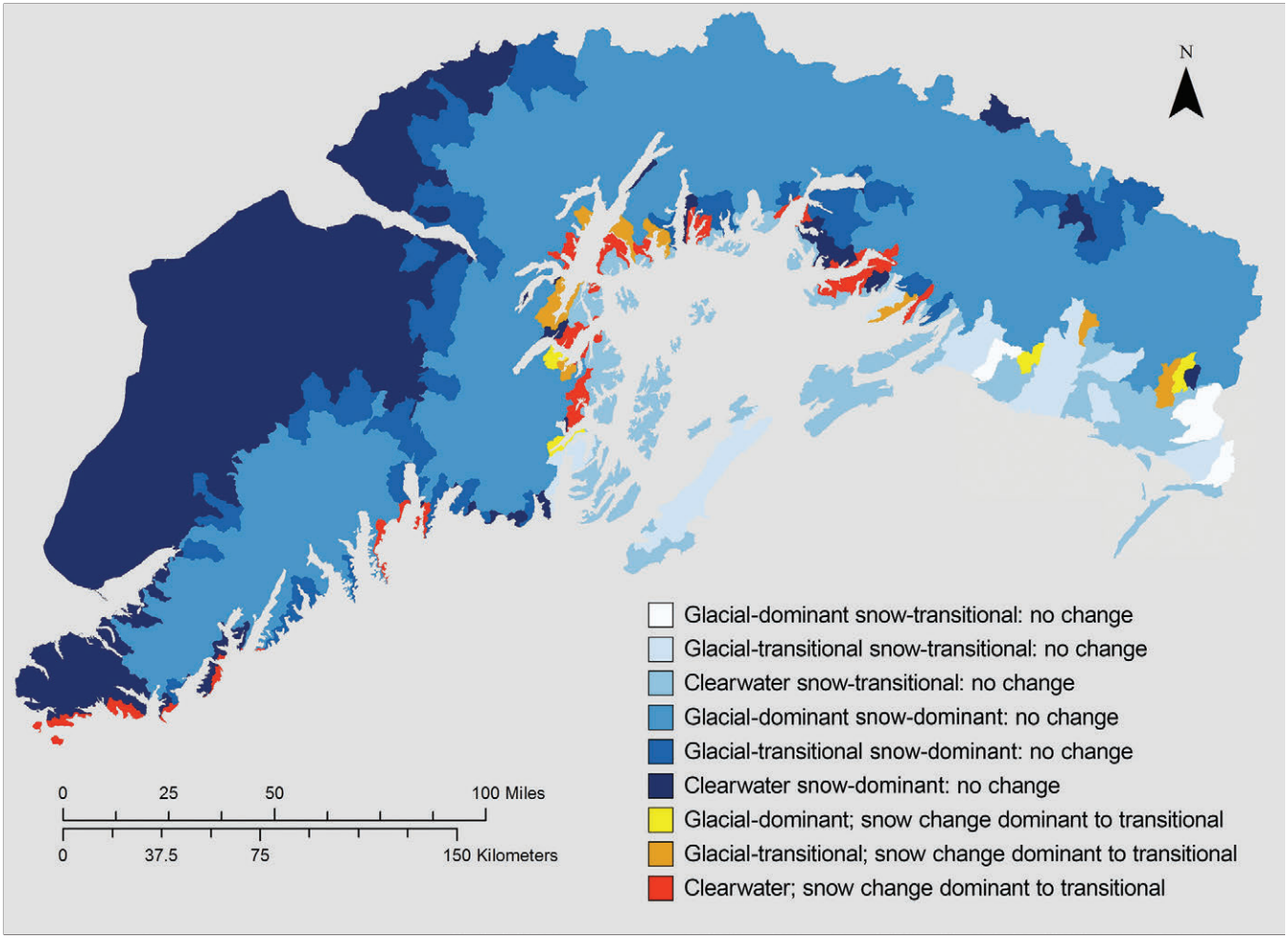


Figure 5-6—Map of evaluation area illustrating location of sixth-field hydrologic unit codes (HUCs), classified into nine categories based on current snowpack and glacier characteristics across the Chugach/Kenai analysis area. Sixty-one sixth-field HUCs expected to change their hydrologic classification by 2060 under the A1 climate scenario based on current and future snowpack conditions are colored yellow, orange, and red.

To evaluate the impact of climate change on hydrologic function, we sought to develop a vulnerability index combining the influence of glacier cover and changing snowpack to indicate which watersheds were likely to experience significantly different hydrographs in the future. We used snowpack index values projected for the years 2030 to 2059 to establish a future scenario (see chapter 3). The difference between current and projected values for the snowpack index ranged from a reduction of 20 percent at one extreme to an increase of 14 percent at the other. However, a majority of the watersheds had shifts in the snowpack index that fell within the interval of -10 to +6 percent change from current conditions (fig. 5-7). Decreases in the snowpack index were associated with lower elevation watersheds of the eastern portion of the Kenai Peninsula and coastal areas (fig. 5-8). Increases in the snowpack index were most frequently associated with higher elevation, more mountainous portions of the assessment area.

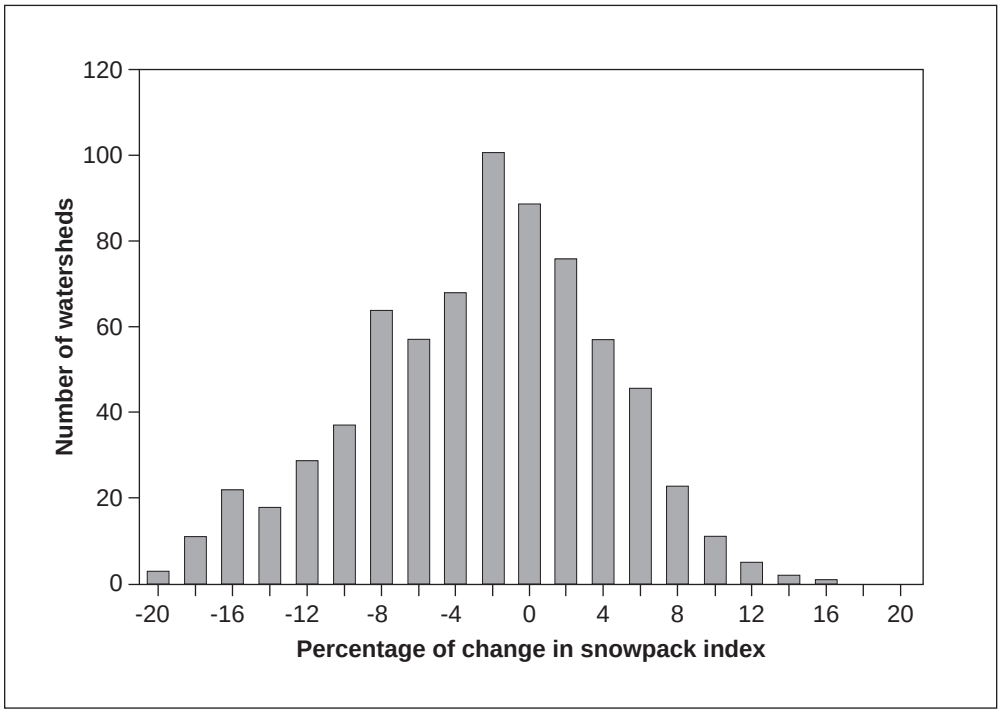


Figure 5-7—Percentage of change in snowpack index for 720 watersheds in the Chugach National Forest/Kenai Peninsula assessment area from current conditions to modeled snowpack six decades in the future.

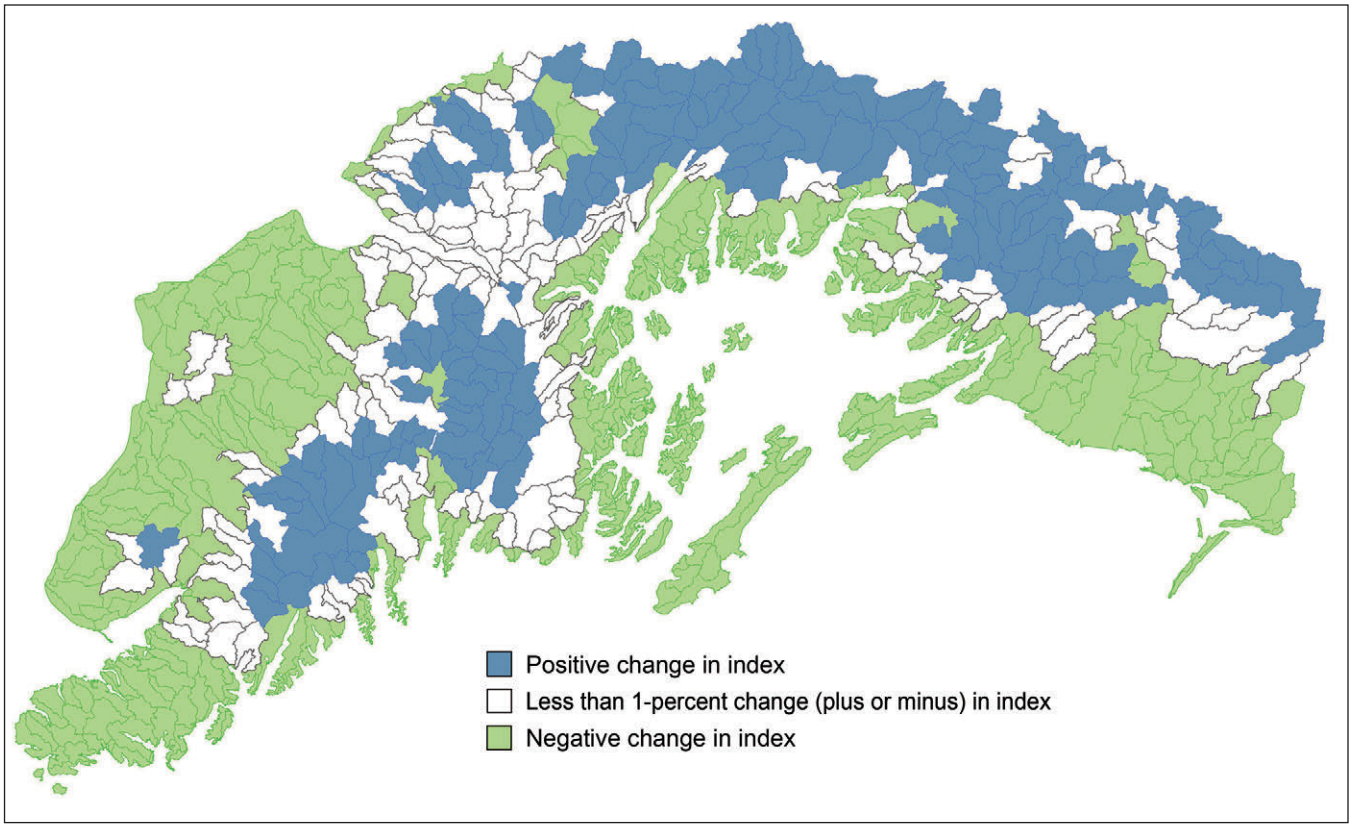


Figure 5-8—Relationship among watersheds expected to experience an increase (blue), no change (white), and decrease (green) in snowpack during the next six decades based on modeling of snowpack (see chapter 3).

Classification of 61 of the 720 watersheds changed from snow-dominant to transitional as a result of expected decreases in the snowpack index.

Watersheds expected to experience an increase in snowfall under climate change scenarios did not move to a different hydrologic category; these watersheds were already in the snow-dominant group. However, the classification of 61 of the 720 watersheds changed from snow-dominant to transitional as a result of expected decreases in the snowpack index (table 5-2). The largest number of changes occurred for clearwater (glacier-free) watersheds, where 48 changed from snow-dominant (CS) to transitional snow (CT). The climate scenario projections for the snowpack index in no instance resulted in a watershed falling into any of the rain-dominant categories.

A shortcoming of our analysis was that we were unable to model glacial changes to compliment the snowpack analysis. A suitable analysis of potential glacier retreat is not available across the 720 HUCs. Therefore, at this point, our watershed vulnerability index reflects only the influence of changes in expected snowpack with the clear recognition that changes in glacier cover, particularly in those systems with less than 10 percent cover, are likely to influence many characteristics of stream function and therefore habitat for fish.

We coined the term "vulnerable watersheds" to represent the watersheds that shifted category under the climate scenario modeling. The term as applied here is primarily meant to identify those places where changes in hydrologic processes are expected to be the most significant, and the potential disruption to the ecology of salmon populations the greatest. However, it is important to emphasize that a "vulnerable watershed" does not necessarily mean that the watershed is at risk; our intention with this label was to flag locations where we believe substantial change in watershed function may occur in the future. We are not predicting that salmon populations will increase or decline, only that hydrologic conditions will change significantly. Furthermore, we emphasize that our scenario for hydrographic change does not currently include the influence of receding glaciers and the associated changes in stream conditions. A model of glacier retreat, even a simple model, will be necessary to add this feature to the analysis.

All the vulnerable watersheds identified in our analysis represented locations where the snowpack index changed from a current value greater than 0.40 (snow-dominant) to a value less than 0.40 (transitional snow) under the climate scenario projection. The geographic distribution of these watersheds across the study area was highly structured, with the majority ringing the mainland shoreline of Prince William Sound (yellow, orange, and red watersheds in fig. 5-6). A number also occurred along the southern coastline of the Kenai Peninsula as well as a few in the vicinity of the Copper River Delta. We have singled out these watersheds on the basis of our analysis that these are the locations at which we expect significant shifts in the hydrograph to occur under climate change. Watersheds not so identified are still expected to be affected, but to a lesser degree. In terms of impacts on salmon, the impact thresholds may be more or less sensitive than the levels we have picked to identify vulnerable watersheds.

In addition to snowpack and glacier conditions, we intended to assess whether hydrological functionality might be mitigated by the stabilizing effect of groundwater or the existence of lakes within the stream network. Both lakes and groundwater play key roles in stream function; however; we found it impossible to quantify such effects in a spatial framework based on available geographic information. Locations and volume of groundwater are poorly documented, although there seems to be an association with peripheral streams that occur within large glacial outwash plains. The effect of lakes on watersheds classified as vulnerable was also difficult to quantify. However, the fact that lakes comprised no more than 5 percent of the total area for these vulnerable watersheds led us to believe that the "lake effect" on the hydrologic process for these specific watersheds was likely minor. We concluded, given the uncertainty related to groundwater flow and the relatively small size of

lakes in relation to watershed area, that the mitigating impacts of these features on the watersheds we classified as vulnerable could not be demonstrated. Therefore, the vulnerable watersheds identified in our analysis were not adjusted for the effect of either groundwater or lakes. This outcome does not mean that the effect of groundwater or lakes is generally not important to hydrologic processes. It is simply that the hydrologic impacts of these two features are not included in the broad analysis to identify vulnerable watersheds in the assessment area.

As illustrated in figure 5-6, most of the vulnerable watersheds were located within Prince William Sound, which is a very large producer of pink and chum salmon. Given this observation, we explored whether or not vulnerable watersheds were disproportionately associated with these two salmon species. To investigate this question of species proportionality, we used a classification of streams based on the aquatic ecosystems associated with quality habitat for four salmon species: Chinook, coho, pink-chum, and sockeye-coho salmon (USDA FS 2014). We labeled the classes "aquatic ecosystem types." When streams classified based on ecosystem types were matched with the hydrologic vulnerability score, we found that none was disproportionately classified as vulnerable (table 5-3).

Table 5-3—The proportion of four aquatic ecosystem types (USDA FS 2014) classified as vulnerable or not vulnerable based on the hydrologic vulnerability of watersheds in the Chugach/Kenai assessment area

Watershed assignment	Chinook	Coho	Pink-Chum	Sockeye-Coho	Number
Vulnerable	0.04	0.13	0.71	0.12	56
Not vulnerable	0.05	0.15	0.63	0.17	347

Although the greatest number of vulnerable watersheds are associated with pink-chum salmon ecosystems, pink-chum ecosystems are by far the most common represented in the area evaluated. Vulnerable watersheds appeared to be projected across this region in a manner that is proportional to the occurrence of each of the four salmon-based ecosystem types, and watershed vulnerability did not appear biased toward any particular species group. Note, however, that this particular comparison focused on watersheds of Prince William Sound and the eastern Kenai Peninsula, and did not include watersheds from the eastern and southwest portion of the climate vulnerability assessment area.

Salmon Population Dynamics

In the second analysis, the Salmon Team developed empirical models based on associations between observed air temperatures and salmon recruitment over the past 30 years for 234 different salmon populations. We then used these associations (model parameters) to project future population responses under two climate change scenarios. This analysis employed a statistical rather than mechanistic model. Therefore, the output does not examine how or why air temperature is related to salmon production. Rather, the model demonstrates whether an association between the two was present.

Our model focused on adult salmon returns measured during annual surveys from 234 sites throughout the assessment area. We measured how much of the observed annual variation in adult return was explained by two predictors: the number of fish that spawned in the parent year (spawners) and an index of annual air temperature at one of four monitoring stations in the region. We sought to determine whether warmer years were associated with the subsequent number of returning salmon.

We selected air temperature as the predictor variable (rather than sea surface temperature or other environmental measures associated with climate change) because estimates of air temperature were available from downscaled climate models for the next 70 years. Such estimates were needed to project how salmon production would change in the future. We made a decision not to use other environmental variables more closely associated with salmon production (e.g., PDO index) because we lacked an objective means for estimating future values.

We used the magnitude and sign (positive or negative) of the temperature parameter estimated for each salmon population to postulate future fish abundance with the underlying assumption that temperature responses observed over the past 30 years would predict abundance over the next 70. Values for projected temperature increases were based on output from two climate change scenarios (a1B and a2), downscaled sufficiently to represent conditions at the four temperature monitoring stations used in the recruitment modeling.

Findings are summarized to illustrate the proportional increase or decrease in average salmon abundance under the two climate scenarios for each population in 70 years. Variation in climate change responses among populations were examined for the possibility of geographic and species-specific patterns.

Estimated numbers of salmon spawning in each of the last 20 to 30 years were compiled from Alaska Department of Fish and Game (ADFG) publications including Begich and Pawluk (2011), Hochhalter et al. (2011), Shields and Dupuis (2012), and Botz et al. (2013). Additional information concerning the annual

estimates of pink and chum salmon spawning in streams of Prince William Sound, as well as fishery catch rates for wild fish in this area, were provided by R. Brenner (ADFG, Cordova).

Analyzing salmon abundance data for the Prince William Sound area was complicated by the large number of hatchery fish returning to this area; in many cases, counts of spawning salmon include hatchery fish that have strayed into the spawning streams. To estimate how many spawners were wild fish produced in the survey streams, we needed to remove hatchery fish from the counts. To estimate the proportion of hatchery fish in each stream, we used results from a model of pink salmon developed by Brenner et al. (2012) and separate ADFG observations of marked hatchery fish on the spawning grounds for chum salmon.

Of the 234 populations with data, the large majority were either pink salmon (199 populations) or chum salmon (27 populations). Sockeye, Chinook, and coho salmon were poorly represented, with data available for only 5, 2, and 1 populations, respectively. Fixed-wing aerial surveys by ADFG staff were used to count numbers of pink and chum salmon; numbers of other species were estimated at fish-counting weirs either visually or using split-beam sonar.

For each population, we used the structure of the Ricker recruitment model to determine if the number of fish returning in a given year (response variable) could be explained by two predictor variables, the number of parental spawners, and an index of air temperature. To do this, we modified a standard Ricker recruitment model (Ricker 1954) to include a second environmental variable such as reported by Chilcote et al. (2011) and as illustrated in equation 1:

$$\ln(R_t) = \ln(S_t) + \ln(\alpha) - \beta S_t + \gamma E \quad (1)$$

where:
R_t is the number of returning wild salmon that were produced from parents that spawned in year t (response variable),
S_t is the number of salmon that spawned in year t (first predictor variable), and
E is the air temperature index (second predictor variable).

In addition, α (alpha), β (beta), and γ (gamma) are model parameters that describe the form of the recruitment curve. For this analysis we are most focused on the value estimated for gamma, which is effectively the temperature-related multiplier of the number of recruits produced. A gamma estimated as positive indicates a positive relationship between air temperature and salmon production, whereas a negative gamma indicates the opposite. We estimated equation 1 parameters (alpha,

beta, and gamma) for each population via nonlinear regression using DataFit® software (Oakdale Engineering, Oakdale, Pennsylvania).[8]

We examined a number of forms of air-temperature data available online from the Western Region Climate Center at http://www.wrcc.dri.edu/. First, rather than using temperature from just one index site, our evaluation included data from four south-central Alaska weather stations that bracketed the study area: Cold Bay (55°12' N, 162°43' W), Alyeska (60°58' N, 149°08' W), Cordova (60°30' N, 143°30' W), and Yakutat (59°31' N, 139°40' W). Second, we used monthly average air temperatures for January, April, July, and October to evaluate whether patterns in salmon production were tied to conditions at a particular time of year (i.e., winter, spring, summer, and fall).

Finally, because salmon life histories span several years, and it was not known which life stage would be most sensitive to temperature, we retarded and advanced the temperature time series relative to the spawning year to determine if there was a lag in the effect of temperature. Sensitive stages, for example, might be during the fall/winter when the eggs were in the gravel or in spring when the smolts first reached the ocean, which could occur shortly after hatching for pink and chum salmon or 2 to 3 years later in the case of coho salmon.

To summarize, for each population we attempted to fit temperature data from each of four weather stations, for the months of January, April, July, and October, and with four different time lags (data series shifts of -1, 0, +1, and +2 years). Effectively, 64 different temperature datasets were fit to spawner and recruit abundance data for each population. This modified the γE term in equation 1 such that it became:

$$\gamma E_{ijt} + _{lag} \qquad (2)$$

where γ represents gamma as before, but E becomes one of 64 temperature values with i = 1 to 4 for the weather stations Cold Bay, Alyeska, Cordova, and Yakutat, respectively; j = 1 to 4 for the months of January, April, July, and October, respectively; t = the year the parent spawned; and *lag* = values from -1 to +2.

For each population, we fit equation 1 for all possible temperature datasets as were identified in equation 2. For each model, we calculated a score for the corrected Akaike's information criterion (AICc) (Burnham and Anderson 2002) and ranked the models based on AICc scores. We selected the model with the lowest score as the best representation of recruitment performance of the population.

[8] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

To project salmon production for future climate change scenarios, we employed temperature projections for the period 2060–2069 from SNAP (see chapter 2) for the months of January, April, July, and October at each of the four weather stations for each of two climate scenarios—a2 and a1B. We estimated the number of salmon recruits for each population using the best recruitment model (see above) using the future temperature estimates. The number of spawners (first predictor variable in equation 1) was set to equal the average number of spawners observed for the population. Baseline (or current) salmon recruitment was estimated using the identical abundance of spawners but air temperature from the average value for the associated weather station from 1977–2012. This time period corresponds to the period used to fit recruitment curves. We then expressed the expected population response under future climate as the proportional change as represented in equation 3:

$$P_{change} = (R_{scenario} - R_{base})/R_{base} \quad (3)$$

where:

P_{change} = proportional change in salmon production with positive values indicating proportional increase in salmon production and negative values indicating proportional decrease in salmon production,

$R_{scenario}$ = the number of recruits predicted under climate scenario conditions, and

R_{base} = the number of recruits expected under average temperature conditions of base period 1977 to 2012.

Salmon Population Dynamics—Findings

We were unable to find parameter solutions to the nonlinear model for 38 of the 234 populations. The 196 populations with suitable models included 173 pink salmon and 16 chum salmon populations. Model fits were also obtained for two chinook populations, four sockeye populations, and one coho population.

Pink salmon abundance increased an average (geometric mean) of 26 percent under both the a2 and a1B climate scenarios.

Pink salmon abundance increased an average (geometric mean) of 26 percent under both the a2 and a1B climate scenarios (table 5-4). Populations varied substantially in modeled response to temperature increase, including a number of populations in which production levels were projected to decline (fig. 5-9). One interpretation of this variability is that it expresses differences in habitat complexity or genetic diversity among pink salmon populations; a conceptual model for Prince William Sound pink salmon not unlike that proposed by Hilborn et al. (2003) and Schindler et al. (2010). We did not detect any geographic ordering of responses across the evaluation area (fig. 5-9). To confirm that the mean positive increase we resolved for pink salmon was significant, we evaluated estimates of salmon

Table 5-4—Modeled response of salmon recruitment for five species in response to increased air temperatures associated with climate scenario models a2 and a1B for the period 2060 to 2069 (expressed as proportional increase or decrease)

Salmon species	Number of populations	Proportional production change		Binomial significance test	
		a1B	a2	a1B	a2
Pink	173	+ 0.26	+ 0.26	< 0.001	< 0.001
Chum	16	- 0.41	- 0.34	0.07	0.07
Sockeye	4	- 0.16	- 0.12	—	—
Chinook	2	- 0.33	- 0.3	—	—
Coho	1	+ 1.17	+ 0.87	—	—

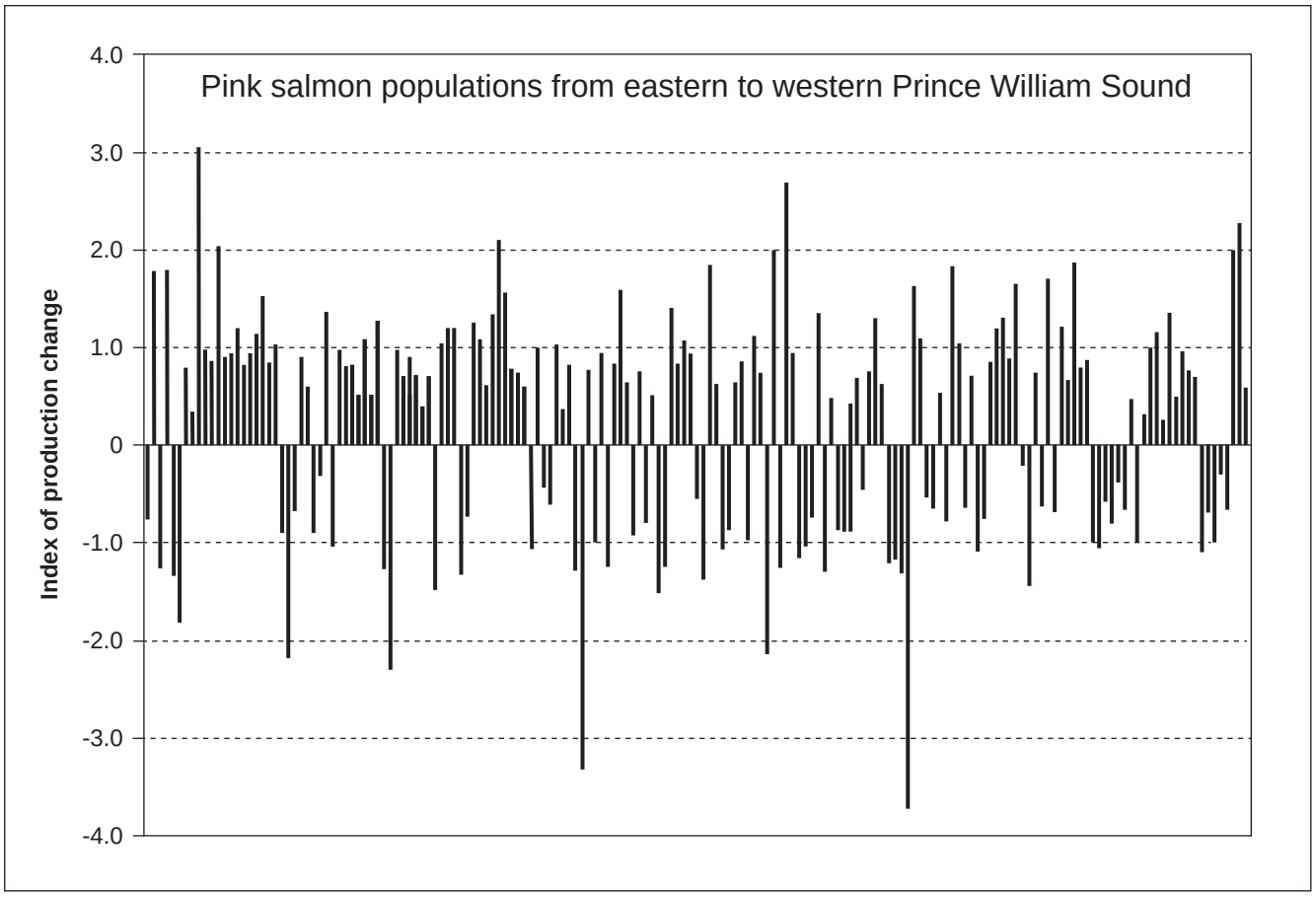


Figure 5-9—Index of production change, expressed as the natural log of P_{change} +1 (see text), for 173 pink salmon populations based on 70-year climate scenario projections under the a1B model; each bar represents a population and is displayed left to right in a sequence that approximately represents an east to west counterclockwise sweep through Prince William Sound.

Chum salmon abundance declined under both the a2 and a1B climate scenarios with the decline ranging from 34 to 41 percent.

response using a binomial test and found that our departure from a random 50/50 distribution of plus and minus values was statistically significant ($p < 0.001$) (table 5-4).

Chum salmon abundance declined under both the a2 and a1B climate scenarios (table 5-4) with the decline ranging from 34 to 41 percent (table 5-4). The analysis included only 16 populations and therefore is not as robust as the pink salmon evaluation. Indeed, a binomial test provided only modest evidence, supporting the conclusion of declining recruitment across populations (11 out of 16: $p = 0.07$). Unlike pink salmon, however, a geographic pattern in the response of chum salmon populations is suggested. Recruitment in populations from the eastern and central portion of Prince William Sound generally decreased in the future, while most from the western Sound were projected to increase (fig. 5-10).

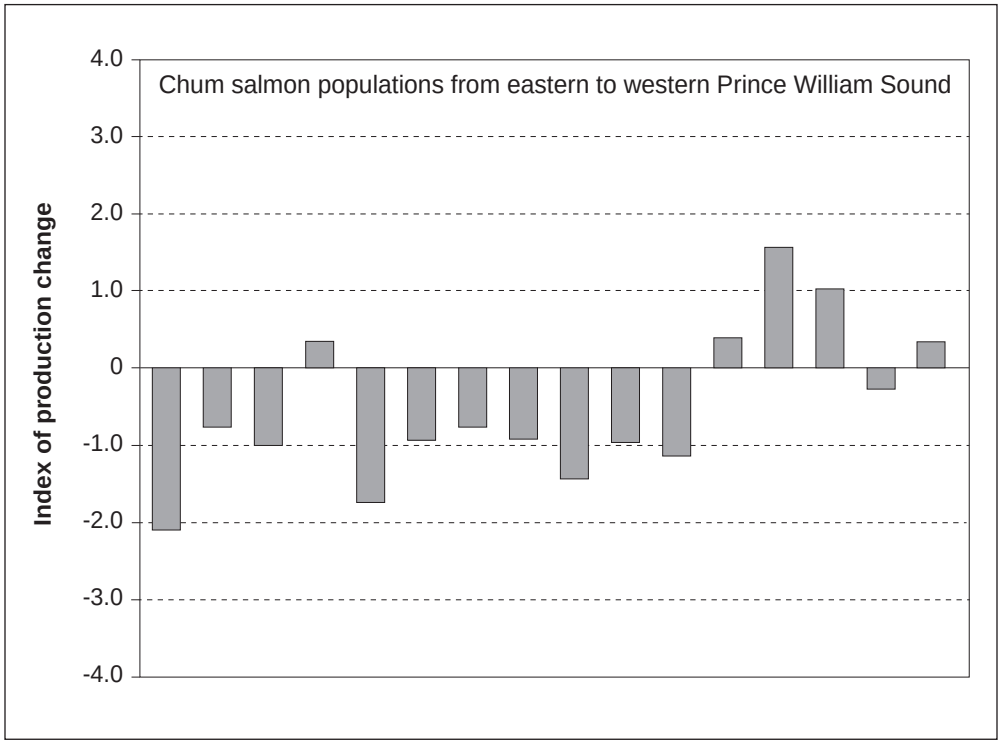


Figure 5-10—Index of change in recruitment expressed as the natural log of P_{change} +1 (see text), for 16 chum salmon populations based on 70-year climate scenario projections under the a1B climate change model. Each bar represents a population and is displayed left to right in a sequence that approximately represents an east to west counterclockwise sweep through Prince William Sound.

Few populations of sockeye, coho, and Chinook salmon had time-series data to support modeling future recruitment. Our models suggested negative responses to warming conditions for both sockeye and Chinook, whereas the single coho population showed a positive response (table 5-4). The limited number of populations studied for these species preclude making any general statements regarding potential response to climate change under this modeling framework.

Our findings were based on the premise that the relationship between air temperature and salmon recruitment in the past can be used to project future salmon spawners. Therefore, our results should not be viewed as predictions about the future production of salmon, but rather one of many possible scenarios that may occur. With that caveat, our population analyses and scenario modeling suggest that the production of pink salmon may increase as the region warms over the next 70 years. In contrast, this same analysis for chum salmon suggests a negative response to warming climate, but the evidence for a decline was weaker. As noted earlier, historical data for sockeye, Chinook, and coho is limited, and our modeling provides inadequate insight into how these species will respond to climate change.

Fish Runs and Fisheries

Our third analysis explored broad-scale relationships between fish abundance and climate using fish catch and run-size estimates (table 5-5). Objective estimates of run-size were regarded as most reliable but were not available for some geographic areas. Therefore, we relied on commercial or recreational fishery catch data for a subset of our analysis (table 5-5). We assumed that harvest was proportional to total run-size. We restricted our analysis to from 1986 to 2012 to establish a baseline or current condition. This time frame was selected as a compromise between accepting all possible datasets, including those with too few years for meaningful analysis, and restricting the analysis to only those few datasets with a longer time series.

Using these sources of information, we were able to compile abundance-related data for 10 groups of fish from the Prince William Sound and Cook Inlet portions of the assessment area. In most cases, the scale of the information was for the entire area (e.g., Prince William Sound). However, representative data were also used that were specific to fish from the intensively managed Kenai River watershed.

We used three climate indices in this analysis. Two were derived from average monthly temperatures recorded at the Cold Bay and Yakutat weather stations as described previously in “Salmon Population Dynamics.” However, unlike the previous analysis, we also examined an annual winter-season temperature index calculated by averaging the sequential monthly temperatures from November to March. For example, the 1990 winter average was calculated as the mean of

Table 5-5—Fish abundance data for ten groups of fish from south-central Alaska used to examine potential relationships between run size and air temperature

Species	Area	Data type	Years	Source
Chum salmon (wild fish only)	Prince William Sound	Total run-size	1986–2012	Brenner (2015)[a]
Pink salmon (wild fish only)	Prince William Sound	Total run-size	1986–2011	Brenner (2015)[a]
Sockeye salmon	Kenai River	Total run-size	1986–2012	Shields and Dupuis (2012)
Sockeye salmon	Prince William Sound	Commercial fishery catch	1986–2012	Botz et al. (2014)
Chinook salmon early run	Kenai River	Total run-size	1986–2012	ADFG (2014), Begich and Pawluk (2011)
Chinook salmon late run	Kenai River	Total run-size	1986–2012	ADFG (2014), Begich and Pawluk (2011);
Coho salmon	Cook Inlet	Commercial fishery catch	1986–2012	Shields and Dupuis (2012)
Coho salmon	Prince William Sound	Commercial fishery catch	1986–2012	Botz et al. (2013)
Dolly Varden char	Kenai River	Recreational fishery catch	1986–2009	Begich and Pawluk (2011)
Rainbow trout	Kenai River (upstream from Skilak Lake)	Recreational fishery catch	1986–2009	Begich and Pawluk (2011)

[a] Brenner, R. 2015. Personal communication. Fishery biologist, Alaska Division of Fish and Game, P.O. Box 115526, Juneau, AK 99811.

monthly averages for November and December of 1989, and January through March of 1990. We used the notations winCB and winYk to represent the indices for Cold Bay and Yakutat, respectively. The SAT_{ARC} (surface air temperature) index described by Johnstone and Mantua (2014) was the basis for the third index used in our evaluation. The authors derived SAT_{ARC} from temperature data collected at 51 stations around the margin of the northeast Pacific Ocean. Using supplemental information referenced by Johnstone and Mantua (2014) we generated a winter version of this index ($winSAT_{ARC}$) by averaging SAT_{ARC} values for the months of November through March.

Our rationale for focusing on the winter time frame was twofold. First, we expected winter temperatures to have a strong influence on snowfall accumulation and subsequent patterns of stream discharge and temperature. These physical factors may have a strong influence on variations in salmon production from year to year. Second, winter air temperatures for this region are strongly associated with sea surface temperatures (SST) (Johnstone and Mantua 2014), and the greatest contrasts in these SST from year to year occur during the winter months (Mantua 2001). Not only did we hope to take advantage of these larger contrasts to resolve temperature associations with fish abundance, we were also aware that correlations between annual fluctuations in PDO, an index of SST, and salmon production as well as other physical factors such as streamflow, flood risk, and snowpack have been demonstrated by others (Mote et al. 2003).

We matched temperature time series with the corresponding start and end dates for fish abundance data (either total run-size or fishery catch) and computed a correlation coefficient, r, for each fish run. We were interested in the direction (positive vs. negative) rather than the size of resulting correlations. A negative correlation indicated that, for the period of record, increased air temperatures were associated with lower fish abundance estimates, while a positive value meant the reverse.

In addition to examining the influence of temperatures during the year of the adult return, we also applied a range of lag periods to match other portions of salmon life history. For example, a pink salmon that spawned in 1990 (year = t) would have been an incubating embryo during the winter/spring of 1989 (year = t – 1). Therefore, to capture the pink salmon life cycle, we matched the temperature index sequences for year t and year t – 1. We applied this temperature lag to all of the fish abundance datasets, employing a range of lag periods to match the life cycle of the species involved. Although the pink salmon life cycle is fixed at 2 years, life cycle length for other species can vary considerably within species. To account for within-species variability, we selected a generic life cycle that spanned all commonly observed ages of adult return in this portion of Alaska: Chinook salmon = 6 years, sockeye and chum salmon = 5 years, coho salmon = 4 years. We assumed a 5-year cycle for Dolly Varden char, cutthroat trout (*Oncorhynchus clarkia*), and rainbow trout.

Fish Runs and Fisheries—Findings

Fish run size and temperature demonstrated a broad range of relationships within and among fish species. Correlation coefficients varied from -0.51 (PWS sockeye salmon, winCB, lag-3) to 0.53 (early run Kenai Chinook, winCB, lag-2) (table 5-6). Across all 10 groups, there was no consistent pattern of positive or negative correlations with temperature. Chum salmon, Kenai sockeye, both Kenai Chinook runs, and Cook Inlet coho abundance were positively related to air temperature, based on the results of a binomial test for statistical departure from the null hypothesis of equal positive and negative temperature associations. From 1986 to 2012, warmer temperatures were associated with more fish and cooler temperatures were associated with fewer fish.

Sockeye salmon from Prince William Sound were the only group showing a consistent negative response to temperature, suggesting asynchronous production between Kenai and Prince William Sound sockeye.

Sockeye salmon from Prince William Sound were the only group showing a consistent negative response to temperature, suggesting asynchronous production between Kenai and Prince William Sound sockeye. Asynchronous production cycles among populations of salmon over long periods (500 years) have been reported in the case of sockeye salmon returning to different watersheds on the Alaska Peninsula (Rogers et al. 2012).

Table 5-6—Relation between fish abundance and winter temperature indices winCB (Cold Bay), winYk (Yakutat), and $winSAT_{ARC}$ (surface air temperature index from Johnstone and Mantua 2014) for ten groups of fish (correlation coefficient), where a grey shading indicates negative correlation coefficients

Group	Time lag	winCB	winYk	$winSAT_{ARC}$
Chum salmon—Prince William Sound	-4	0.01	-0.09	-0.05
	-3	0.18	0.24	0.10
	-2	0.15	0.22	0.05
	-1	0.11	0.17	0.01
	0	0.07	0.25	0.23
Pink salmon—Prince William Sound	-1	-0.28	0.03	-0.09
	0	0.33	0.18	0.16
Sockeye salmon—Kenai	-4	-0.20	0.21	0.02
	-3	0.10	-0.09	-0.21
	-2	0.35	0.13	-0.12
	-1	0.30	0.08	0.14
	0	0.30	0.29	0.38
Sockeye salmon—Prince William Sound	-4	-0.47	0.04	-0.03
	-3	-0.51	-0.10	-0.20
	-2	-0.36	-0.03	-0.18
	-1	-0.18	-0.07	-0.15
	0	-0.19	0.16	0
Chinook salmon—Kenai early run	-5	0.15	0.13	0.07
	-4	0.17	-0.23	-0.17
	-3	0.50	0.28	0.38
	-2	0.53	0.08	0.15
	-1	0.23	0.27	0.29
	0	0.25	-0.09	0.17
Chinook salmon—Kenai late run	-5	-0.24	0.11	0
	-4	0.03	0.12	0.11
	-3	0.41	0.35	0.33
	-2	0.51	0.28	0.30
	-1	0.52	0.40	0.49
	0	0.33	0.24	0.40
Coho salmon—Cook Inlet	-3	0.33	0.15	0.02
	-2	0.20	0.18	0.13
	-1	0.48	-0.06	-0.13
	0	0.23	-0.05	0.13
Coho salmon—Prince William Sound	-3	0	0.13	-0.03
	-2	-0.11	0.21	0.13
	-1	0.35	0.17	0.13
	0	0.22	-0.05	0.11
Dolly Varden—Upper Kenai	-4	-0.17	-0.38	-0.17
	-3	0.17	-0.30	0.01
	-2	0.04	-0.14	-0.08
	-1	-0.06	0.29	0.18
	0	-0.33	-0.18	-0.30
Rainbow trout—Upper Kenai	-4	-0.12	0.09	0.20
	-3	-0.21	0.02	0.03
	-2	-0.42	0.01	-0.10
	-1	0.03	0.33	0.18
	0	-0.31	-0.17	-0.38

Coho salmon were the only other species for which Kenai versus Prince William Sound groupings could be compared. In this case, the pattern of fish abundance appeared positively correlated with air temperature, although only the Kenai group demonstrated strong evidence of a positive correlation between the abundance of spawners and previous air temperatures.

Numbers of early- and late-run Kenai River Chinook were both positively associated with air temperature. However, there appeared to be a difference between the two groups in terms of the lag period that was associated with the largest correlation coefficients. The best correlations were found using a -3-year lag for the early run and a -1-year lag for the late run. Although these correlations may be spurious, it is also possible that they indicate different temperature impacts acting on the survival of Chinook, which occur at a later life stage in the late run (-1 lag) than the early run (-3 lag).

With the exception of Chinook, we did not find any evidence that a particular lag period was consistently associated with the highest correlation coefficients. Had there been a particular temperature-critical stage in the life history of one of these groups, we expected to find that reflected as consistently higher correlation coefficients for a specific lag period matching the age at the critical life history stage. That we found evidence of this only in the case of Chinook may mean that the logic behind this expectation was flawed, that there was significant mixing of age groups in individual runs (except for pink salmon which are all the same age at return), or that the data were not sufficient to detect this feature.

The relationship between temperature and fish abundance suggested in this analysis is dissimilar to those obtained in the previous section (see "Salmon Population Dynamics—Findings") based on population dynamics modeling. In particular, we found that chum salmon abundance was positively associated with temperature in this section but negatively associated with temperature in the former section, and that pink salmon abundance was unrelated to temperature in this section but positively associated with temperature for the majority of runs in the former.

The reason for these inconsistencies may simply be that the methods used to derive the estimates are so different that forcing a comparison will invariably yield meaningless outcomes. Another possibility is that the time series used in each was not long enough to establish a reliable association with observed air temperatures. We found some evidence to support the latter explanation.

Total run-size estimates for wild pink and chum returning to Prince William Sound are available for years prior to 1977, but not for the other fish groups evaluated in this report. For pink salmon, the full data set runs from 1960 to 2011 and for chum salmon it runs from 1970 to 2012. When we repeated the temperature-fish

For this longer time series, all of the associations tested between fish abundance and temperature were positive, indicating that across all combinations, warmer conditions were associated with more fish.

abundance correlation analysis of this section for this longer dataset, the results were different and seemed more consistent in terms of which life history stage was most sensitive to temperature variations.

For this longer time series, all of the associations tested between fish abundance and temperature were positive, indicating that across all combinations, warmer conditions were associated with more fish (table 5-8). For both chum and pink salmon, there was strong evidence for a positive relationship (more positive correlations than expected by chance, $p < 0.05$). In addition, for chum salmon the highest correlations for all three temperature indices occurred for the -3 year lag; corresponding to the first winter of ocean residence. For pink salmon, the picture was less clear. For two of the three indices, the largest correlation occurred for the 0 lag time, which represents the last winter of ocean residence.

Table 5-7—Number of positive and negative correlations between fish abundance and air temperature indices for each of 10 groups of fish (p-value associated with binomial tests for equal proportions of positive and negative correlations)

Fish abundance dataset	Correlation count		Statistical probability
	Positive	Negative	
Chum salmon—Prince William Sound	13	2	0
Pink salmon—Prince William Sound	4	2	0.23
Sockeye salmon—Kenai Peninsula	11	4	0.04
Sockeye salmon—Prince William Sound	2	13	0
Chinook salmon—Kenai Peninsula (early run)	15	3	0
Chinook salmon—Kenai Peninsula (late run)	17	1	0
Coho salmon—Cook Inlet	9	3	0.05
Coho salmon—Prince William Sound	8	4	0.12
Dolly Varden—Upper Kenai Peninsula	5	10	0.09
Rainbow trout—Upper Kenai Peninsula	8	7	0.20

Table 5-8—Relationship between chum and pink salmon estimates of total run-size and temperature indices for an extended time series of 1970–2012 (chum) and 1960–2011 (pink) (p-value associated with binomial tests for equal proportions of positive and negative correlations)

Group	Time lag	winCB	winYk	$winSAT_{ARC}$
Chum salmon (1970–2012)	-4	0.31	0.19	0.17
	-3	0.33	0.33	0.28
	-2	0.21	0.17	0.06
	-1	0.06	0.27	0.19
	0	0.26	0.28	0.25
Pink salmon (1960–2011)	-1	0.07	0.28	0.27
	0	0.49	0.31	0.22

It appears that, over the long term, both pink and chum salmon numbers are greater when temperatures are warmer. For pink salmon in particular, the positive relationship is different from the ambivalent result for the shorter 1986–2011 period. We are unable to evaluate relationships over this longer period for the other salmon because the necessary data were not available.

It appears that, over the long term, both pink and chum salmon numbers are greater when temperatures are warmer.

Examining a longer time series for pink and chum salmon, we found that the fish abundance was more likely to have a positive association with the temperature indices (tables 5-7 and 5-8). If this association represents a biologically significant linkage with temperature, and if this linkage remains into the future as temperatures increase, we expect an increase in the number of fish for each of these groups. The exceptions were the results for Prince William Sound coho salmon, which was somewhat ambiguous, and the negative temperature association found for Prince William Sound sockeye salmon.

The two non-salmon fish, Dolly Varden char and rainbow trout from the upper Kenai River, demonstrated no association between fish abundance and temperature (table 5-7). Because the life history of neither population includes an ocean phase, all of the potential temperature effects would occur in fresh water. It is possible that the lack of association between fish numbers and temperature in this case could mean purely freshwater species in this region are less susceptible to annual temperature variations than those that are anadromous, such as salmon. If this were true, perhaps these species would be less affected by the warmer temperatures of the future. The corollary to this hypothesis might be that the primary driver of the linkage between temperature and fish abundance was associated with the ocean environment. However, it is also possible the catch of these two freshwater species in recreational fisheries, which is the basis for the data used in our analysis, is influenced by other unique factors such as annual variations in the clarity of water conditions, how many salmon eggs are accessible to predation, and stream temperature. Finally, it is also possible that the nature of the temperature-fish abundance associations for these two groups, along with Prince William Sound coho salmon, is such that their detection requires the analysis of data over a longer time period, similar to pink salmon.

Effects on Salmon Ecosystem Services

In this section, we summarize how salmon harvested in the assessment area are used by people and how the benefits provided by these fish—the ecosystem services from salmon—might be affected by the climate scenarios discussed in the preceding sections.

Between 29 million and 104 million salmon were caught annually during the period of 2009 through 2013; the average was 61 million fish.

Salmon in the assessment area are caught by commercial fishers, by sport anglers, by subsistence users, and by Alaska residents participating in "personal use" fisheries. As discussed in appendix 3, between 29 million and 104 million salmon were caught annually during the period of 2009 through 2013; the average was 61 million fish. Based on 2011 and 2012 data, more than 96 percent of all salmon were caught for commercial purposes (table 5-9 and fig. 5-11). However, the breakdown differs significantly between sockeye and pink salmon, the two most important species when measured by volume or market value. Sockeye, which typically have a commercial value per fish exceeding five times that of pink salmon, are highly valued by sport, subsistence, and personal-use fishers in the assessment area. Pink salmon are not.

Table 5-9—Distribution of commercial, sport, subsistence, and personal-use harvest of salmon based on average salmon catch from 2011 and 2012 harvest years in the assessment area

	Sockeye	Pink	All salmon
Number of fish:			
Commercial	8,108,500	30,855,000	42,484,500
Sport	529,826	47,820	904,588
Subsistence	9,212	1,621	12,817
Personal use	767,438	5,077	784,028
Total	9,414,976	30,909,517	44,185,933
Share of fish:			
		Percent	
Commercial	86.1	99.8	96.1
Sport	5.6	0.2	2.0
Subsistence	0.1	0	0
Personal use	8.2	0	1.8
Total	100.0	100.0	100.0

Note: personal use includes the Chitina Subdistrict dip net fishery.

Also apparent from these data is the overwhelming importance of personal-use sockeye salmon fisheries to Alaska residents living in the assessment area. More than 44,000 permits were issued in recent years (2011–2012) to households participating in the Cook Inlet and Chitina Subdistrict personal-use dip net fisheries. Personal-use fisheries are dominant because almost the entire Anchorage and Kenai Peninsula regions are classified as the "Anchorage-Matsu-Kenai Nonsubsistence Area" by the Alaska Joint Board of Fisheries and Game (Fall et al. 2014). The personal-use fisheries are undoubtedly used by many households from the urban areas of Anchorage and surrounding communities who consider their fishing to be for "noncommercial, customary, and traditional uses." In other words, for many

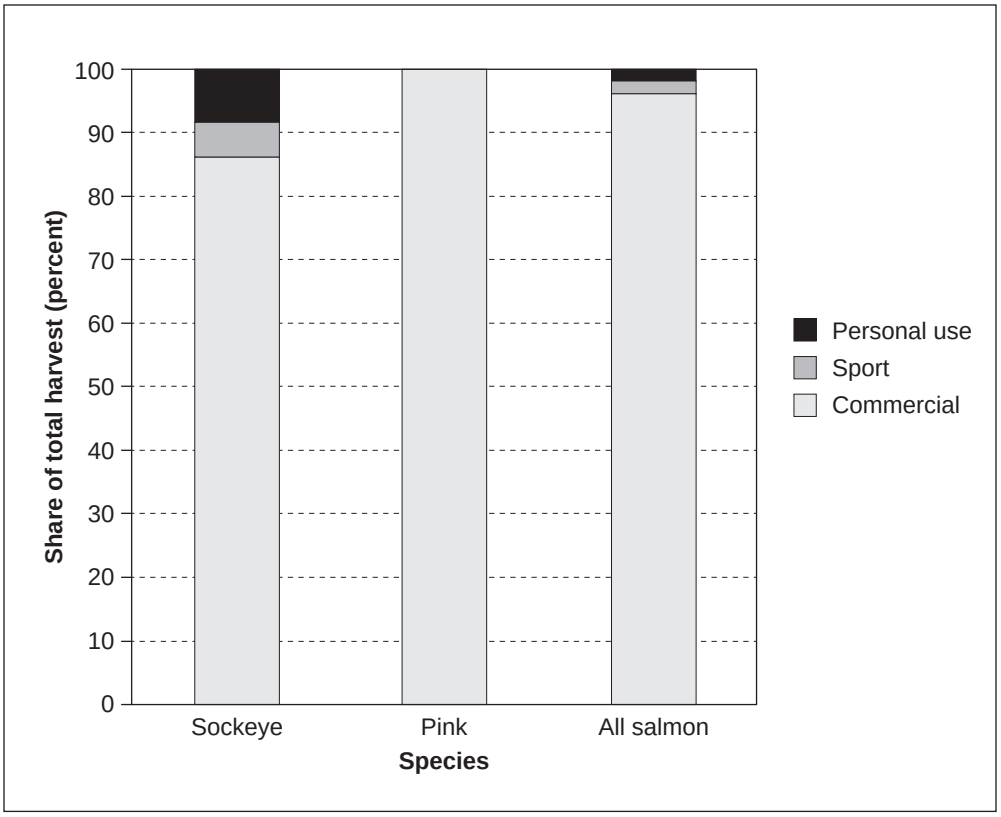


Figure 5-11—Relative numbers of salmon caught in the commercial, sport, and personal-use fisheries within the assessment area based on average 2011 and 2012 data. Subsistence use is not shown owing to low values. Personal-use numbers include the Chitina Subdistrict dip net fishery. Source: author calculations using data from ADFG (2014, 2015) and Fall et al. (2013, 2014).

people the personal-use fishery provides the same benefits as an officially designated subsistence fishery.

In addition to providing direct benefits to people, salmon also play an important role in nutrient cycling that benefits upstream ecology (Post 2008). We do not consider these services in greater detail.

We now consider some further aspects of the commercial, sport, subsistence and personal-use salmon fisheries in relation to the findings presented earlier in this chapter. We consider two broad scenarios. First, the ecological impact of warming conditions may lead to more fish, especially pink salmon in Prince William Sound. Second, substantial variations in response to climate change among populations and species will mean declines in fish abundance may occur, with a focus on sockeye salmon. These two scenarios, which represent very different outcomes, represent useful scenarios to examine because of the substantial uncertainty in future salmon populations based on the combined effects of freshwater and marine life history stages.

In discussing these scenarios, we focus in this section on social and economic factors and outcomes. The findings about salmon abundance reported above relate to what we may call the biophysical subsystem. There is also what we may call the social-economic subsystem, which exerts significant influence on the overall salmon-related social-ecological system (SES). The two subsystems interact directly through annual fish harvest management and catch effort, and indirectly through actions that affect fish habitat.

Commercial Salmon Harvest

The Alaska commercial salmon harvest fluctuates significantly over time (fig. 5-12). This fluctuation results in part from numerous factors affecting total salmon biomass (which is, of course, not directly measurable). People directly influence some of these factors. Hatcheries—which accounted for about 37 million Prince William Sound pink salmon in 2015 (PWSSC 2015)—provide one salient example of this direct influence. Habitat alteration operates over longer time scales to affect biomass through biophysical channels.

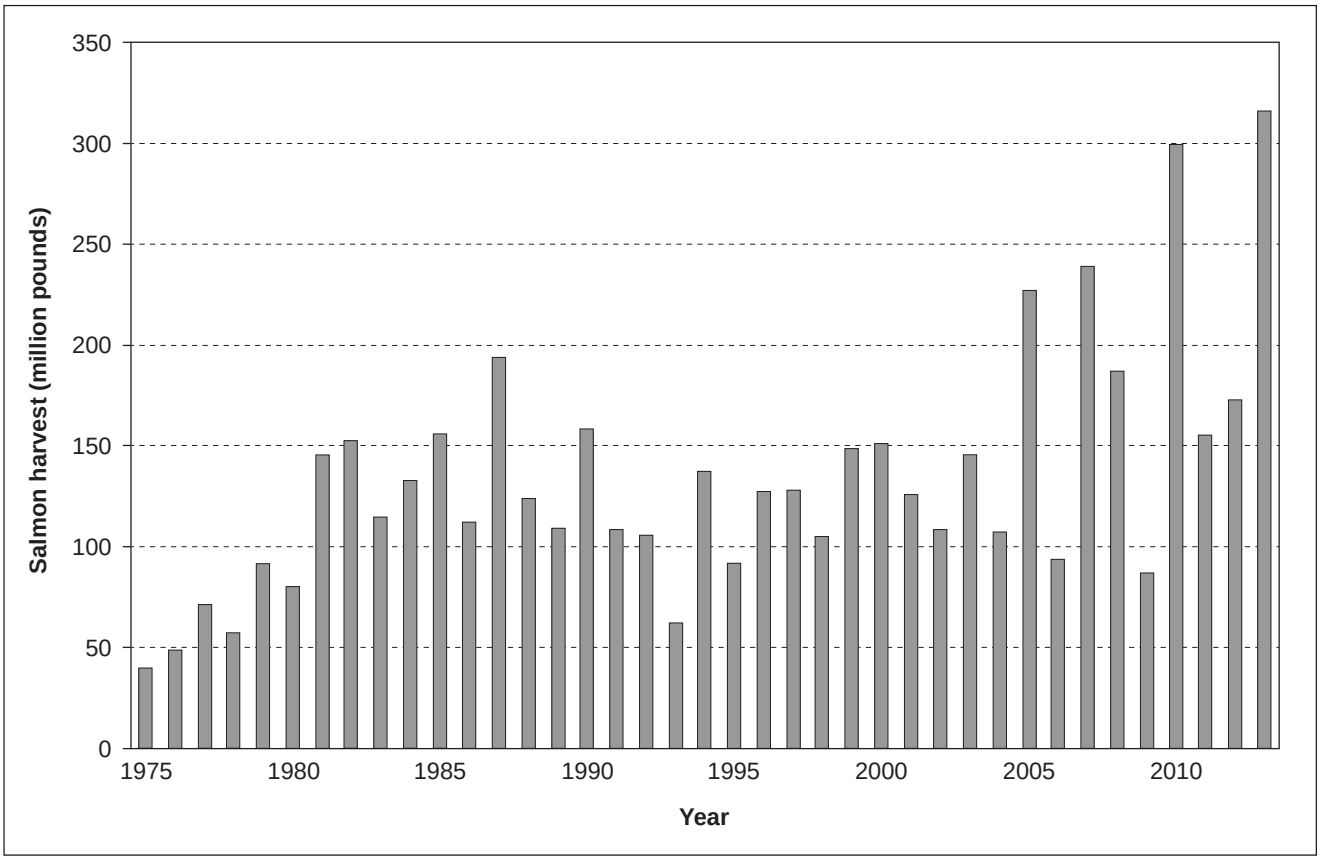


Figure 5-12—Volume of commercial salmon harvested from the combined Prince William Sound and Cook Inlet fisheries. Source: author calculations using raw data from the Alaska Commercial Fisheries Entry Commission. http://www.cfec.state.ak.us/fishery_statistics/earnings.htm.

Changes in fish biomass do not translate directly into changes in jobs, income, or profits to fish harvesters and others engaged in the seafood industry. There are several important intervening steps in the process that bear separate consideration when determining the social and economic vulnerability of the commercial fishing industry to climate change. Indeed, the social-economic subsystem exhibits its own sensitivity, exposure, and adaptive capacity, all of which determines the extent to which changes in biophysical abundance ultimately affect both total harvests and the allocation of those harvests among competing groups.

Changes in fish biomass do not translate directly into changes in jobs, income, or profits to fish harvesters and others engaged in the seafood industry.

The first linkage is from biomass abundance to commercial harvest. This connection is mediated by the behavior of harvesters and fishery managers. Alaska fish harvesters have a long history of adapting their harvesting efforts to different places, different species, different technologies (such as fish traps or weirs), and different "rules of the game." If salmon abundance shifts primarily geographically, harvests could plausibly shift as well.

The second link is from harvest volume to initial harvest value ("ex-vessel value"). This link depends critically on the price per pound received by harvesters. Ex-vessel price has fluctuated at least as much as harvest volume during the past 40 years, with prices sometimes doubling or falling by half during 2- or 3-year periods. Volatile prices are determined by numerous factors, most of which are not directly affected by climate change. These include foreign exchange rates, shifts in consumer tastes, and the abundance and prices of other salmon—both wild (Russian) and farm-raised substitutes (chiefly farmed Atlantic salmon, which now accounts for two-thirds of total world salmon supply (Knapp 2013)).

Figure 5-13 shows, for the combined Prince William Sound–Cook Inlet salmon fishery, how salmon volume, price, and ex-vessel value have changed since 1975. The simple correlation coefficient for volume and value is only 0.3. However, when only the past 20 years are considered, the correlation between volume and value is actually much stronger ($r = 0.8$). The correlation between harvest volume and price during this 20-year period is slightly negative ($r = -0.3$), indicating that high volumes might depress the price. If this is true, then the increase in pink salmon volume resulting from warmer temperatures might be attenuated by lower prices, with uncertain effects on harvester earnings.

There are additional links in the social-economic subsystem between ex-vessel or gross value, and measures of net economic benefit such as profits to fish harvesters or wages to participants in the processing industry (many of whom live in Alaska). In the short run, variable inputs can be adjusted, and in the longer run technological innovation could take place, all directed at reducing costs. Fundamental institutional innovation is also possible (Ulmer and Knapp 2005). For example,

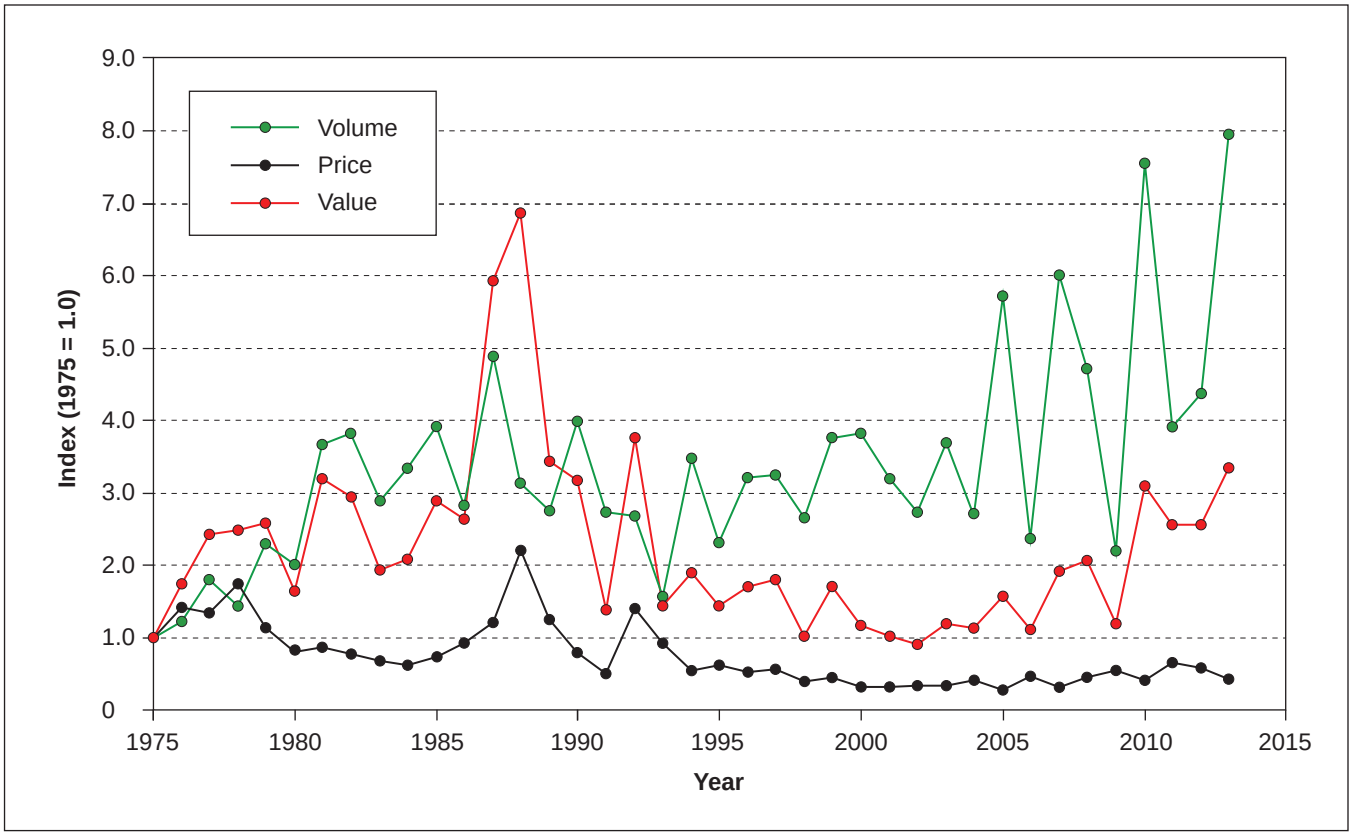


Figure 5-13—Salmon volume, price, and value relative to 1975 for the combined Prince William Sound and Cook Inlet fisheries. Values for 1975 are set equal to 1.00. Source: author calculations using raw data from Alaska Commercial Fisheries Entry Commission. http://www.cfec.state.ak.us/fishery_statistics/earnings.htm.

the current system for salmon is based on limited entry into the fishery but unlimited rights to catch fish during openings. This system could be changed to a catch-share system such as the one now used for halibut, under which each harvester must own the harvesting rights to a specific number of fish.

The commercial pink salmon harvests in the assessment area are mostly of hatchery-raised fish. The overwhelming factor affecting the profitability of hatcheries is the return rate of adult fish from the ocean back to the hatchery. Because hatcheries have high fixed costs, they are vulnerable to complete shutdown if returns drop below some minimum threshold. Conversely, under a scenario of increased biomass associated with warmer temperatures, hatcheries could enjoy major economic benefits because their fixed costs are already covered so that additional fish contribute directly to net income.

Next, we consider the second scenario of possible declines in some fish populations and species resulting from the large variability in expected responses to ecological changes brought on by a warming climate.

For sockeye salmon, if climate change results in a decline in numbers, the impact could be quite negative for the Alaska commercial industry. There are three reasons for this concern. First, the findings reported in this chapter are neutral-to-negative regarding any countervailing positive effects of warmer air temperatures on sockeye abundance. Second, it is possible that warming temperatures may correlate with reduced fishery catches of sockeye, even though the supporting data upon which this finding is based are quite limited. Third, sockeye are far more valuable (per fish) than pinks and cannot be easily augmented by hatchery technology. The average annual ex-vessel value of sockeye from the assessment area was about $70 million during the period from 2009 to 2013. A 40 percent decline in abundance could result in about $30 million of lost ex-vessel value, which equals 18 percent of total commercial salmon ex-vessel value.

Sport Salmon Harvest

The economic importance of sport fishing to the Alaska economy is well documented (Colt and Schwoerer 2009, Fay et al. 2007, Haley et al. 1999, Northern Economics 2009). As discussed in appendix 3, total spending by anglers in 2007 on sport and personal-use fishing activities in south-central Alaska was about $1 billion. This spending supported 11,535 jobs and generated $386 million of labor income (Southwick Associates 2008). These numbers are based on all species and include spending on the personal-use fisheries. Salmon constituted 74 percent of all fish caught by these groups (ADFG 2014), and the annual number of salmon caught was about 900,000 (sport) and 800,000 (personal use). Assuming that sport anglers spent three times as much per fish as personal-use dip netters, a rough estimate of spending on sport-fishery salmon harvesting is about $575 million, which would support about 6,600 total jobs. This calculation also yields the figure of $636 per fish for expenditures on sport fishing for salmon.

A rough estimate of spending on sport-fishery salmon harvesting is about $575 million, which would support about 6,600 total jobs.

Because sockeye account for 59 percent of total sport-fishery salmon, by applying the figure of $636 per fish we can estimate that the assessment area sport sockeye fishery generates about $337 million of angler spending and supports about 3,900 jobs. Even if the total sockeye abundance were to drop by 40 percent, and even if that decline were allocated proportionately to sport fishing, it is unlikely that sport anglers would reduce their effort and spending by 40 percent. Nonresidents in particular are arguably paying for a fishing experience rather than a certain number of fish. However, even if sport-fishing effort and spending were cut by only 20 percent the result would be a loss of more than $67 million of spending and 777 fishing-related jobs. When considering these potential losses of jobs and spending,

keep in mind that the spending by Alaska residents would likely be redirected to other activities, and not lost from the economy altogether.

Subsistence Salmon Harvest

Only about 9,000 sockeye salmon—less than one-tenth of 1 percent—are caught by participants in officially designated subsistence fisheries (table 5-9). Because this number is so small, and because subsistence fisheries must be given a preference in times of shortage, it is reasonable to project that even if sockeye abundance were to fall by 20 or even 40 percent the salmon allocations to official subsistence fisheries could and likely would remain the same.

A potentially more important effect of warming for these fisheries could be changes in run timing. There is already some tension in some Alaska communities between participation in subsistence and participation in cash jobs and school (Colt et al. 2003). To the extent that participation in subsistence provides cultural benefits, it will be important for institutions such as schools and employers to attempt to accommodate shifts in the scheduling of subsistence fishing.

Personal-Use Salmon Harvest

The personal-use salmon fishery is completely focused on sockeye salmon, and accounts for about 8 percent of the total sockeye harvest from the assessment area (including the Chitina Subdistrict dip net fishery). Although some participants may derive cultural and educational benefits from participating, many if not most are seeking to fill their freezers with high-quality protein. It appears that personal-use dip net fishers currently have no interest in substituting pink salmon for sockeye. It also seems less likely that fishery managers would reallocate sockeye salmon from commercial or sport harvests to maintain the size of the personal-use fisheries. It is also the case that personal-use participants are not interested in nor directly affected by the commercial price of sockeye salmon.

The personal-use fishery appears to be the most vulnerable to a significant decline in sockeye salmon biomass that result from ecological shifts brought on by climate change.

For all these reasons, the personal-use fishery appears to be the most vulnerable to a significant decline in sockeye salmon biomass that result from ecological shifts brought on by climate change. Conversely, it would not benefit from an increase in pink salmon biomass. There were 44,125 permits issued for personal-use fisheries (average of 2011 and 2012 data) (Fall et al. 2013, 2014). That number equates to 17.77 fish caught per permit. Assuming an average weight of 6.55 pounds (ADFG 2015), each personal-use permit holder (typically one household) harvested 116.4 pounds of sockeye salmon in 2011 and 2012. If this harvest were to be reduced by 20 or by 40 percent, participating households would see declines of 23 or 46 pounds, respectively.

Ecosystem Services Summary of Findings

As this chapter has emphasized, warmer air temperatures may be associated with more pink salmon, while changes in sockeye abundance are much less certain and may be negative. There are likely to be many ways by which the commercial fishing industry can adjust to these possible changes in the abundance or location of salmon. The industry has a long history of adapting to both abrupt and gradual changes. The sport-fishing industry would likely have a more difficult time dealing with a major decline in sockeye salmon abundance simply because it is more focused on one species, and each fish is associated with significant spending and employment. However, reduced spending by Alaska residents on sport fishing would likely shift to other activities but would remain within the regional economy. Officially designated subsistence salmon fisheries in the assessment area could easily be maintained because they are currently allocated very few fish. (Of course, this conclusion would not be valid for other areas of Alaska with major subsistence fisheries, such as the Yukon River watershed.) Finally, the personal-use fisheries, which are exclusively focused on harvesting sockeye salmon by dip net, appear to be most vulnerable to a warming climate. A potential increase in pink salmon abundance would likely provide no increase in ecosystem services to this fishery. However, a decrease in sockeye abundance in the assessment area could translate directly into significant losses of food protein for more than 40,000 Alaskan households.

A decrease in sockeye abundance in the assessment area could translate directly into significant losses of food protein for more than 40,000 Alaskan households.

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Patricia Hayward



Fall color above Eklutna Lake, Chugach Mountains, Alaska.

Chapter 6: Vegetation

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Introduction

A challenging task is to assess current vegetation patterns across a gradient that extends from marine intertidal communities along the Prince William Sound and Kenai Peninsula coastlines, to coniferous forests and alpine tundra at higher elevations. Assessing future vegetation patterns is even more difficult. However, because vegetation is one of the most critical biotic components of terrestrial systems, describing the patterns of plant communities and species in the assessment area is a necessary initial step toward understanding the effects of climate change. Subsequent steps include projecting future patterns in these plant groups and a synthesis of expected changes in the vegetation patterns and potential alterations of ecosystem services.

Climate strongly influences plant species distributions at broad spatial scales, while species interactions, disturbance patterns, and soil conditions generally drive plant distributions at the local level (GBIF 2015, Pearson et al. 2003). With dramatic increases in mean annual temperature in Alaska in the last century (Wendler et al. 2012) and continued increases in growing-season length (SNAP 2012) (see

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chapter 3), plant distributions in this region are expected to change. Climate change is expected to affect plant species that are both of ecological significance (e.g., dominant trees) and of conservation concern (i.e., rare species and invasive species). Many examples are accumulating of distribution changes in response to climate or of spatial mismatches between optimal climates and the current climate the species experiences (e.g., McLane and Aitken 2012).

Climate change affects the distribution of plant species in multiple ways. It can cause rapid range contraction, in which direct climate effects (conditions being too hot, too dry, too wet, or too cold) result in large-scale mortality. It can also cause slow range contraction, in which direct climate effects affect successful regeneration and establishment of seedlings of long-lived species. Climate change modifies interactions among species in both simple and complicated ways. For instance, climate alters competitive ability by differentially affecting growth, mortality, and regeneration for co-occurring (sympatric) species. Recent examples of large-scale tree mortality in North America (Abella and Fornwalt 2014, Bentz et al. 2010, Berg et al. 2006, Cudmore et al. 2010, Mitton and Ferrenberg 2012) suggest that climate-related alterations in disturbance regimes—particularly fire and insects—are even more important factors in rapidly shifting distributions than are direct physiological impacts from climate change.

Ecological Setting

The Copper River Delta on the eastern side of the assessment area comprises the largest wetland on the west coast of North America—an area of rapid wetland succession occurring as a result of multiple disturbance processes, which include flooding by one of the largest rivers along the west coast and changes in saltwater influence stemming from tectonic uplift (the 1964 earthquake) and gradual subsidence (Plafker et al. 1992). Prince William Sound dominates the center of the study area, supporting 4,355 islands (those larger than 100 m^2) that result in varying degrees of biological isolation and challenges for species movement and establishment since the last glacial maximum. Like the islands of Prince William Sound, the Kenai Peninsula, which marks the western portion of the assessment area, is partially isolated from mainland biota and experiences substantial differences in climate from east to west as result of a north-south mountain range that intercepts the generally east-to-west flow of storm systems. As a consequence, the Kenai currently supports coastal rain forest along its eastern shores and transitional boreal forest on northwestern lowlands, with montane and alpine habitats in between. Elevations in the assessment area range from sea level along the extensive coast to Mount Marcus Backer in the Chugach Mountains at 4016 m.

Understanding the potential influences of climate change on vegetation in south-central Alaska is impossible without some underlying knowledge of current vegetation patterns within the context of the directional development of vegetation that has occurred over the past 3,000 to 14,000 years following the last glacial maximum. In this chapter, we take a four-pronged approach to addressing vegetation change within the context of climate change:

Understanding the potential influences of climate change on vegetation in south-central Alaska is impossible without some underlying knowledge of current vegetation patterns.

(1) We begin with a broad overview of environmental history and a description of historical vegetation patterns, with particular emphasis on these patterns in relation to climate change in the past.

(2) We follow the historical overview by reviewing current vegetation patterns. This includes linking current patterns to past climate, abiotic factors, and succession.

(3) We then outline scenarios of future vegetation cover.

(4) To close, we emphasize the potential consequences of a changing climate on wildfire, which is one of the most important vegetation disturbance agents in this system. Throughout the second and third sections of this chapter, we employ a hierarchical approach, looking at current and future patterns in biome-level vegetation, landcover types, coniferous spruce trees, rare species, and invasive species. As in the other chapters of this assessment, we close with consideration of the potential consequences for ecological services resulting from changes in physical and ecological conditions.

Summary of Historical Vegetation Patterns

- Vegetation across the assessment area is dynamic—the region has exhibited directional vegetation change for thousands of years. Except for limited glacial refugia found on the Kenai Peninsula and on a few nunataks in Prince William Sound, vegetation across the assessment area developed during the past 10,000 to 14,000 years of glacial retreat, with relatively similar patterns of primary succession and eventual development of forest on sites capable of supporting tree growth.
- Vegetation development from bare ground, or primary succession, which can be observed near recent areas of glacial retreat, illustrates the process of directional vegetation development that has occurred throughout the region since the last glacial maximum.
- Conifer forests were rare east of the Kenai Mountains until about 2,000 years ago. Sitka spruce woodlands likely formed on the eastern side of the Kenai Peninsula and on islands throughout the Sound beginning 3,000

years ago, but well-developed temperate coastal rain forests became common only in the last 2,000 years. Boreal forest to the west of the Kenai Mountains formed earlier by migration of species from ice-free refugia. Boreal forests spread across the western Kenai about 4,600 years ago.

- Migration of plants via seed and vegetative reproduction occurred from source populations in southeast Alaska, small areas of glacial refugia throughout the assessment area, and for boreal species, from forests to the north.
- Historically, fire has not played a major role in the ecosystems of coastal temperate rain forests. In the boreal region of the Kenai, fire was historically important and was tightly linked to historical vegetation patterns.

The Future Is Contingent On the Past: Historical Changes in Vegetation

Climate ultimately determines the potential distribution of vegetation at broad spatial scales (Cain 1944, Woodward 1987). However, ecological processes, regional climate variation, geographic barriers to dispersal, and soil factors all act to influence the realized distribution of species, thereby determining their historical and current geographic distribution (Kruckeberg 2002). Almost complete glacial cover during the last glacial maximum, followed by gradual deglaciation over the past 12,000 to 20,000 years, and more rapid ice lost since the end of the Little Ice Age (circa 1850) created a geologically "new" landscape that was quickly colonized by short-lived species that can thrive post-disturbance (fig. 6-1). Below, we examine the short- and long-term ecological history of the assessment area to illustrate how climate resulted in directional change that has occurred for millennia and to provide context from which to evaluate potential future changes resulting from human-induced climate change in the future.

Long-Term Vegetation History

Inspection of the fossil record reveals that dramatic changes in vegetation occurred repeatedly in the past in response to changes in global climate. Particularly striking was the occurrence of temperate hardwoods such as oak, hickory, beech, chestnut, elm, and sweetgum in interior and south-central Alaska during the Miocene (17 to 14.5 mya). Following an abrupt transition from the extremely warm Miocene period, temperatures oscillated and tree species diversity was extremely high compared to the present. The region supported a range of conifers including Douglas-fir, redwood, pine (related to lodgepole pine), and firs (Ager 2007). Tree species diversity declined during glacial/interglacial cycles of the Pliocene (2 to 6 mya),

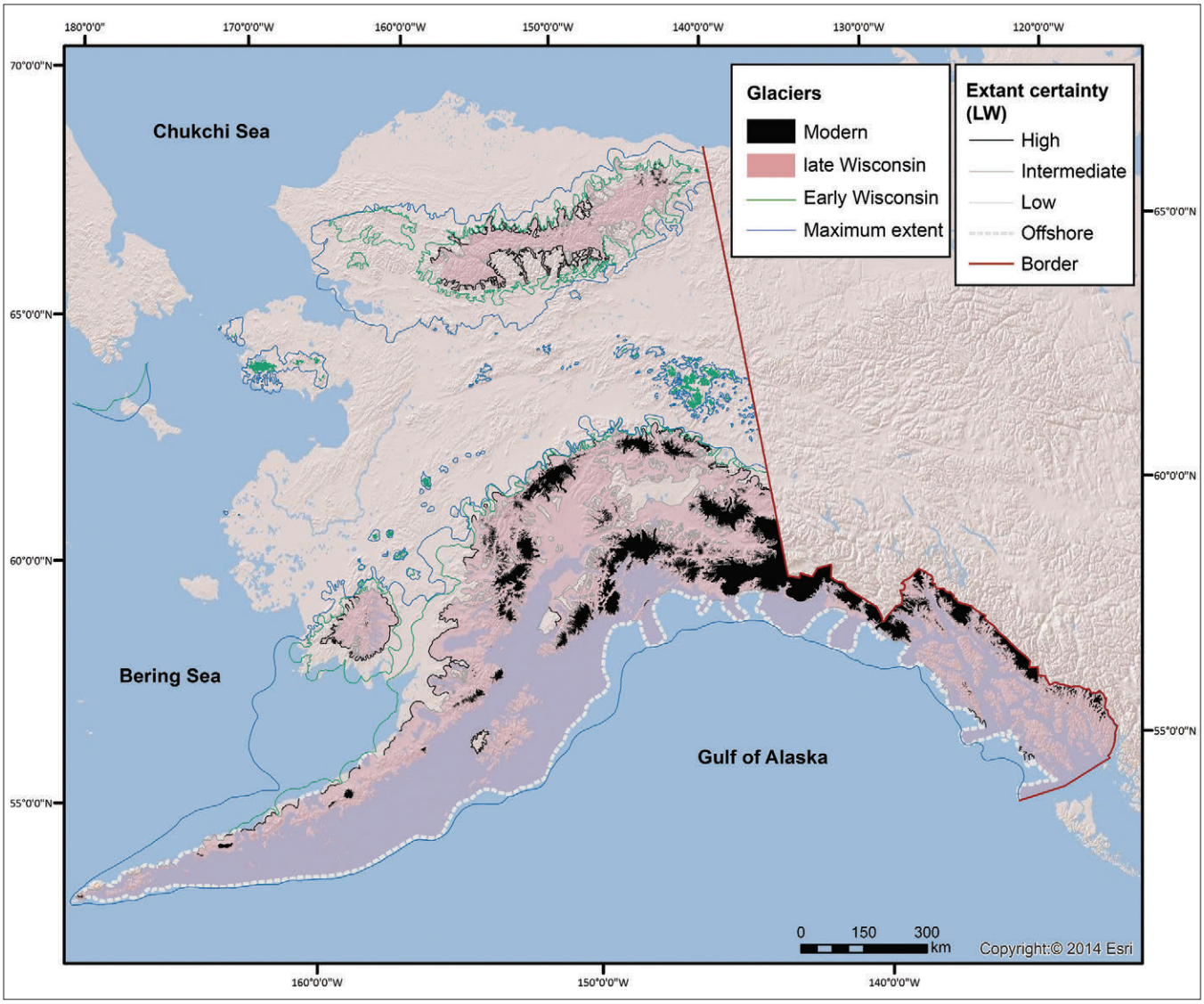


Figure 6-1—Extent of glacial ice at different periods in the past, demonstrating the directional decline in glacier cover during the past 20,000 years or more and the current extent of glaciers. Source: Alaska PaleoGlacier Atlas (version 2) (Manley and Kaufman 2016).

resulting in the loss of hemlock, fir, and pine from interior forests (Ager 2007). The last time temperatures in Alaska were warm enough to support extensive forest in the interior was 125,000 years ago during the last interglacial—a warm period that lasted about 20,000 years and represented one of many brief warm periods in the past 2 million years. During this period, the mean annual temperature of interior Alaska was 2 °C warmer than today (fig. 6-2) (Ager 1997, 2007). During the most recent glaciation (ending about 27,000 to 12,000 years ago), sea level dropped about 125 m below its current level, and ice extended far onto the continental shelf of the current Gulf of Alaska (Ager 2007: 9–18). Vegetation in nearby regions that

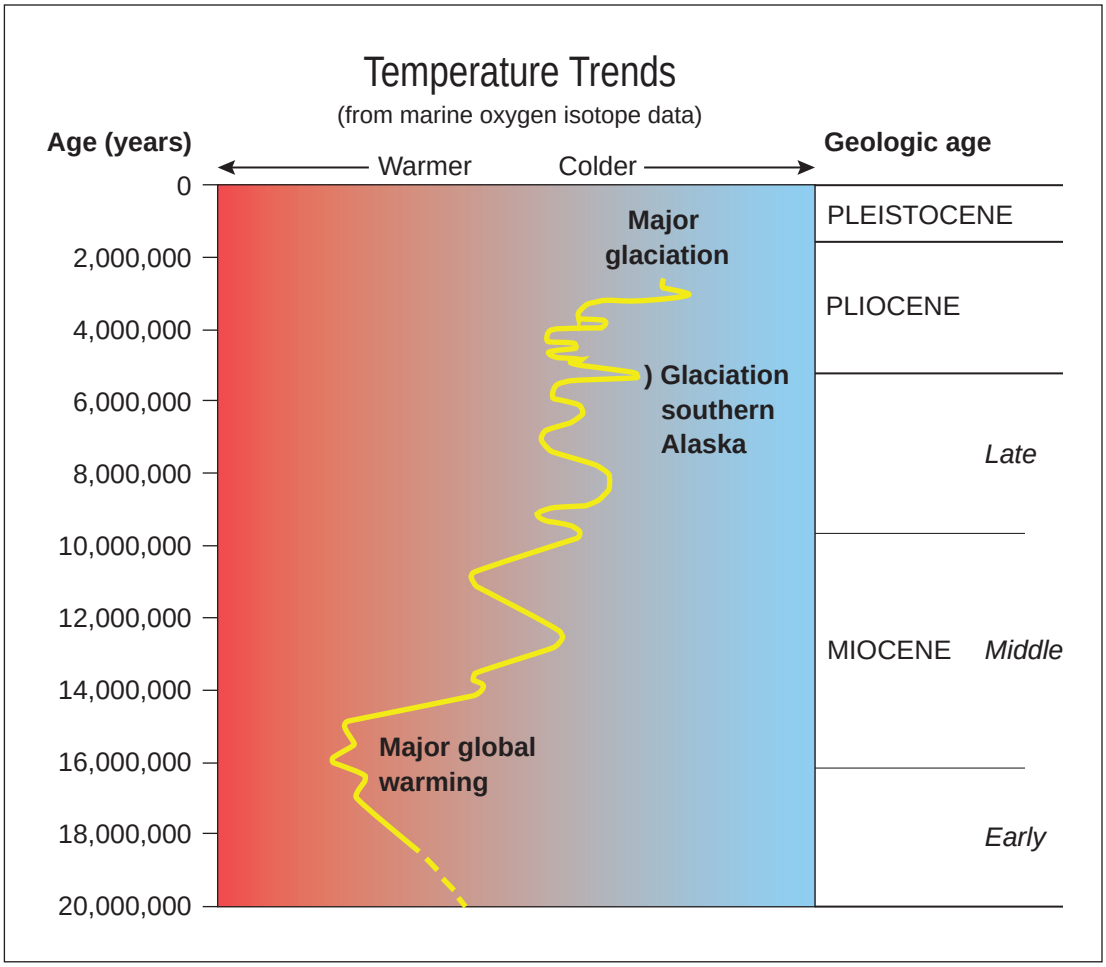


Figure 6-2—Illustration of dramatic variation in long-term global temperatures that influenced vegetation in the assessment area. Figure presents general trends in Pacific Ocean seawater temperature from oxygen isotope measurements in marine fossils. Source: Ager (1997).

were not overrun by glaciers 13,000 years ago appears to have been dominated by species present in contemporary wet and mesic meadows and *Empetrum* heathlands (Peteet and Mann 1994).

Short-Term Vegetation History (~10,000 Years BP)

The vast majority of land in the assessment area was covered with ice for much of the past 100,000 years, setting the stage for a dynamic change in vegetation and resulting in the array of tundra, shrublands, wetlands, boreal forest, and coastal rain forest we observe today (Ager 2007, Jones et al. 2009). Deglaciation, which began earlier on the western Kenai Peninsula than on Prince William Sound and the Copper River Delta, set the stage for vegetation development. However, proximity of plant seed sources, prevailing storm tracks and wind (dispersing some seeds),

topography, and climate gradients all strongly influenced this pattern. Several small areas within the assessment area remained ice-free during the last glacial period. Such areas are called refugia. Identified biological refugia include several mountaintop nunataks (exposed land) on Hinchinbrook, Montague, and Knight Islands, and more extensive areas on the western Kenai, including the far northern lowlands, an area between Skilak and Tustumena Lakes, and portions of the Caribou Hills north of Homer (Ager 2001, Heusser 1983). The significance of refugia is that, post-glaciation, these areas often served as seed sources for colonization and continue to disproportionately harbor rare and widely disjunct populations (Carlson et al. 2013). However, most plants are believed to have established from dispersal events from outside the region, notably from southeast Alaska.

Mountain ranges interact with prevailing storm tracks that typically bring westerly winds, strongly influencing the pattern of plant dispersal. The Kenai Mountains, forming a north-south spine dividing the peninsula, and Chugach Mountains forming the northern boundary of the assessment area, were particularly important. Several authors have suggested that coastal rain forest species migrated from coastal Canada or southeast Alaska following deglaciation, and that this dispersal was dependent on prevailing winds (Ager 2001, Jones et al. 2009). Other dispersal routes of plants into the assessment area appear to have been along the Copper River drainage and low passes in the Talkeetna and Chugach Mountains.

Broad climatic gradients appear to have been maintained through much of the post-glacial vegetation development. The strong moisture and temperature gradients that led to very wet conditions throughout Prince William Sound and the Copper River Delta, along with mild summer and winter temperatures in this same region, structured the resulting vegetation. A rapid decline in precipitation and more extreme summer and winter temperatures occur from east to west. As a consequence, substantially different patterns of vegetation recolonization occurred on the eastern and western side of the Kenai Mountains (Ager 2007, Heusser 1983, Jones et al. 2009). In most areas throughout the assessment area, coastal and sedge tundra initially occupied newly exposed land. In the western Kenai and Anchorage regions, where present-day boreal forest types occur, post-glacial vegetation transitioned from tundra to shrub birch, alder, and willow, followed by establishment of white spruce by 8,500 BP and black spruce by 4,600 BP (Ager 2001, Anderson et al. 2006). The source of spruce and other trees is uncertain—some trees may have remained in refugia on the Kenai, or the boreal forest trees moved southward from the interior through low passes in the Talkeetna Mountains (Ager 2007, Jones et al. 2009). Regardless of their origins, boreal forest trees were present 8,500 years ago and boreal forests began forming 4,600 years ago in the western Kenai.

Forest development occurred much later east of the Kenai Mountains in the broad region from the Delta through western Prince William Sound. Deglaciation occurred later in this region because ice thickness was greater and melting slower, resulting in development of vegetation beginning as late as 10,000 to 9,000 years ago in portions of the Sound as compared to 100,000 years ago on the western Kenai (Heusser 1983). Cooler summer temperatures and higher precipitation also supported alder, sedge, and fern communities that persisted for long periods. In some areas, alder appeared to dominate large areas for more than 1,000 years (Ager 2007, Heusser 1983). Mountain hemlock and Sitka spruce moved in from the east around 3,000 years ago (Ager 2001), and forest communities of hemlock and spruce did not develop in the western Sound until about 2,000 years ago (Heusser 1983). Currently, Sitka spruce continues to migrate westward along the Gulf of Alaska on Kodiak Island at a rate estimated at about a mile per century (Griggs 1934), and can be found along the northeast coast of the Alaskan Peninsula. Western hemlock currently has not migrated into Cook Inlet (Heusser 1983), but Sitka spruce has, and reaches its northern limit near Palmer, Alaska (Viereck and Little 2007). An expansion of black spruce in the Kenai lowlands may have followed the end of the Little Ice Age in the 1850s (Berg et al. 2009).

Fire and defoliating and wood-boring insects also influenced past forest conditions.

Fire and defoliating and wood-boring insects also influenced past forest conditions in the assessment area. Historically, fires were not uncommon in the western Kenai. During the early and mid Holocene, estimated mean fire-return intervals on landscapes in the Kenai lowlands ranged from 77 years during birch/willow/cottonwood phases to 138 years during shrub/herb tundra phases. White spruce and black spruce forests experienced fire-return intervals of about 80 and 130 years, respectively (Anderson et al. 2006). Historically, fires were notably infrequent in the eastern portion of the assessment area. Since the establishment of coastal rain forest dominated by Sitka spruce and hemlock about 3,000 years ago, fire has played little role in ecosystem dynamics.

During the past couple centuries, human ignitions have become more important in the western portion of the assessment area. Although Alaska Native peoples have been present in south-central Alaska for thousands of years, there is no evidence that they used fire as a land management tool. Gold miners set fires to clear land for prospecting, particularly in the Kenai Mountains, and seem to have unintentionally created extensive moose habitat.[12]

Major fires occurred on the western Kenai during a number of years beginning in the late 1800s (Lutz 1960 as cited by Morton et al. 2006). The basic cause for

[12] **Boraas, A. 2013**. Personal communication. Professor of anthropology, Kenai Peninsula College, Soldotna, AK 99669.

these fires was attributed to railroad activity igniting 95 fires between 1932 and 1953. The drought conditions following the 1912 Katmai Volcano eruption also contributed to fire behavior by creating favorable weather for burning. Holbrook (1924) reported that "the region has been visited by numerous fires and most of the better grade of timber has been burned." He mapped about 12 000 ha of burned area on the forest. These large fires included the Resurrection Creek watershed covering 4050 ha. Following World War II, several large fires occurred in the western Kenai. Fires in 1947 and 1969 burned 125 000 and 34 800 ha, respectively. From 1990 throught 2012, about 57 000 ha of forest burned. Near the end of the 20th century, an average of 66 wildfires occurred on the peninsula each year, most being very small (fig. 6-3).

The historical influence of insects on forest structure and composition was more dramatic west of the Kenai Mountains—the boreal forest region rather than the coastal region. In the boreal forests, over time, defoliators periodically erupt and remove the majority of leaves across large areas. Similarly, in the recent past, spruce bark beetle represents a dominant disturbance in the boreal forest, with a mean return interval of around 50 years on the Kenai Peninsula (Berg and Anderson 2006). Based on tree-core evidence, Berg et al. (2006) found that an outbreak of spruce beetle occurred on the Kenai in the late 19th century. The late-20th-century outbreak appears to be representative of past spruce mortality events and indicates that beetles represent an important part of the ecological history of the western Kenai Peninsula.

Summary: Current Vegetation

- There are nine vegetation cover types within the assessment area.
- Spruce is the dominant conifer in the assessment area, with Sitka spruce dominating in the temperate rain forest and white and black spruce dominating in the boreal forest.
- Across the assessment area, there are 53 rare-to-imperiled plant species that are found in eight different habitat types.
- 159 taxa of non-native species have been found within the assessment area, occupying approximately 0.04 percent of the total area of the region.
- Fire continues to be rare in the temperate coastal rain forest. However, in the western Kenai where boreal (and transition-boreal) vegetation occurs, large fire events, although uncommon, are an important factor in structuring the current vegetation pattern. Fire events are often linked to broad climatic patterns, although human activity has also played a role in promoting fire in the assessment area.

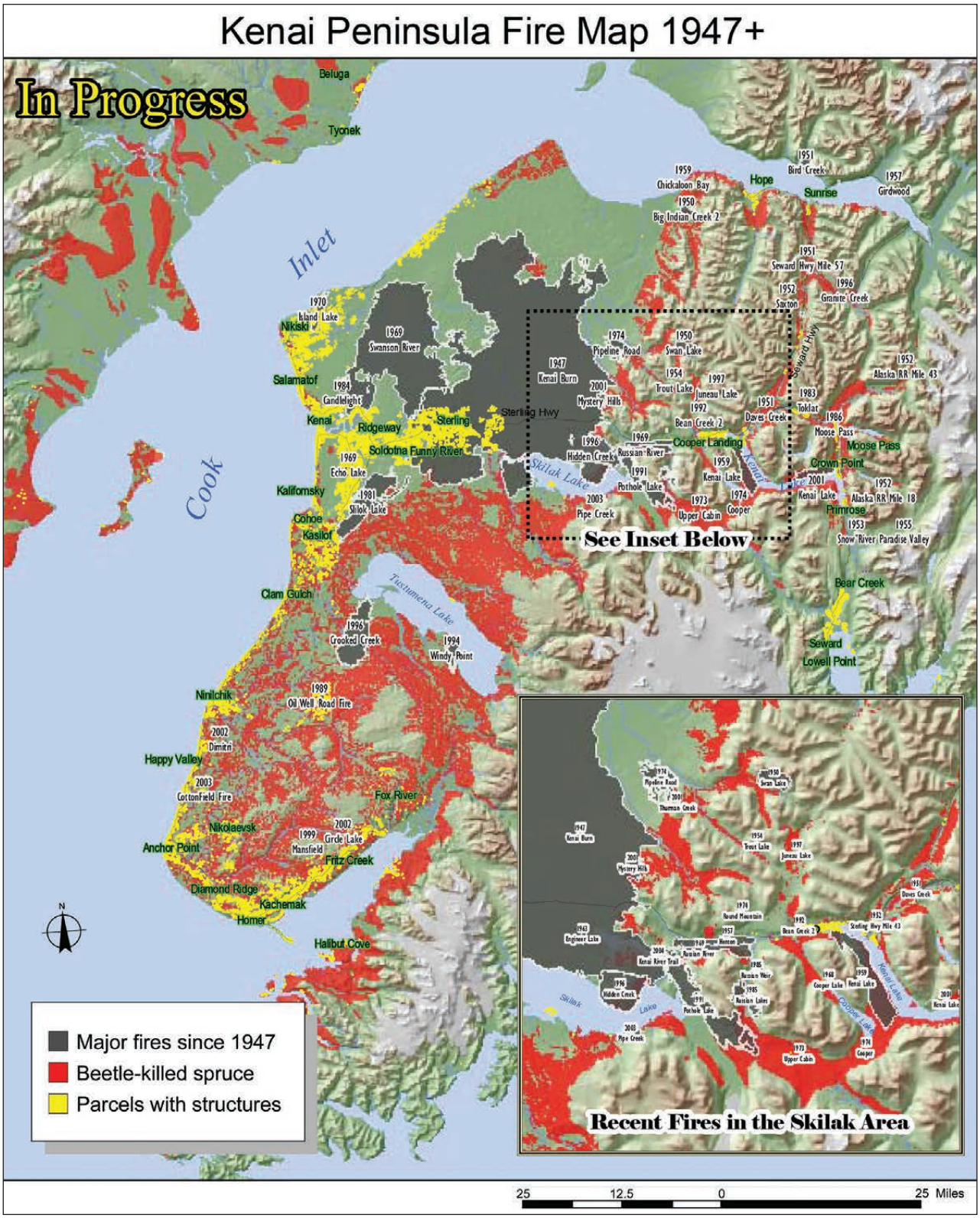


Figure 6-3—Distribution of major wildland fires from 1947 through 2002 on the Kenai Peninsula, illustrating the concentration of large fires to the west of the Kenai Mountains. This map also illustrates the extent of beetle-killed spruce and distribution of human infrastructure on the peninsula. Source: KPBOEM (2004).

Case Study: Historical and Current Patterns of Spruce Beetle Outbreaks and Long-Term Consequences on Vegetation

John Lundquist, supervisory forest entomologist, Chugach National Forest

The history of spruce beetle outbreaks on the Kenai Peninsula was reconstructed for a period extending from the 1770s to the mid 1990s by using tree-ring growth-pulse profiles (Berg and Anderson 2006, Berg et al. 2006). Based on these chronologies, Berg and his colleagues found that sites differed in specific outbreak histories, but that distinct widespread outbreaks occurred in the 1810s, 1870s, 1910s, 1970s, and 1990s (fig. 6-4). Outbreaks in the 1810s, 1910s, and 1970s were mild (they killed a low proportion of trees in any single area) but extensive, creating a diversity of forested and nonforested patches across the landscape. Because these outbreaks affected forest patterns across broad areas, they helped maintain landscape heterogeneity, and, presumably, reduced the chances of future regional catastrophes caused by various disturbance agents, including spruce beetles or wildfire.

The 1880s and 1990s outbreaks were exceptions. The earlier outbreak killed so many trees that it reset large contiguous areas of unmanaged spruce forests to a common age, reducing the inherent patchy heterogeneity of the

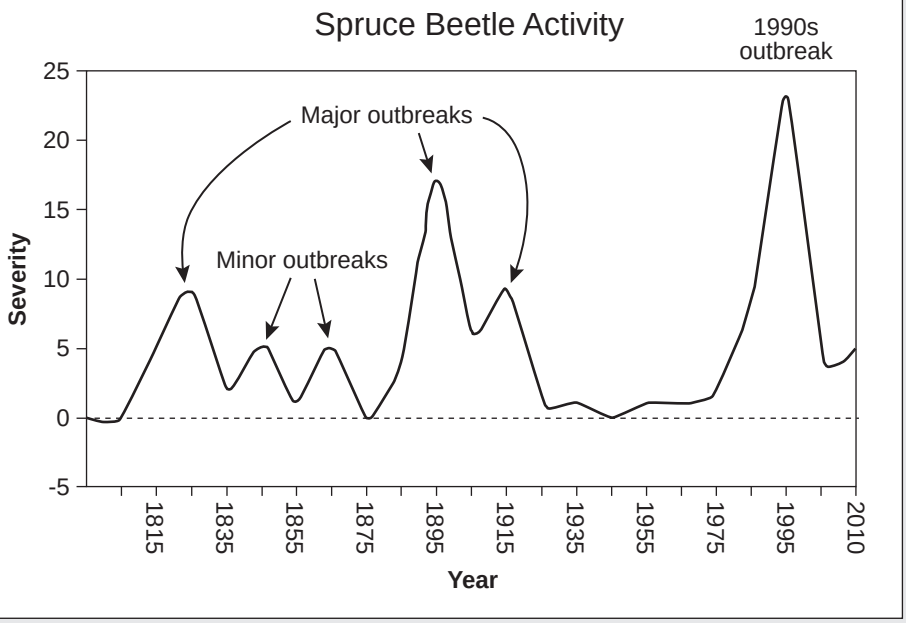


Figure 6-4—Intensity of spruce bark beetle infection on the Kenai Peninsula over a 200-year period based on a variety of evidence (adapted from Berg et al. 2006).

forested landscape. Without additional disturbances, from 50 to 70 years would be required for the surviving forest to reach crown closure and for individual trees to become large enough to be susceptible to spruce-beetle attack. By the 1990s, vast areas of the forests on the Kenai had grown dense and into relatively large trees of susceptible size. In this way, the 1880s outbreak predisposed forests on the Kenai Peninsula to the 1990s outbreak, even though the two events were separated in time by more than 100 years!

In addition to forest conditions and the size class of trees, climate also plays a role in spruce-beetle outbreak dynamics, but its role may not be entirely obvious. Research based mostly on the 1990s outbreak has led to several hypotheses about the cause of changes in beetle behavior (table 6-1), and they are all directly or indirectly related to warming temperatures.

Table 6-1— Hypotheses on what caused the 1990s Kenai spruce beetle outbreak

Attack hypothesis	Climate condition	Spruce beetle response
Winter beetle mortality	Moderate winter temperatures and abundant snowfall	Low winter mortality
Early spring	Early increasing spring temperatures	Early emergence, attack, oviposition, and egg hatch
2- to 1-year life cycle	Early increasing spring temperatures	Switch from 2- to 1-year life cycle
Host stress	Increasing summer temperatures with lower precipitation	Increased host tree susceptibility caused by water deficit stress
Frozen root	Cold soil, frozen roots while temperatures warm in spring	Increased host tree susceptibility caused by increased demand for water while the amount roots can supply are limited
Growth season length	Lengthened growth season	Longer time to cause damage

A conceptual ecological model represents a foundation from which to discuss the potential influence of a changing climate on bark beetle dynamics, their impacts, and the resulting patterns of recovering forest growth. There is an inherent limit to the frequency of broad-scale, intense bark beetle mortality events, given the substantial lag needed for trees to grow to susceptible size classes between catastrophic mortality events. But warming temperatures could increase tree growth rates, reducing this inherent time-lag between outbreaks. Low winter temperatures could reduce overwinter survival of beetles, slowing rates of beetle population growth. Earlier onset of spring could trigger changes in the number of annual life cycles, leading to exponential increases in beetle

abundance. Depending on patterns of moisture, changing climate could reduce the probability of broad-scale beetle outbreaks if precipitation increases to relieve water stress, and if moisture patterns become less variable between years. Alternatively, high variation in precipitation, especially if a combination of temperature and precipitation leads to late-summer water stress, could result in periodic conditions that promote effective beetle attacks.

Maps of the statewide distribution of spruce beetles, based on Forest Health Management surveys since the 1940s, show that the earliest reports of infestations occurred simultaneously at several different locations across south-central Alaska. Foci can be identified around Copper River, near Wasilla, on Afognak Island, and near McGrath (fig. 6-5). Subsequently, populations of spruce beetles spread unevenly across the geography of Alaska. The paths they took were probably influenced by the topography, climate, elevation, and latitude. In this regard, two notable jumps in distribution occurred from 1980 to 1990 and from 1990 to 2000. Another notable jump occurred in 2007 and is indicated by the lobe jutting northeastward toward the Charlie River at the northeast side of the state. Arguably, the pattern suggests that outbreaks of increasing severity migrating northward, which is likely to continue with further warming. ■

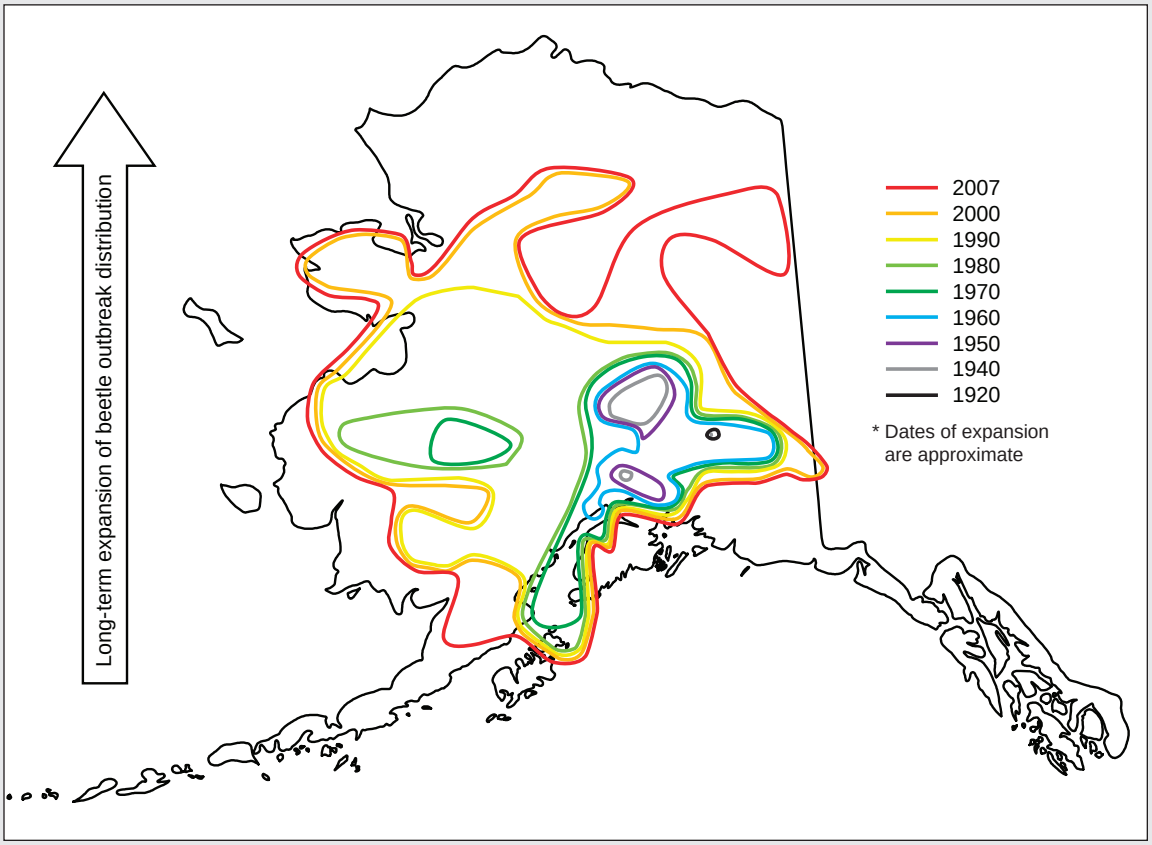


Figure 6-5—Historical distribution of reported spruce beetle outbreaks in Alaska, and the large-scale, long-term trend of their spread across the state (Lundquist 2009).

Context for Climate Change: Current Vegetation Patterns and Plant Distributions

Current Disturbance Regimes

Study of more recent fire history suggests broad patterns that are similar to the long-term record described above. Fire continues to be rare and never covers more than a few hectares in the coastal rain forest. As in the past, the transitional boreal forests of the western Kenai Peninsula have experienced a relatively complex pattern of fire in response to existing vegetation, human ignition rates, and interannual variation in weather.

Currently, fires are relatively uncommon in the boreal forests of the western Kenai. However, when they occur, they are an important part of the disturbance ecology because individual events can be large. Natural fire occurs in the Kenai boreal biome based largely on climate conditions—uncommonly dry windy conditions, particularly in spring before green-up, result in high rates of spread. Fires in 1947, 1969, and 2014 resulted in large disturbances—310,000, 86,000, and 194,000 ac (125 000, 35 000, and 78 500 ha) burned, respectively. Nonforest vegetation also experiences fire, but fires in these vegetation types are more difficult to characterize because they leave less-discernible legacies.

Climate ultimately determines the potential distribution of vegetation at broad spatial extents, while interactions among disturbances, soils, weather, and history determine the character of vegetation at finer spatial scales.

Climate ultimately determines the potential distribution of vegetation at broad spatial extents (biomes), while interactions among disturbances, soils, weather, and history determine the character of vegetation at finer spatial scales. Recent patterns of fire occurrence and the probability of fire differ substantially across the assessment area (fig. 6-6).

More than 500 000 ha of bark beetle activity was recorded (Werner et al. 2006) on the Kenai Peninsula during the 1990s, and an estimated 1.6 million ha of spruce forest in south-central Alaska was affected. In many stands, tree mortality reached 85 to 98 percent of all spruce over 6 inches diameter at breast height. The bark beetle episode lasted about 10 years at high intensity. Tree mortality resulting from bark beetle attack changed the character of the landscape, setting in motion a sequence of changes in the probability of fire and the potential spatial extent of individual fire events across the western Kenai. Although fire conditions changed rapidly, the level of change was not unique to this bark beetle event.

Regardless of the historical pattern of bark beetles on the Kenai (see case study on page 173), the recent bark beetle event changed fuel characteristics on the peninsula, and vegetation development following the event continues to change the probability of fire and the potential pattern of disturbance given an ignition. The greatest increase in fine fuels is represented by native bluejoint grass (*Calamagrostis canadensis*) (Wahrenbrock 2009) that increased in extent following

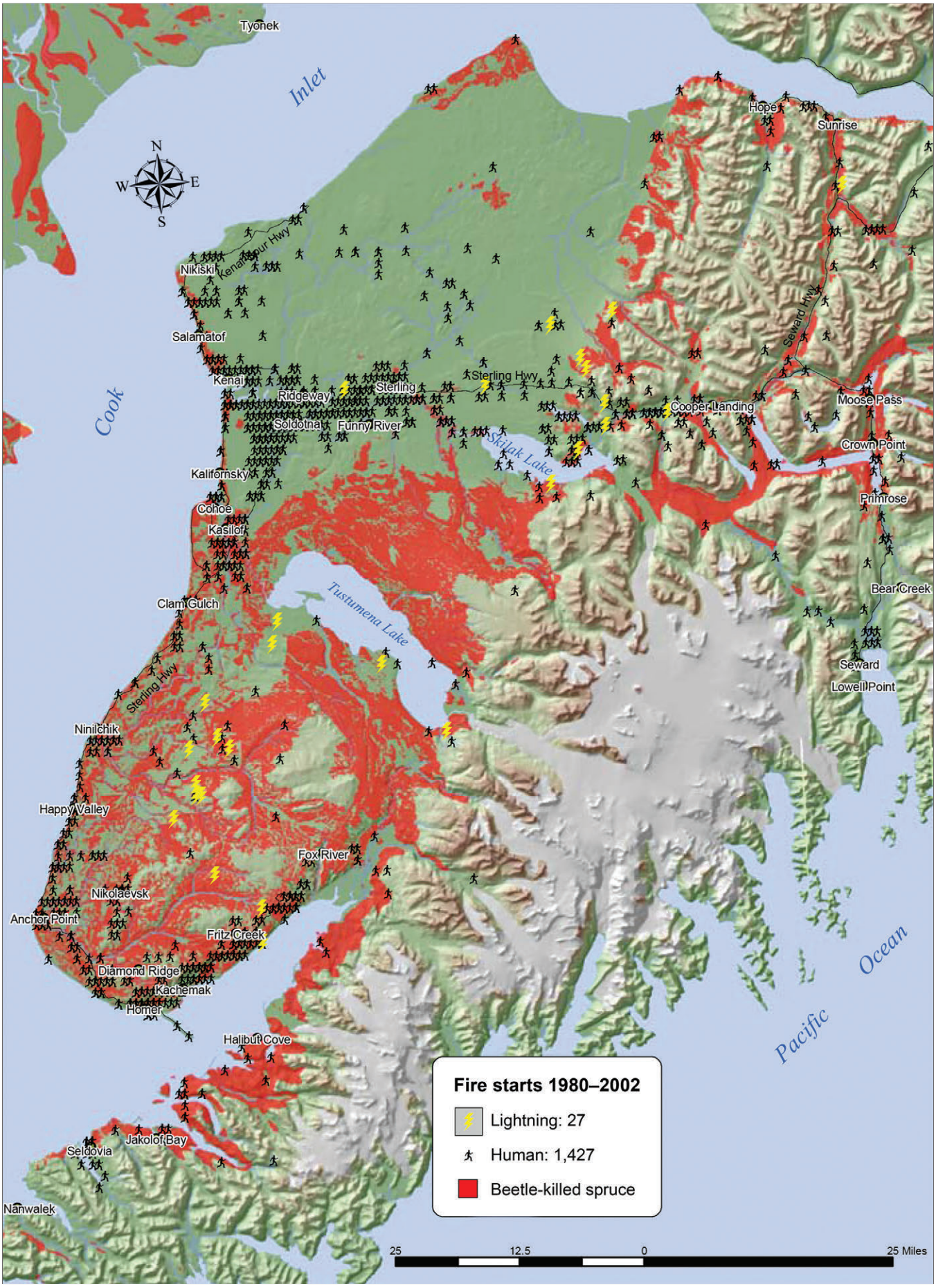


Figure 6-6—Distribution of the location fires that were initiated on the Kenai Peninsula from 1980 through 2002, illustrating the strong relationship between the road system and fires, but also the low number of occurrences east of the Kenai Mountains. Source: KPBOEM (2004).

mortality of spruce. Spruce mortality contributed to the accumulation of both fine and large fuels. Over time, as trees lose branches and fall, the characteristics of fuels, particularly large fuels, are changing.

In 2004, the Kenai Peninsula Borough released an action plan for fire prevention and protection (KPBPEM 2004), hereafter called the All Lands Action Plan. A major focus of this interagency effort was development of a fire hazard and risk classification for a large portion of the Kenai Peninsula. The report represents the best overview of current conditions on the portion of the assessment area where fire is an important ecological and economic agent (fig. 6-7). Other assessments of fire hazard or risk have also been produced (e.g., Hansen and Naughton 2013); however, the Kenai Borough product seems most relevant to our assessment and will be applied below. The U.S. Forest Service has not produced a fire regime map nor mapped fire hazard/risk for the area (see recent fire management plan) (USDA FS 2014).

Current Distribution of Biomes and Land Cover Types

Ecological communities can be classified at multiple spatial scales. Biomes are the broadest ecological unit and are defined mainly by climate. Different classification schemes have defined slightly different biome delineations for the assessment area. Depending on the classification, there are two or three major biomes in the assessment area (fig. 6-8), and within these biomes a variety of species occur with only minimal overlap in distribution. Coastal temperate rain forest and transitional boreal forest in the Kenai lowlands are always delineated as biomes (Nowacki et al. 2001). Other classifications also break out alpine tundra in the mountains as a distinct biome (Brown et al. 1998, Viereck et. al.1992).

The 11 land cover types in south-central Alaska include nine vegetation cover types and two types free of vegetation.

Land cover types are generalized vegetation classes, such as deciduous or evergreen forests that are defined at finer spatial scales than a biome. The spatial distribution of land cover types is mediated by climate and other regional factors such as dispersal barriers and hydrology. Eleven land cover classes have been identified in south-central Alaska using standard remote-sensing approaches (fig. 6-9; table 6-2). These 11 land cover types include nine vegetation cover types and two types free of vegetation. The nine vegetation cover types include deciduous forest, evergreen forest, mixed forest, dwarf scrub (including alpine), shrub/scrub, grassland/herbaceous, woody wetlands, emergent herbaceous wetlands, and sedge/herbaceous (table 6-3).

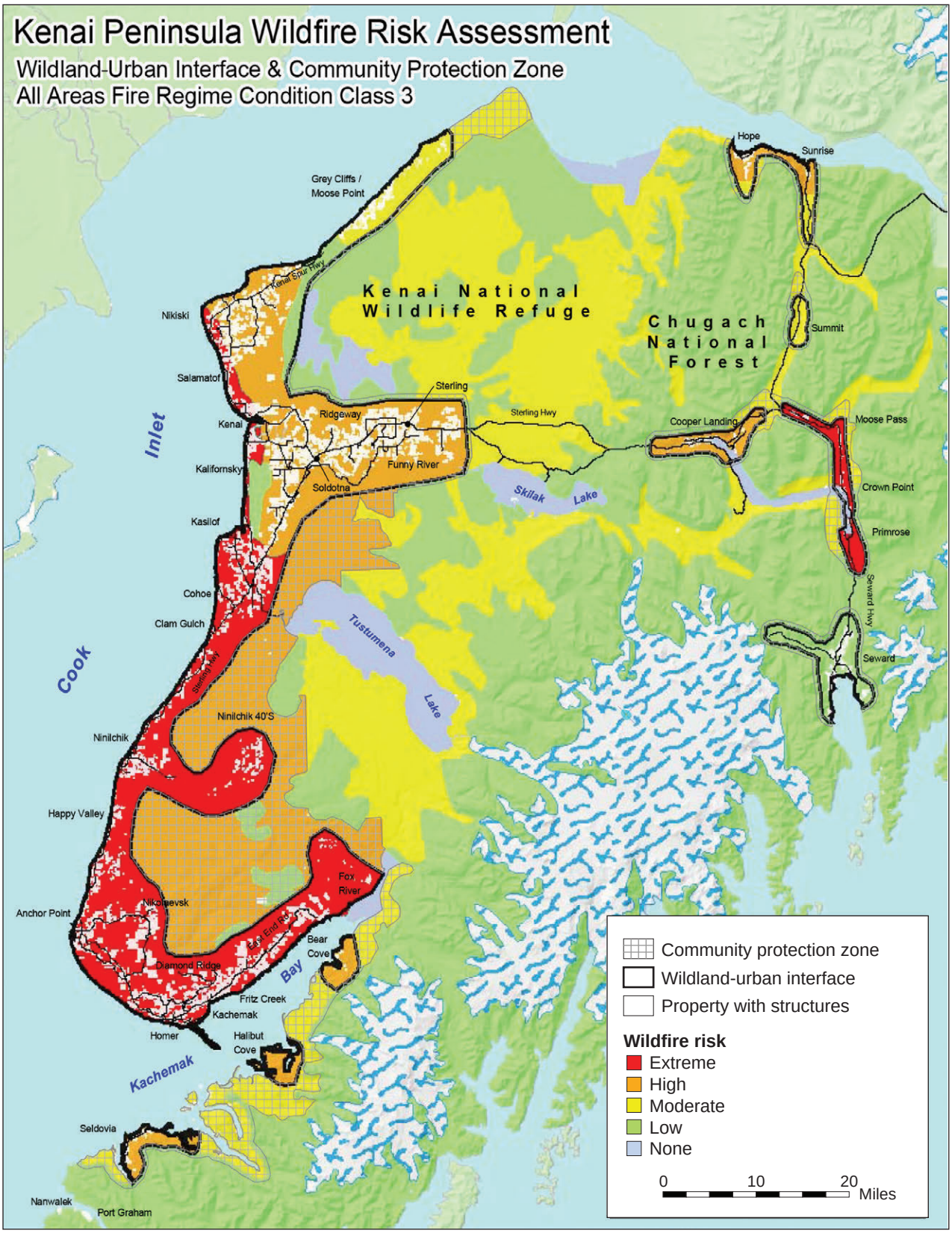


Figure 6-7—Interagency classification of wildfire risk to human infrastructure on the Kenai Peninsula, Alaska. Source: KPBOEM (2004).

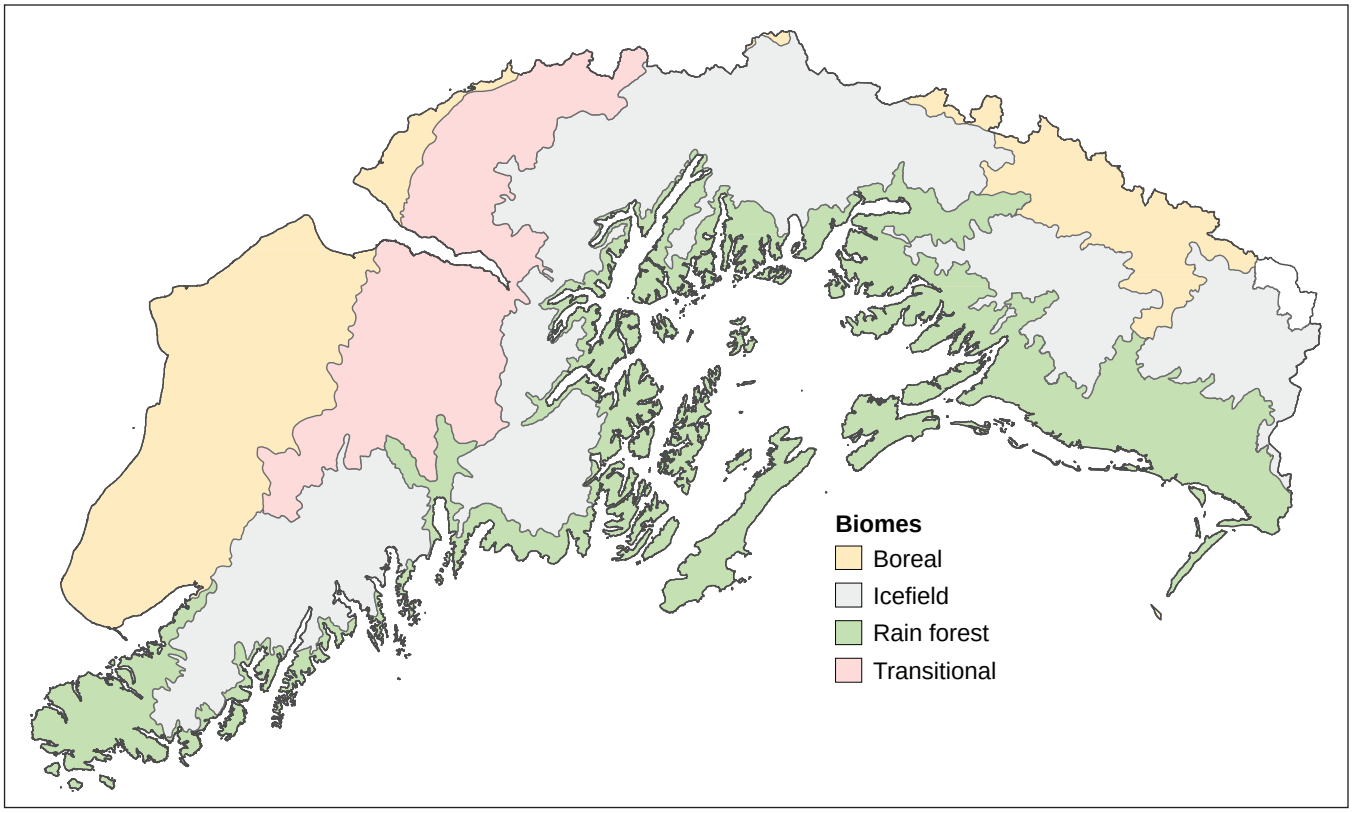


Figure 6-8—Biomes of the Chugach-Kenai climate vulnerability assessment area. The four biomes are aggregates of Davidson (1996) ecological subsections.

Sitka spruce (*Picea sitchensis*), mountain hemlock (*Tsuga mertensiana*), and western hemlock (*T. heterophylla*) are dominant trees in evergreen forests of the coastal rainforest biome. White spruce (*Picea glauca*), black spruce (*P. mariana*) and Lutz spruce (*P.* × *lutzii*) are dominant trees in the evergreen forests of the transitional boreal biome. Birch (*Betula papyrifera* var. *kenaica* and *B. neoalaskana*), aspen (*Populus tremuloides*), and black cottonwood (*P. balsamifera* ssp. *trichocarpa*) are common deciduous trees in the boreal forest. Although black cottonwood is the only deciduous species to occur in the rain forest, it is only rarely dominant. Diverse shrublands, classified as shrub/scrub, include Sitka alder (*Alnus viridis* spp. *sinuata*), salmonberry (*Rubus spectabilis*), multiple species of willow (Salix spp.), and bog birch (*Betula nana* and *B. glandulosa*). Alpine vegetation, generally classified as dwarf shrub, occurs on mountains above about 1,500 ft. (450 m) in the absence of glaciers or rock. Some species include *Loiseleuria procumbens*, *Empetrum nigrum*, *Cassiope stelleriana*, *Hierochloe alpina*, *Phleum alpinum*, *Carex pyrenaica*, *Artemisia arctica*, and *Phyllodoce aleutica*. Peatlands also occur across the assessment area and support dominant vegetation ranging from

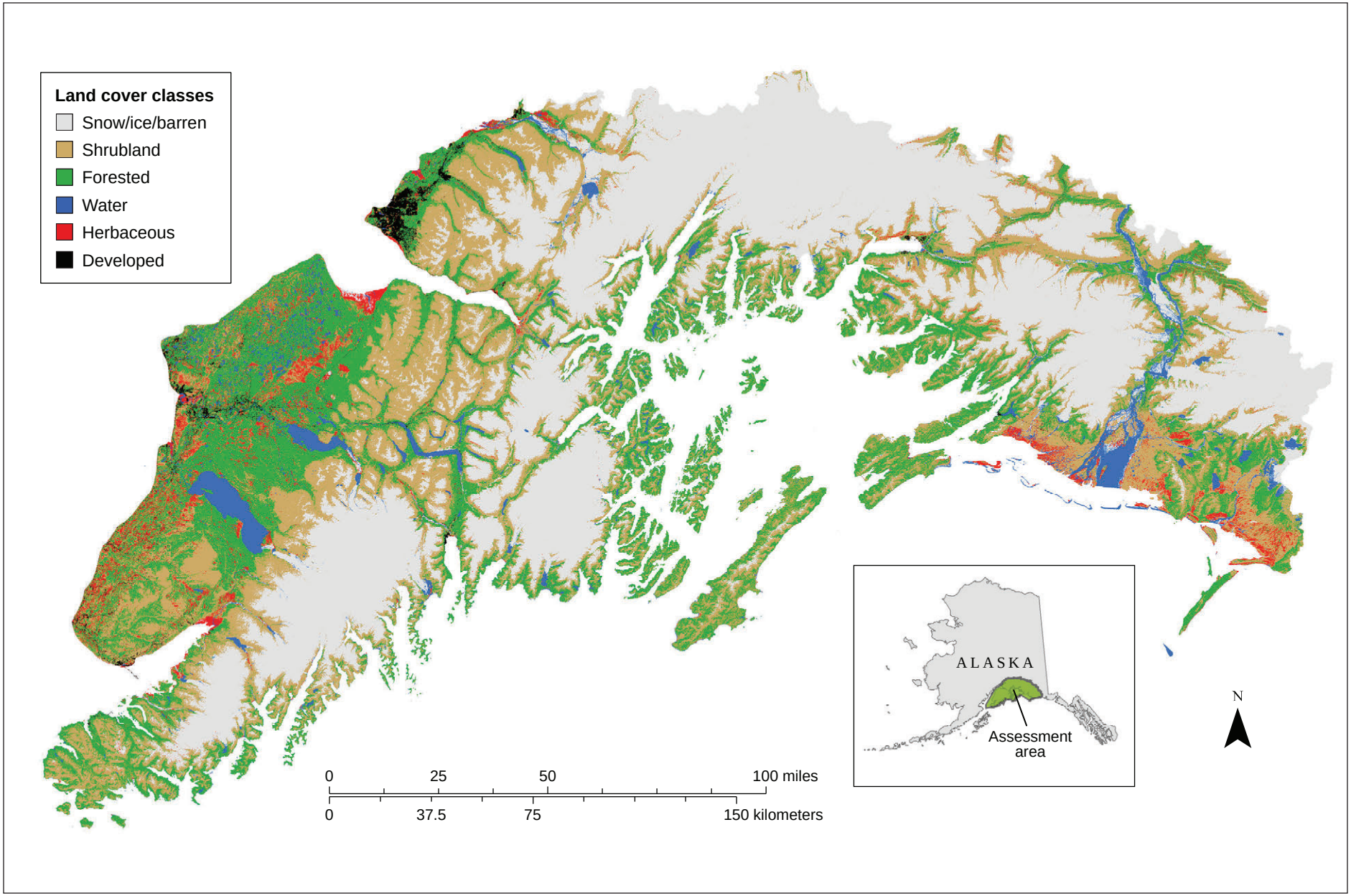


Figure 6-9—Distribution of 11 National Land Cover Database (NLCD) classes across the assessment area. See table 6-2 for details of vegetation classes.

Table 6.2—Descriptions of the 11 land cover types in south-central Alaska

Label	Description
Perennial ice/snow	All areas characterized by a perennial cover of ice or snow, generally greater than 25 percent of total cover.
Barren land (Rock/sand/clay)	Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15 percent of total cover.
Deciduous forest	Areas dominated by trees generally greater than 5 m tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen forest	Areas dominated by trees generally greater than 5 m tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
Mixed forest	Areas dominated by trees generally greater than 5 m tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover
Dwarf scrub	Alaska only areas dominated by shrubs less than 20 cm tall with shrub canopy typically greater than 20 percent of total vegetation. This type is often co-associated with grasses, sedges, herbs, and nonvascular vegetation tundra and may be periodically or seasonally wet and/or saturated with water. This type commonly occurs in alpine or tundra areas and may contain permafrost.
Shrub/scrub	Areas dominated by shrubs less than 5 m tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Grassland/herbaceous	Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling, but can be used for grazing.
Woody wetlands	Areas where forest or shrub land vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is persistently saturated with or covered with water.
Emergent herbaceous wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is persistently saturated or covered with water.
Sedge/herbaceous	Alaska only areas dominated by sedges and forbs, generally greater than 80 percent of total vegetation. This type can occur with significant other grasses or other grass-like plants, and includes sedge tundra, and sedge tussock tundra and may be periodically or seasonally wet and/or saturated. This type may contain permafrost.

forest (black spruce), to shrublands (e.g., *Empetrum nigrum*, *Cassiope stelleriana*, *Vaccinium uliginosum*), to herbaceous cover (e.g., *Sphagnum fuscum*, *Carex limosa*, *Trichophorum caespitosum*, *Eriophorum angustifolium*, *Andromeda polifolia*). Depending on the primary composition, peatlands are classified as woody wetlands (forest or shrub cover >20 percent) or emergent herbaceous wetlands (perennial herbaceous vegetation cover >80 percent).

Table 6-3— Percentage of the assessment area occupying 11 land cover types

	Percent
Barren land (rock/clay/sand)	24.34
Shrub/scrub	23.87
Perennial ice/snow	19.86
Evergreen forest	14.67
Dwarf shrub	5.89
Deciduous forest	3.89
Woody wetland	3.08
Mixed forest	2.90
Emergent herbacous wetlands	1.42
Grassland/herbaceous	0.06
Sedge/herbaceous	0.03

Current Distribution of Spruce Species

Spruce occur as dominant species in several vegetation types that cover significant portions of the assessment area. As dominant taxa, these spruce, which include white, black, and Sitka spruce, exert a strong influence on ecosystem composition, structure, and function. For example, they can change soil temperature (through shading), soil chemistry (through litterfall), and soil turnover rates (through tree-fall and tip-up mounds) (Alban et al. 1978, Bonan and Shugart 1989, Schaetzl et al. 1988). They influence fire behavior because of their flammability and architecture (Cronan and Jandt 2008). Spruce forests provide habitat for many birds, small mammals, insects, and pathogens, and therefore help determine the biodiversity of landscapes. Examining trends in distribution of spruce species provides significant insight into current and future ecosystem conditions. Here, we review the current distribution of black, white, and Sitka spruce across the assessment area to provide a context for examining a scenario for changes in their distribution.

The distribution of Alaska's three spruce species corresponds with two distinct forest biomes: Sitka spruce distribution matches the temperate rain forest, and black spruce and white spruce distribution reflects the boreal forest.

The distribution of Alaska's three spruce species corresponds with two distinct forest biomes: Sitka spruce distribution matches the temperate rain forest, and black spruce and white spruce distribution reflects the boreal forest (fig. 6-10). A series of mountain ranges separates these two biomes along most of the Gulf of Alaska. However, the Kenai Peninsula and the forests surrounding Cook Inlet represent a rare transition zone between the two biomes lacking the mountain barrier found elsewhere. As a geographic area with rapid transition between biomes, but lacking a clear physical barrier, the Cook Inlet/Kenai Peninsula region has the potential to experience substantial climate change effects, shuffling the distribution of these two biomes.

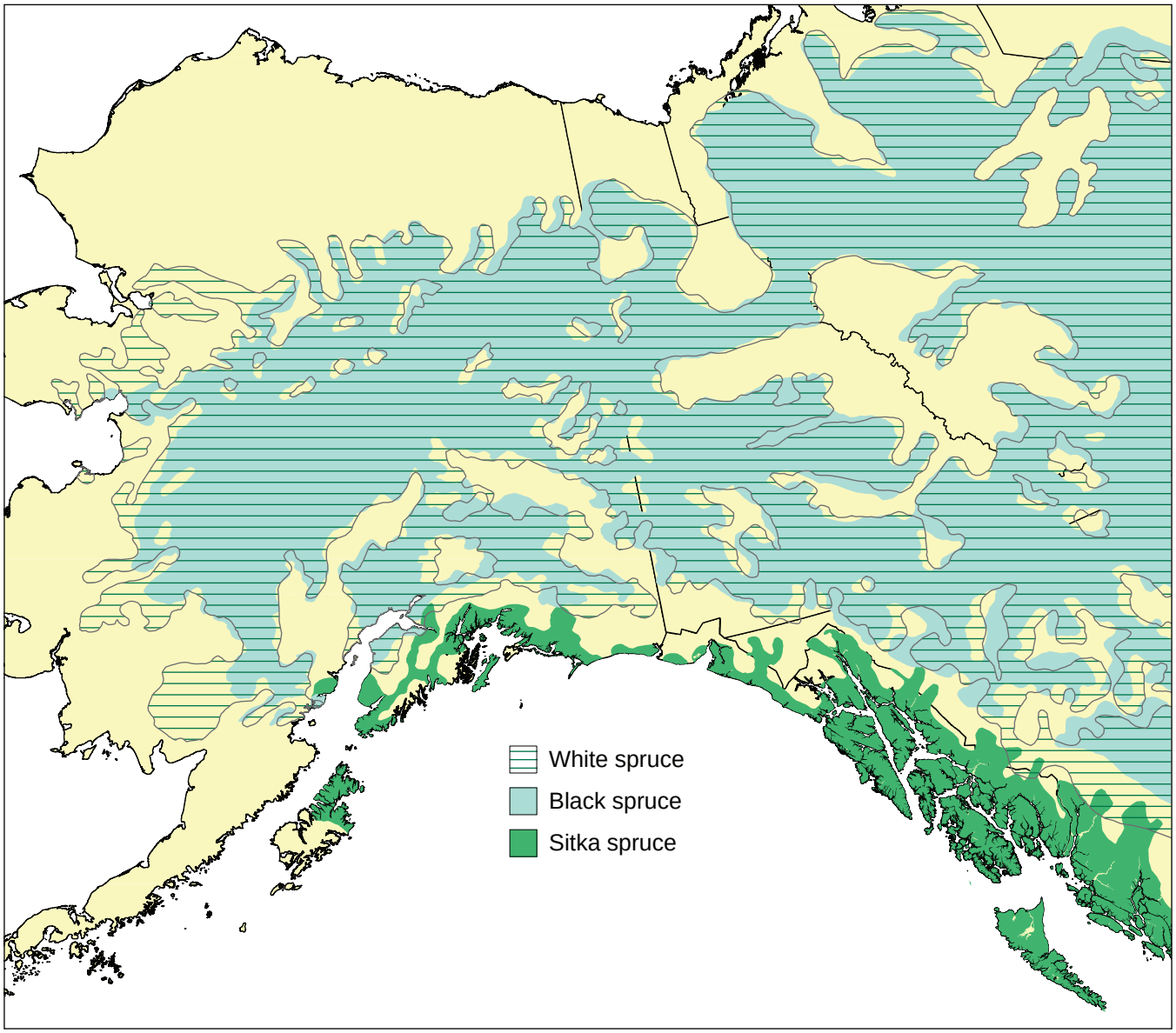


Figure 6-10—The distribution of Sitka spruce indicates the temperate rain forest biome in Alaska, while black spruce and white spruce distribution define the boreal forest biome. Note: geographic information system data for species ranges was obtained from Les Viereck and corresponds to Viereck and Little (2007).

In the past, spruce has exhibited fairly low potential migration rates. Following the most recent deglaciation, it took thousands of years for Sitka spruce to recolonize Prince William Sound from southeast Alaska. Dispersal attributes for Alaska spruce species include:

- Minimum seed-bearing age: 10 to 40 years
- Seed type: winged seed 10 to 12 mm long.
- Seed dispersal mode: wind.
- Large seed crop frequency: 2 to 12 years.
- Seed dispersal distance: 30 to 800 m; most seed falls within 100 m.
- Lifespan: varied, from 800 years (Sitka spruce) to about 200 years (black spruce).

Current Distribution of Rare Species

In contrast to dominant species such as trees, rare plant species are more likely to be affected by more subtle and finer spatial-scale environmental change. Additionally, despite their low abundance, rare plant species represent an important component of biodiversity and in some cases contribute to ecological resiliency (see Mouillot et al. 2013). Rare species themselves, however, are typically quite sensitive to ecological perturbations and are vulnerable to extinction (Gaston 1994).

Despite their low abundance, rare plant species represent an important component of biodiversity and in some cases contribute to ecological resiliency.

The concept of "rarity" incorporates multiple spatial, demographic, and ecological elements for a given species in a region. Species are classified as rare based on their geographic range size, degree of habitat specificity, and population size (Rabinowitz 1981). Thus a species may be considered rare if it has a limited geographic range (narrowly endemic) even if it is locally abundant. Alternatively, a species may be widely distributed but tightly restricted to unusual habitat types (e.g., inland sand dunes or serpentine soils), and a rare species may be widespread but always occur at chronically low population sizes. Last, species may encompass multiple forms of rarity, such as those that are narrowly endemic and are habitat specialists. See AKNHP (2014) for a description of rarity ranks used in Alaska. The forms of rarity that are most vulnerable to extirpation are those with narrow geographic range sizes or those that specialize in habitats that are also likely to be affected by resource development.

Patterns of plant rarity in Alaska are notably different from other states. The density of rare plants is considerably lower (i.e., 15× lower) relative to Pacific Northwest states such as Washington and Oregon. A larger proportion of rare species in Alaska are widely distributed habitat specialists rather than narrow endemics (Carlson and Cortés-Burns 2012). Finally, fewer globally rare and federally listed plant species are known from Alaska (Carlson and Cortés-Burns 2012). The low number of species at risk of extirpation in Alaska is due to a combination of the

biogeography of biodiversity and the extent of wilderness, which results in fewer threats from habitat conversion, the primary cause of species endangerment (Meffe and Carroll 1997, Wilcove and Master 2005).

Recorded populations of rare plants occur throughout the assessment area, but with lower densities in the Kenai Mountains and lowlands, and in the Chugach Mountains near Prince William Sound. Fewer recorded plants in these regions are likely owing to lower collection intensity and large regions of unsuitable habitat (ice fields). A large number of rare plants has been recorded in the Anchorage Bowl and adjacent western Chugach Mountains. This high density is partially an artifact of very high collection intensity, as well as high topographic, environmental, and geologic complexity.

Fifty-three rare-to-imperiled plant species have been documented in the assessment area by the Alaska Natural Heritage Program (see http://aknhp.uaa.alaska.edu/botany/rare-plant-species-information/) (table 6-4). The global and regionally rare taxa are found in a range of habitat types: four species are restricted to freshwater aquatic habitats and seven are associated with intertidal and supratidal habitats. Nine species are associated with wetlands; six with woodlands; 17 with meadows; two with steppe bluffs; and seven with rock outcrops and alpine slopes. One species is found in multiple habitat types. More than half of the rare wetland species are associated with neutral, calcareous, or alkaline substrates. Rare taxa are strongly represented by the Cyperaceae (14 taxa), Poaceae (seven taxa), and Brassicaceae (four taxa). The majority of these species are secure globally, but reach their distributional limits in the Chugach. For example, western fescue (*Festuca occidentalis*) is ubiquitous in the Pacific Northwest and British Columbia, but is known from only three populations in Alaska, two of which are on the Kenai Peninsula. Six taxa are considered rare globally: Sessileleaf scurvygrass (*Cochlearia sessilifolia*), Harold's milkvetch (*Astragalus robbinsii* var. *harringtonii*), fourpart dwarf gentian (*Gentianella propinqua* ssp. *aleutica*), Alaska hollyfern (*Polystichum setigerum*), Pacific buttercup (*Ranunculus pacificus*), and Alaska mistmaiden (*Romanzoffia unalaschcensis*).

Current Status of Non-Native Species

Invasive species represent one of the greatest threats to ecosystems and economies globally and are a challenging issue for land managers at the regional and local level. Non-native species with the capacity to form large and self-sustaining populations in new regions (i.e., "invasive") can displace native plant and wildlife populations, reduce habitat quality, alter ecosystem functions, and reduce the overall economic value of the landscape (Pimentel 2009).

Table 6-4—List of rare plant taxa tracked by the Alaska National Heritage Program occurring in the assessment area

Family	Taxon name	State rank	Global rank
Asteraceae	*Agoseris glauca*	S2S3Q	G5
Asteraceae	*Artemisia dracunculus*	S1S2	G5
Fabaceae	*Astragalus robbinsii* var. *harringtonii*	S3	G5T3
Brassicaceae	*Boechera lyallii*	S1	G5
Brassicaceae	*Boechera stricta*	SU	G5
Cyperaceae	*Bolboschoenus maritimus* ssp. *paludosus*	S3	GNRTNR
Ophioglossaceae	*Botrychium virginianum*	S3	G5
Cyperaceae	*Carex atratiformis*	S3	G5
Cyperaceae	*Carex bebbii*	S1S2	G5
Cyperaceae	*Carex deflexa* var. *deflexa*	S2S3	G5
Cyperaceae	*Carex deweyana* var. *deweyana*	S2S3	G5
Cyperaceae	*Carex heleonastes*	S3	G4
Cyperaceae	*Carex interior*	S3	G5
Cyperaceae	*Carex parryana*	S2	G4
Cyperaceae	*Carex phaeocephala*	S3	G4
Cyperaceae	*Carex preslii*	S1	G4
Cyperaceae	*Carex sprengelii*	S1	G5?
Orobanchaceae	*Castilleja hyetophila*	S2S3	G4G5
Poaceae	*Catabrosa aquatica*	S1S2	G5
Brassicaceae	*Cochlearia sessilifolia*	S2Q	G1G2Q
Crassulaceae	*Crassula aquatica*	S1S2	G5
Brassicaceae	*Draba incerta*	S3	G5
Cyperaceae	*Eleocharis quinqueflora*	S2	G5
Cyperaceae	*Eriophorum viridicarinatum*	S2S3	G5
Poaceae	*Festuca occidentalis*	S1	G5
Gentianaceae	*Gentianella propinqua* ssp. *aleutica*	S3	G5T2T4
Rosaceae	*Geum aleppicum* ssp. *strictum*	S3	G5T5
Apiaceae	*Glehnia littoralis* ssp. *leiocarpa*	S2S3	G5T5
Poaceae	*Glyceria striata*	S3	G5
Cupressaceae	*Juniperus horizontalis*	S3	G5
Plantaginaceae	*Limosella aquatica*	S3	G5
Caprifoliaceae	*Lonicera involucrata*	S3	G4G5
Asparagaceae	*Maianthemum stellatum*	S3	G5
Saxifragaceae	*Micranthes porsildiana*	S2	G4
Ericaceae	*Monotropa uniflora*	S1	G5
Haloragaceae	*Myriophyllum farwellii*	S1	G5
Hydrocharitaceae	*Najas flexilis*	S3	G5
Orobanchaceae	*Pedicularis groenlandica*	S2	G5
Zosteraceae	*Phyllospadix serrulatus*	S3	G4
Poaceae	*Poa macrantha*	S1S2	G5
Poaceae	*Poa secunda* ssp. *secunda*	S1S2	G5TNR
Poaceae	*Podagrostis humilis*	S3	G5
Dryopteridaceae	*Polystichum setigerum*	S3	G3
Potamogetonaceae	*Potamogeton robbinsii*	S2	G5
Rosaceae	*Potentilla drummondii*	S2S3	G5
Ranunculaceae	*Ranunculus orthorhynchus* var. *orthorhynchus*	S2S3	G5T5
Ranunculaceae	*Ranunculus pacificus*	S3S4	G3
Hydrophyllaceae	*Romanzoffia unalaschcensis*	S3S4	G3
Salicaceae	*Salix hookeriana*	S2S3	G5
Poaceae	*Schizachne purpurascens*	S2	G5
Amaranthaceae	*Suaeda calceoliformis*	S1S2	G5
Cyperaceae	*Trichophorum pumilum*	S1	G5
Violaceae	*Viola sempervirens*	S1	G5

Although invasive species rank second to outright habitat conversion as a threat to biodiversity globally and nationally (Simberloff 2009, Wilcove and Master 2005), in Alaska and the circumpolar North, invasive species are not known to have caused the degree of damage observed at lower latitudes (Carlson and Shephard 2007, Lassuy and Lewis 2013, Sanderson 2012).

The more restricted impact of invasive species in Alaska is likely due to a range of factors. These may include preemptive colonization of disturbed habitats by native ruderal species in relatively young post-glaciation landscapes; high former biogeographic exchange between Nearctic and Palearctic floras (cf. Abbott and Brochmann 2003) prior to human-aided dispersal (leaving a smaller pool of potential species that would be new introductions); shorter growing seasons and lower temperatures; and low rates of species introduction by human vectors as a consequence of low human population density, minimal agriculture, and a confined transportation network. However, human population growth is increasing in Alaska, and consequently, the diversity and geographic scope of non-native species is expanding. Formerly pristine landscapes are increasingly being threatened (Carlson and Shephard 2007). The state of non-native species establishment in Alaska is in an early stage with continued geographic expansion. Ecological and economic consequences are expected to increase as certain invasive species expand (Bella 2011, Carlson and Shephard 2007, Jarnevich et al. 2014). Evaluation of the scope of threat posed by invasives is incomplete.

South-central Alaska is an area with the potential to experience a significant impact by invasive species.

South-central Alaska is an area with the potential to experience a significant impact by invasive species. The region encompasses some of the highest densities of people and infrastructure in the state, and the region harbors intact wilderness adjacent to invasive-species sources. Although the diversity and biomass of non-native plants are currently low, non-native plants have become an inescapable component of many habitats in the region.

Of about 40,000 invasion records in the assessment area, 159 taxa have been documented, encompassing 3128 ha of 11 007 ha surveyed (AKEPIC 2014), which represents a very small percentage (0.04 percent) of the total area. Most invasions are associated with urban areas and road corridors. Areas without non-native plants are generally restricted to habitats off of the anthropogenic footprint (fig. 6-11). About 20 percent of weed records in the assessment area are found in the Anchorage Bowl. Of the 20 plant species with the capacity for the greatest ecological damage, half are known from only 30 or fewer records, and seven species are known from more than 100 populations (table 6-5). Seven invasive species are currently geographically restricted to the Anchorage Bowl. Nearly one-third of the documented species in the region have not been evaluated for perceived ecological risk.

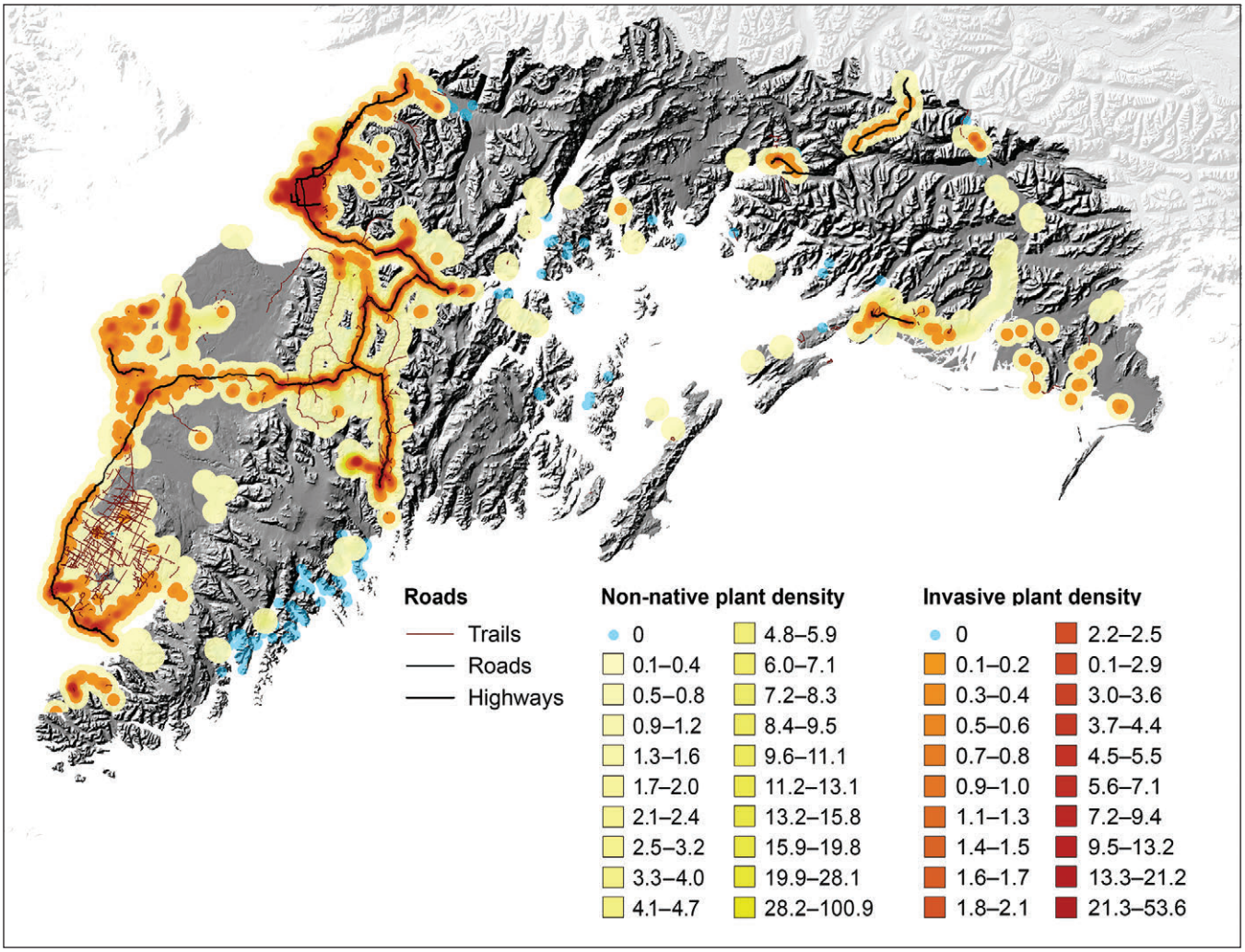


Figure 6-11—Density of non-native plant invasions in the Kenai Peninsula-Chugach National Forest region. Yellow circles indicate densities of all non-native plants. Orange to red circles indicate densities of infestations of species considered moderately to highly invasive. Areas that have been surveyed and no non-native species observed are shown as blue points. Also shown are trails, roads, and highways.

Sweetclover (*Melilotus albus*), orange hawkweed (*Hieracium aurantiacum*), and waterweeds (*Elodea canadensis*, *E. nuttallii*, and their hybrids) are considered ecologically damaging non-native species that are found in intact ecological communities, as well as in the anthropogenic footprint. Reed canarygrass (*Phalaris arundinacea*) is considered a highly invasive species, which in this region is likely composed of mixed Eurasian-American cultivars (a few isolated native Pleistocene relict populations persist in interior Alaska at warm springs) (see Jakubowski et al. 2013).

Although a few species are expected to be highly damaging in more remote natural areas, most non-native plants that have established in these areas tend to be those of lower predicted ecological impact. The species that most commonly

Table 6-5—List of highly invasive plant species and number of records in the assessment area

Name	Invasiveness rank	Number of records
Bromus tectorum L.	78	5
Caragana arborescens Lam.	74	16
Centaurea stoebe L.	86	50
Cirsium arvense (L.) Scop.	76	311
Elodea sp. Michx.	79	30
Fallopia ×bohemica (J. Chrtek & Chrtkov) Bailey	87	1 [a]
Hieracium aurantiacum L.	79	436
Hieracium caespitosum Dumort.	79	28
Impatiens glandulifera Royle	82	15 [a]
Lupinus polyphyllus Lindl.	71	227
Lepidium latifolium L.	71	2 [a]
Lythrum salicaria L.	84	14 [a]
Melilotus albus Medikus	81	883
Phalaris arundinacea L.	83	1089
Prunus padus L.	74	335 [a]
Prunus virginiana L.	74	63 [a]
Rosa rugosa Thunb.	72	2 [a]
Sonchus arvensis ssp. *arvensis* L.	73	72
Sonchus arvensis ssp. *uliginosus* L.	73	6
Vicia cracca ssp. *cracca* L.	73	913

[a] Species currently restricted to the Anchorage Bowl.

occur outside of the anthropogenic footprint are common dandelion (*Taraxacum officinale*), annual bluegrass (*Poa annua*), Kentucky bluegrass (*Poa pratensis* ssp. *irrigata*/ssp. *pratensis*), common plantain (*Plantago major*), and disc mayweed (*Matricaria discoidea).* These species are disturbance specialists that are unlikely to persist in later successional stages and rarely achieve densities that exclude native plants or change ecosystem processes significantly.

Case Study: Using Repeat Field Measurements to Detect Change in Forests of the Chugach/Kenai Region

Tara Barrett, research forester, Pacific Northwest Research Station

Change in plant species composition is often rapid within small areas as individual plants regenerate, grow, and die. Over very large regions, vegetation change reflects broad shifts in climate, management, or disturbance regimes. In this case study, we look at recent changes in aboveground live-tree biomass and discuss possible causes. We used a set of 1,079 forested field plots installed from Ketchikan to Kodiak in the period of 1995–2003, then remeasured in 2004–2010, to assess recent change in unmanaged forests at a very broad spatial scale (see Barrett [2014] for methods).

The Chugach National Forest experienced a recent increase in live-tree biomass during the remeasurement period, estimated as an overall 4.5-percent increase, which is equivalent to an increase of 501 kg of dry biomass per forest acre per year. The 95-percent confidence interval of the live-biomass increase ranged from 1.5 to 7.6 percent, indicating uncertainty in the amount of change, but providing strong evidence for an increase in biomass. Significant (p-values < 0.10) increases of live-tree biomass occurred for Sitka spruce and white spruce species. For stands classified by their dominant species, significant increases in biomass occurred in the cottonwood, paper birch, western hemlock, and white spruce forest types. No forest type showed a significant decrease in live-tree carbon mass.

The Chugach National Forest has primarily temperate rain forest tree species (western hemlock, Sitka spruce, and mountain hemlock), but its western edge does border the boreal forest. To look at change in the larger region surrounding the forest, plots were grouped into three ecoregions (fig. 6-12): (1) the Cook Inlet Basin ecological section; (2) southeast Alaska; and (3) the western portion of the temperate rain forest, referred to here as the Gulf Region.

The Cook Inlet region, composed primarily of boreal forest species, showed no significant change in live-tree biomass overall. The region had an annual turnover in live-tree biomass of about 2.4 percent, and both growth and mortality were high. There was modest evidence for an increase in aspen biomass (fig. 6-13); the p-value was 0.047 for a two-sided t-test with a null hypothesis that change had not occurred, but there were only 26 forested plots with aspen.

Southeast Alaska also showed no change in within-forest live-tree biomass overall, although biomass increases are occurring on gentler slopes, and forest area appears to be increasing (Buma and Barrett 2015). There is an estimated

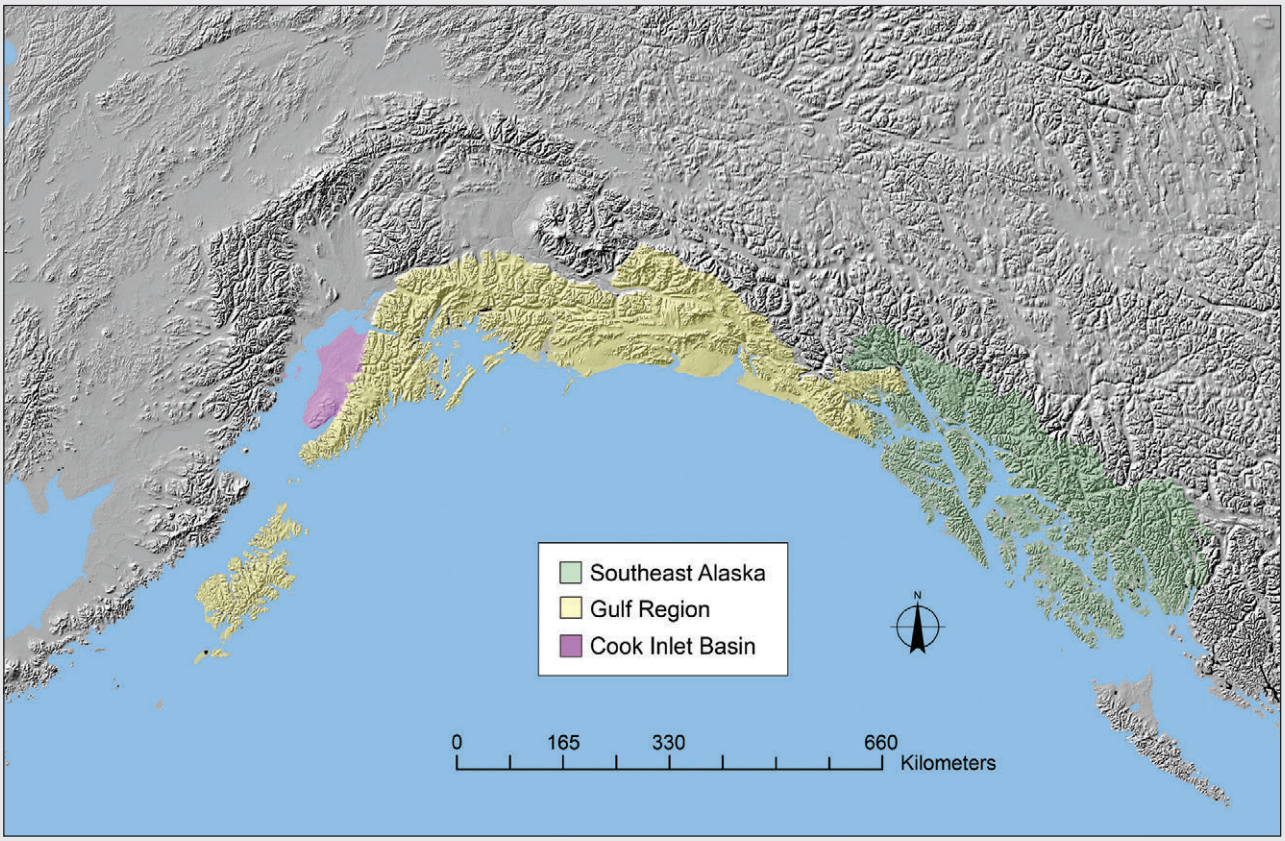


Figure 6-12—Ecoregions (combined ecological sections) used for analysis of biomass change for live trees. Based on Nowacki (2001).

annual increase in western redcedar biomass of 0.6 ± 0.1 percent (fig. 6-13), and there is some evidence for a decrease in shore pine (estimated rate of change in live tree biomass is -3.1 percent per decade with significant error of 1.9 percent and a p-value of 0.096 for a test against no change). Shore pine is mostly found in the same low site productivity areas as yellow-cedar, a species that has experienced widespread mortality events in the past century, thought to be related to climate change (Hennon et al. 2012). Annual turnover of live-tree biomass was about 0.6 percent, much lower than the turnover in the western Kenai Peninsula (fig. 6-14).

In contrast to the other two regions, evidence is quite strong for within-forest live-tree biomass increases in the Gulf Region, where the Chugach National Forest is found. Estimated rate of change was an average annual increase of 0.8 ± 0.2 percent (p-value < 0.001). This change is primarily driven by an average annual increase in Sitka spruce live-tree biomass of 0.9 ± 0.3 percent. Increases also occurred in paper birch and cottonwood (fig. 6-13).

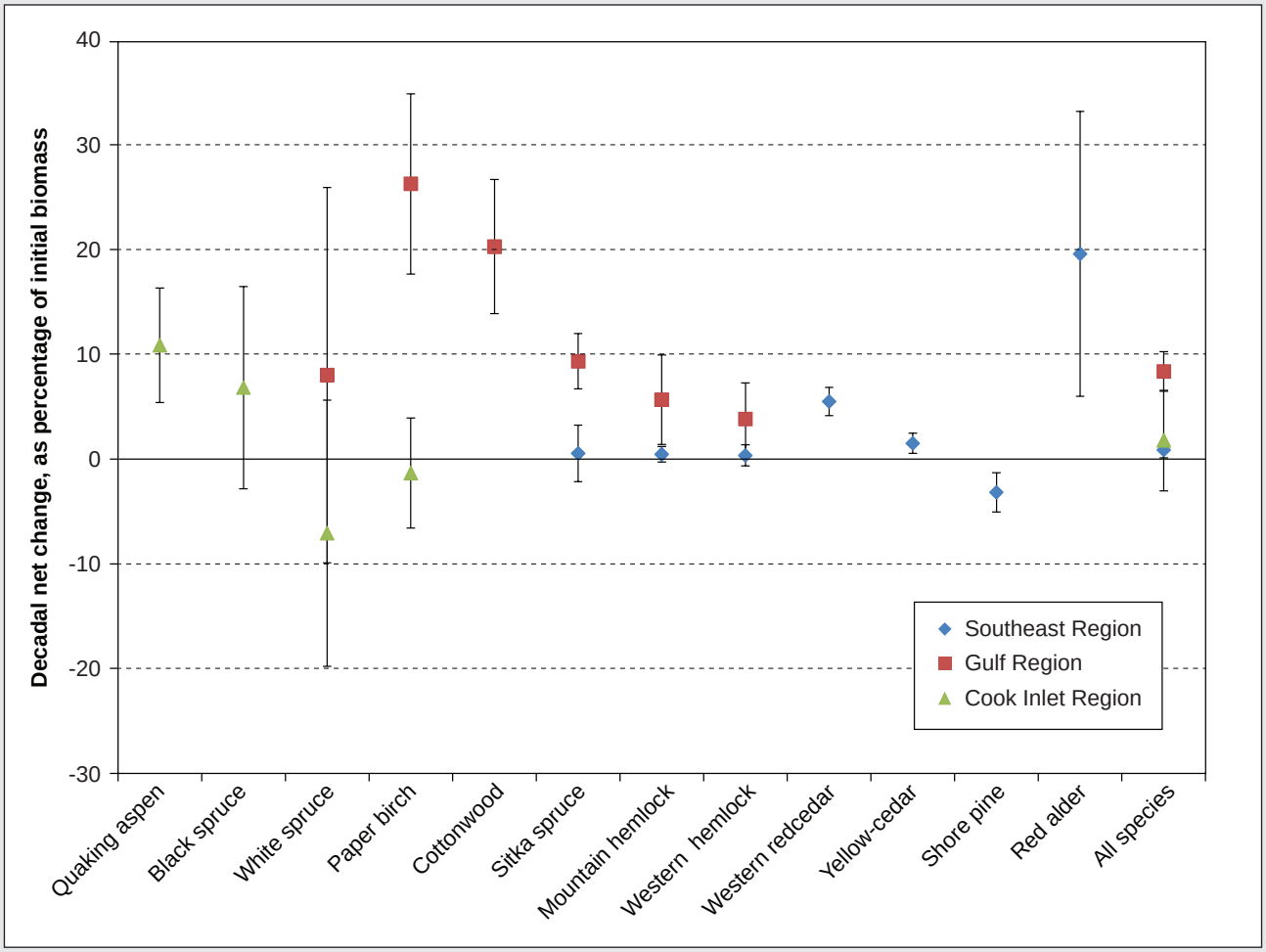


Figure 6-13—Net decadal change in live-tree biomass by species and ecoregion from 1,079 plots in unmanaged forest. Plots were installed from 1995 to 2003 and were remeasured from 2004 to 2010.

Is the increase in live-tree biomass related to climate?—

Climate affects live biomass growth and mortality in multiple ways. It can change disturbance mortality from insects, windthrow, ice storms, disease, or fire; it can alter background mortality through drought or temperature extremes; and

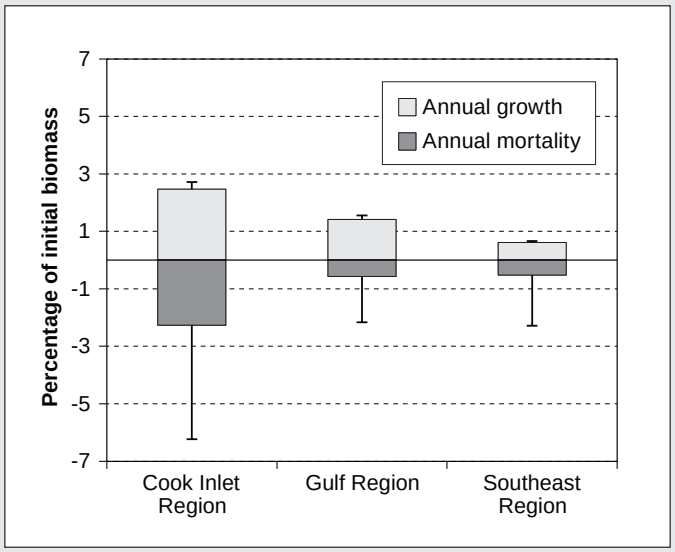


Figure 6-14—Annual growth and mortality for live tree biomass by ecoregion. Numbers equal 134 plots for the Cook Inlet Region, 265 for the Gulf Region, and 680 for the Southeast Region.

it can change basic tree growth rates. Increasing levels of CO_2 in the atmosphere could also positively affect tree growth. Mortality rates are similar for the major species (western hemlock, mountain hemlock, and Sitka spruce) between southeast Alaska and the Gulf region, suggesting that the reason for the increase in the Gulf region is higher growth rather than reduced mortality. Tree ring analysis could more closely examine the potential influence of tree growth rates on the estimated biomass increase found in our analysis.

There are likely to be few direct negative consequences from faster tree growth, but improved growing conditions for trees may mean that forests are encroaching into shrublands or alpine environments. Indirectly, increased growth might lead to more opportunities for commercial use of wood for forest products or bioenergy, although the effects on site productivity are likely to be modest. Perhaps most importantly, the results suggest that large-scale alterations in ecosystem processes suggested by climate model projections may already be occurring. Shifts in species composition within a forest, or between forest, shrubland, and grassland, can affect everything from aesthetics to wildlife habitat, with complex and wide-ranging consequences that may be positive or negative depending on social goals. ■

Summary: Future Vegetation

- Over a quarter of the land cover in the assessment area is projected to change by 2060.
- By 2050, expanded suitable habitat is projected for Sitka spruce and decreasing habitat for white spruce.
- Changes in disturbance regimes and antagonistic and mutualistic interactions are likely to have equal or greater impacts on rare plant species than are direct effects of climate.
- Anthropogenic and fine-scale habitat variables may be the most important factors in determining vulnerability to invasive species.
- Successful management of invasive species in the assessment area depends on the evaluation of sources of uncertainty. These uncertainties include type and rate of spread, policy irreversibility, efficiency, economic damages, and spatial considerations.
- Climatic factors will limit the extent to which fire will increase within the study area.

- The combined influence of property development (e.g., a 53 percent increase in number of private structures) and changing climate (which may increase the frequency and intensity of fire) on the western Kenai Peninsula will increase the vulnerability of the built landscape to fire. The value of structures at risk to fire is projected to grow by 66 percent on private lands by 2065. The projected value of structures in landscapes with high to extreme fire risk may approach $3.8 billion in 2065 (based on 2014 dollars).
- In regions in which insects are currently affecting forest structure and function, we can expect a continued effect of insects on landscape fragmentation.
- Changes in vegetation could have impacts on recreation infrastructure in the assessment area; in particular, the afforestation and spread of invasive species.

Examining the Future: Potential Vegetation Change

Insights into future environmental conditions can be informed by considering conditions at several levels of biological organization, from organisms to biomes. In this section, we look at the results of four modeling exercises to develop scenarios for potential future trends for broad biomes, tree distributions, rare plant distributions, and non-native species. Then, we look at potential scenarios in key disturbance regimes (fire and insects) with a specific focus on the effects on vegetation. These studies were designed to give managers and scientists some examples of future scenarios and vegetation patterns. Because each modeling exercise is unique, we acknowledge that each scenario we present (from biome to species) has varying degrees of uncertainty. All scenarios use a fairly robust evaluation of future climate based on integration of a variety of climate models. However, the scenarios themselves differ in the robustness of the outcome. For example, the biome and ecosystem modeling has a particularly strong foundation because the outcome (i.e., scenario) is built on previous biome shift modeling in Alaska and uses considerable current vegetation modeling that has been peer-reviewed and published extensively (Magness and Morton n.d., Wang et al. 2012). On the other hand, rare plant modeling is constrained by a limited number of known plant locations from which to draw associations with explanatory variables. Detailed methods for our scenarios modeling, as well as an indepth discussion about model confidence and robustness, can be found in appendix 4. We begin this section, however, with a brief overview of climate-envelope modeling for those less familiar with this common approach to developing scenarios for ecological response to shifting climate.

Climate-Envelope Modeling: Using Current Climate Niches to Evaluate Potential Changes in the Future

Generating scenarios is a rapid and cost-effective method for considering potential consequences of climate change. Scenarios can employ climate-envelope modeling to illustrate where suitable conditions for species occur in today's climate and where suitable conditions may occur in future climates.

Climate-envelope models are used to identify the climate niche occupied by a species, land cover type, or biome (Guisan and Thullier 2005, Hamann and Wang 2006, SNAP and EWHALE 2012). For example, a particular tree species may occur in areas with mild rainy winters and cool cloudy summers, such as the case of Sitka spruce. By combining an understanding of climatic limits for species or ecological units with scenarios for future climate, these models help identify possible shifts in geographic distribution of the climate niche as the climate changes. If climate models for areas in southeast Alaska with mild rainy winters and cool cloudy summers suggest shifts upward in elevation and northward in direction, models for species associated with that climate will show similar distributional responses.

Climate-envelope models provide information about how the distribution of the climate space is changing.

Climate-envelope models provide information about how the distribution of the climate space is changing. They have ecological limitations that influence interpretation. The future distributions of species or ecosystems may not match changing climate conditions. Plants and animals must be able to find and disperse into these suitable climate spaces. Other important ecological factors not included in climate-envelope models, such as soil properties or competitive interactions, may make an area unsuitable for a species even when the climate is favorable. Extreme or rare climate events, such as drought or storm events, may be extremely important drivers of distribution, but are not represented in downscaled climate models, and therefore are not included in the climate-envelope models. Ecological transition and species migration may also exhibit considerable time lags. Ecological transitions, or regime shifts, often occur suddenly when structuring properties, such as climate, exceed a tipping point (Hughs et al. 2013). When disturbance triggers these transitions, established trees and plants may hang on in unsuitable climate conditions, but not reproduce. Finally, the future climate may not be represented by current conditions, and models built based on current conditions cannot explain parts of the niche that are not yet available to be described (Williams et al. 2007). In summary, climate-envelope models may not predict species distribution when the niche space is not completely described or when differences exist between the fundamental niche and realized niche.

Other uncertainties can be introduced by the modeling approach and available data. Models of local climate are particularly difficult to develop in Alaska, where digital elevation models are coarse and weather stations are few and biased toward lower elevations. Future projects vary across the range of global climate models (GCMs) and modeling algorithms (Elith and Graham 2009). Consequently, climate-envelope models should not be considered predictors of the future, but instead the foundation for scenarios or hypotheses regarding differential shifts in species or land cover distribution. However, climate-envelope models can be useful tools for exploring the range of future climate conditions and potential ecological outcomes associated with climate change.

Biomes to Organisms: Future Scenarios of Change

Biomes—

Changes to the climate space associated with biomes can provide information about broad climatic changes that are likely to influence ecological structure and function. We review climate-envelope models in the literature for Alaska (Murphy et al. 2010), Alaska and Canada (SNAP and EWHALE 2012), and North America (Rehfeldt et al. 2012).

Land cover types—

Understanding potential changes in land cover can provide a context within which to consider individual species and also lend insight into potential future vistas, future fire characteristics, potential changes in future wood fiber resources, and other fundamental characteristics of the ecosystems that humans will encounter. Therefore, we looked at possible changes in land cover based on climate constraints across the Kenai/Chugach analysis area 50 years into the future (called "Change in land cover across the Chugach/Kenai Peninsula" throughout the rest of the section). Broad land cover types in the assessment area were modeled, and redistributions of future climate envelopes estimated for a range of emission scenarios employing multiple GCMs. The emission scenarios and GCMs are sources of uncertainty that were then used along with model outputs to identify robust trends when compared with other lines of evidence (empirical data, published mechanistic models, climate-envelope models from other spatial scales).

Spruce species—

We used a climate-envelope model to look at potential changes in the distribution of Sitka spruce, black spruce, and white spruce (called "Change in spruce distributions" throughout the rest of this section). Western hemlock, mountain hemlock, yellow-cedar, quaking aspen, balsam poplar, black cottonwood, Alaska paper birch, Kenai birch, and a number of willow and alder species also occur in the assessment

area, often in association with the three spruce species. By focusing on three dominant tree species, this modeling illustrates the potential varied responses to changing climate that may be observed by the wide range of trees that occur in the region.

Rare species—
We modeled future habitat suitability for three rare plant species in the Chugach-Kenai region: *Aphragmus eschscholtzianus*, *Papaver alboroseum*, and *Romanzoffia unalaschcensis*, based on current ecological niches and future climate scenarios (called "Change in habitat suitability for three rare plants" throughout the rest of the section). Similarly to the modeling of three spruce species, the results from these rare plants illustrate the varied response to climate change that may be expected from the much broader group of rare plants that occur in the assessment area.

Invasive plant species—
Twenty-eight non-native plant species that represented a spectrum of current distributions in Alaska (table 6-6) were selected based on perceived impacts to wetland, riparian, coastal, and aquatic habitats that are critical to fish, wildlife, hydrological functions, fire regimes, and other ecosystem functions. Three species are currently not known in the state; nine species have fewer than 50 known invasions, and 16 have between 50 to more than 5,000 documented invasions in the state. In general, the area of suitable habitat was not projected to change dramatically in the future for most species, but the locations of the suitable habitat did change. Results of four species are discussed in greater detail:

1. *Cirsium arvense* (creeping thistle) is a short-lived perennial that has been spreading in mixed forb and grasslands in south-central Alaska, particularly around Anchorage and communities on the Kenai.
2. Waterweeds (*Elodea canadensis*, *E. nuttallii*, and their hybrids) are a very ecologically damaging aquatic species of ponds and slow-moving streams and rivers that have recently been recorded from a number of lakes and ponds in south-central Alaska (Lissuzo 2011, see references in Nawrocki et al. 2011, AKEPIC 2014.
3. Sweetclover (*Melilotus albus*/*M. officinalis*) is a biennial to short-lived perennial legume that has spread widely over the state, particularly on mineral soils along roads and along river bars. It is capable of fixing atmospheric nitrogen, can alter soil chemistry (Sparrow et al. 1993), is associated with lower native diversity and higher mortality of willows (Spellman and Wurtz 2010), and alters plant-pollinator relationships.[13]

[13] **Schneller, L.; Mulder, C.H.P.; Carlson, M.L. [N.d.].** Invasive *Melilotus albus* alters plant-pollinator networks in boreal Alaska. Manuscript in preparation.

Table 6-6—Species included in habitat suitability models

Common name	Scientific name	Alaska occurrence[a]	Worldwide occurrence[b]
Garlic mustard	*Alliaria petiolata* (M. Bieb.) Cavara & Grande	13	1,192
Cheatgrass	*Bromus tectorum* L.	13	557
Siberian peashrub	*Caragana arborescens* Lam.	57	335
Spotted knapweed	*Centaurea stoebe* L. ssp. *micranthos* (Gugler) Hayek	50	221
Creeping (Canada) thistle	*Cirsium arvense* (L.) Scop.	328	1,227
Bull thistle	*Cirsium vulgare* (Savi) Ten.	169	1,430
Scotch broom	*Cytisus scoparius* (L.) Link	31	1,138
Elodea (waterweed)	*Elodea canadensis* Michx, *E. nuttallii* (Planch.) H. St. John and hybrids	80*	1,500*
Leafy spurge	*Euphorbia esula* L.	1	369
Knotweed complex (Japanese, giant, bohemian)	*Fallopia japonica* (Houtt.) Ronse Decr., *F. sachalinensis* (F. Schmidt ex Maxim.) Ronse Decr., *F. ×bohemica* (J. Chrtek & Chrtkov) J. P. Bailey, Watsonia.	331	734
Hempnettle (splitlip, brittlestem)	*Galeopsis bifida* Boenn., *G. tetrahit* L.	334	1,972
Giant hogweed	*Heracleum mantegazzianum* Sommier & Levier	1	322
Hawkweed complex (orange, meadow, narrow-leaf)	*Hieracium aurantiacum* L., *H. caespitosum* Dumort., *H. umbellatum* L.	2,212	1,114
Hydrilla	*Hydrilla spp. Rich.* (mainly *H. verticillata* (L. f.) Royle)	0	655
Ornamental jewelweed	*Impatiens glandulifera* Royle	30	496
Oxeye daisy	*Leucanthemum vulgare* Lam.	2,222	2,045
Butter-n-eggs	*Linaria vulgaris* Mill.	742	1,310
Purple loosestrife	*Lythrum salicaria* L.	13	1,513
Sweetclover (yellow or white)	*Melilotus officinalis* (L.) Lam.	2,286	863
Eurasian watermilfoil	*Myriophyllum spicatum* L.	4	599
White waterlily	*Nymphaea alba* L.	0	664
Reed canarygrass	*Phalaris arundinacea* L.	5,142	1,556
European bird cherry	*Prunus padus* L.	272	985
Himalayan blackberry	*Rubus armeniacus* Focke	2	1,247
Cordgrass complex (smooth, Atlantic, saltmarsh)	*Spartina alterniflora* Loisel., *S. anglica* C.E. Hubbard, *S. densiflora* Brongn., *S. patens* (Ait.) Muhls	0	971
Common tansy	*Tanacetum vulgare* L.	354	641
Scentless false mayweed	*Tripleurospermum perforatum* (Mérat) M. Lainz	81	261
Bird vetch	*Vicia cracca* L.	912	1,747

[a] Source: AKEPIC (2014).
[b] Source: Subsampled from the Global Biodiversity Information Facility (http://www.gbif.org/).

4. Reed canarygrass (*Phalaris arundinacea*) cultivars were widely planted in south-central and southeastern Alaska for roadside stabilization and as forage. This species is particularly threatening to riparian and wetland systems (Galatowitsch et al. 1999, Lavergne and Molofsky 2004, Miller et al. 2008).

Projected Changes in Vegetation

Biome shifts—

We compared the general results from three biome-scale climate-envelope models that forecast future climate conditions in relation to biomes for the assessment area. The coastal rain forest biome remains stable in future forecasts in all three models. On the Kenai lowlands, the boreal forest biome was forecast to be outside of the boreal climate niche in the future. However, the most similar biome climate niche relative to future conditions differed among models and ranged from forested to nonforest biomes. The Kenai lowlands converted to a climate that was more similar to the Aleutian meadows biome in the south and the montane cordillera biome in the north by 2060 (Murphy et al. 2010), with some areas similar to the Saskatchewan prairie and grassland biome (SNAP and EWHALE 2012) and the Rocky Mountain montane conifer forest biome (Rehfeldt et al. 2012). All three models used different biome classifications and spatial extents, changing the biomes available to match future climate conditions. However, the lack of convergence between model signals suggests that a dissimilar and open climate niche may develop on the Kenai lowlands. The boreal biome north of the coastal rain forest biome on the mainland may also be transitional. Two models show this area shifting to climate conditions more similar to the southern boreal forests, and to the potential for the coastal rain forest biome to expand northward (Rehfeldt et al. 2012, SNAP and EWHALE 2012,). When alpine tundra biome was delineated, this biome lost area (Rehfeldt et al. 2012) across the assessment area.

Changes in land cover—

Our model of land cover change used 10 vegetation categories based on the National Land Cover Database (NLCD) system and data (fig. 6-9). Climate envelopes representing potential vegetation in 2060 suggested that 19 percent of the land area across the assessment area will change (4 percent will shift from forested to deforested and 15 percent will shift to a climate niche that suggests afforestation), while 82 percent will remain the same (60 percent will remain nonforested and 22 percent will remain forested) (fig. 6-15). Afforestation occurred mainly in subalpine and alpine elevations, though not in all climate projections. Deforestation occurred in the Kenai lowlands and around the Caribou Hills north of Homer, but deforestation in the Kenai lowlands has less model convergence across the

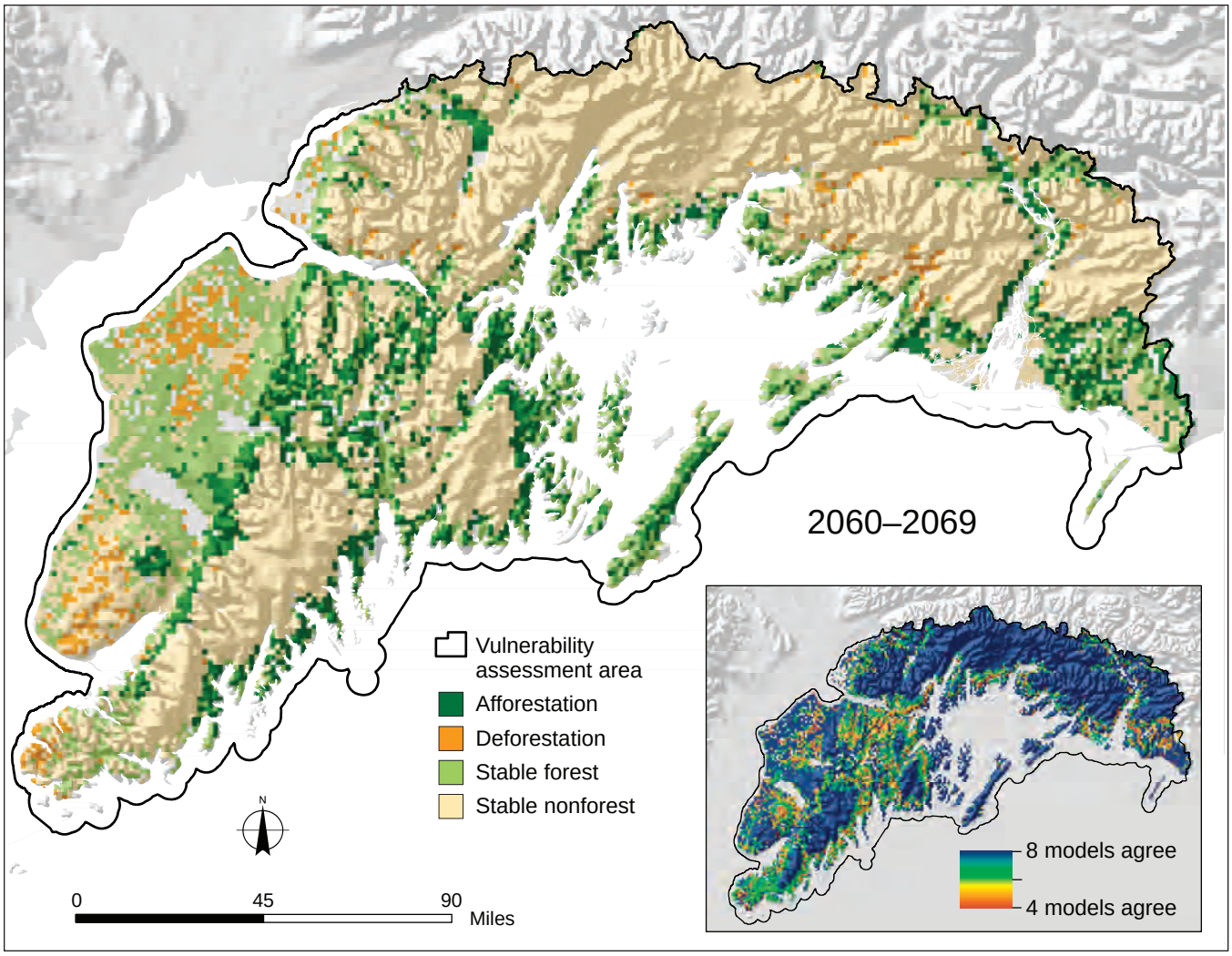


Figure 6-15—Deforestation and afforestation forecast in 2069 across the eight climate projections representing five global climate models (GCMs) and the five-model average GCM and three emission scenarios

climate projections. In other words, the areas of deforestation in the Kenai lowlands converted to deciduous forest in some scenarios. These classifications excluded glaciers, water bodies, and other areas that currently do not support vegetation.

Across the range of climate projections, 32 to 43 percent of the assessment area was forecast to have a climatic envelope shift by 2069. The subalpine zone and southwestern Kenai Peninsula were consistently transitional (fig. 6-16). Ice field core areas and evergreen coastal forest remained stable. The land cover trajectory was less certain in the subalpine zone and had a greater diversity of land cover types forecast (fig. 6-17). Although various climate projections produced multiple responses across all climate projections there were some consistent land cover trajectories (table 6-7; figs. 6-18 and 6-19). This is significant because it points to land cover types that are most likely to shift:

Across the range of climate projections, 32 to 43 percent of the assessment area was forecast to have a climatic envelope shift by 2069.

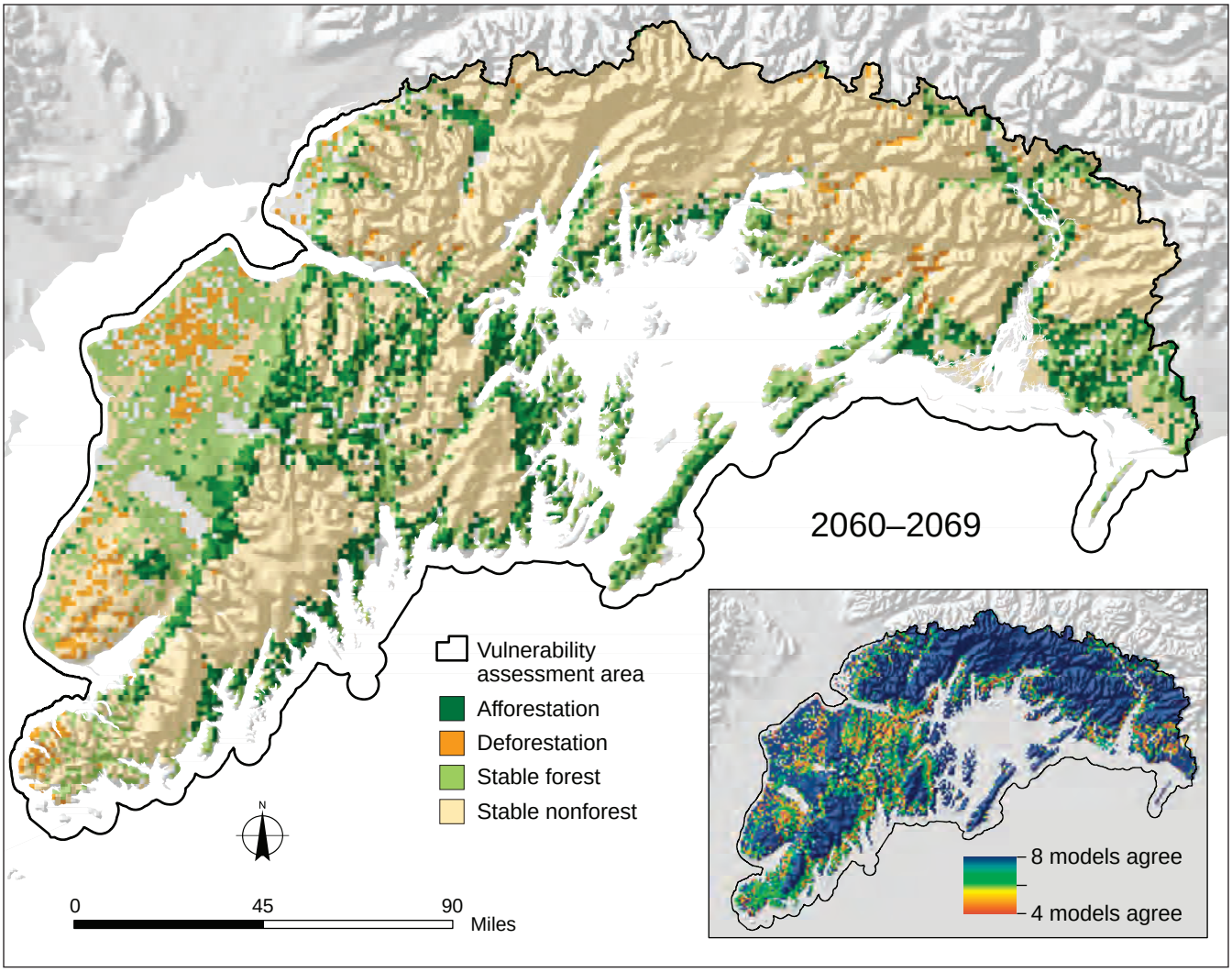


Figure 6-16—Number of the eight climate projections representing five global climate models (GCMs) and the five-model average GCM and three emission scenarios that agree that a pixel will remain the same (stable or refugia).

1. Subalpine shrub (dwarf shrub) and alpine tundra (barren) declines and converts to forest (evergreen, deciduous, and mixed), shrub/scrub, or grassland/herbaceous vegetation. Although there were some regional patterns, the conversion pathway was uncertain and variable among models.

   The alpine conversion trajectory, which results in treeline moving upward in elevation, is supported by well-documented recent observations and other modeling (e.g., Magness and Morton n.d.). Treeline has risen 10 m per decade from 1950 to 1990 on cool aspects of the Kenai Peninsula, and both shrub and tree cover increased above 700 m across all aspects (Dial et al. 2007). Climate-envelope models from other spatial scales also support this trajectory. The area within a suitable climate envelope for alpine tundra land cover declined by 87

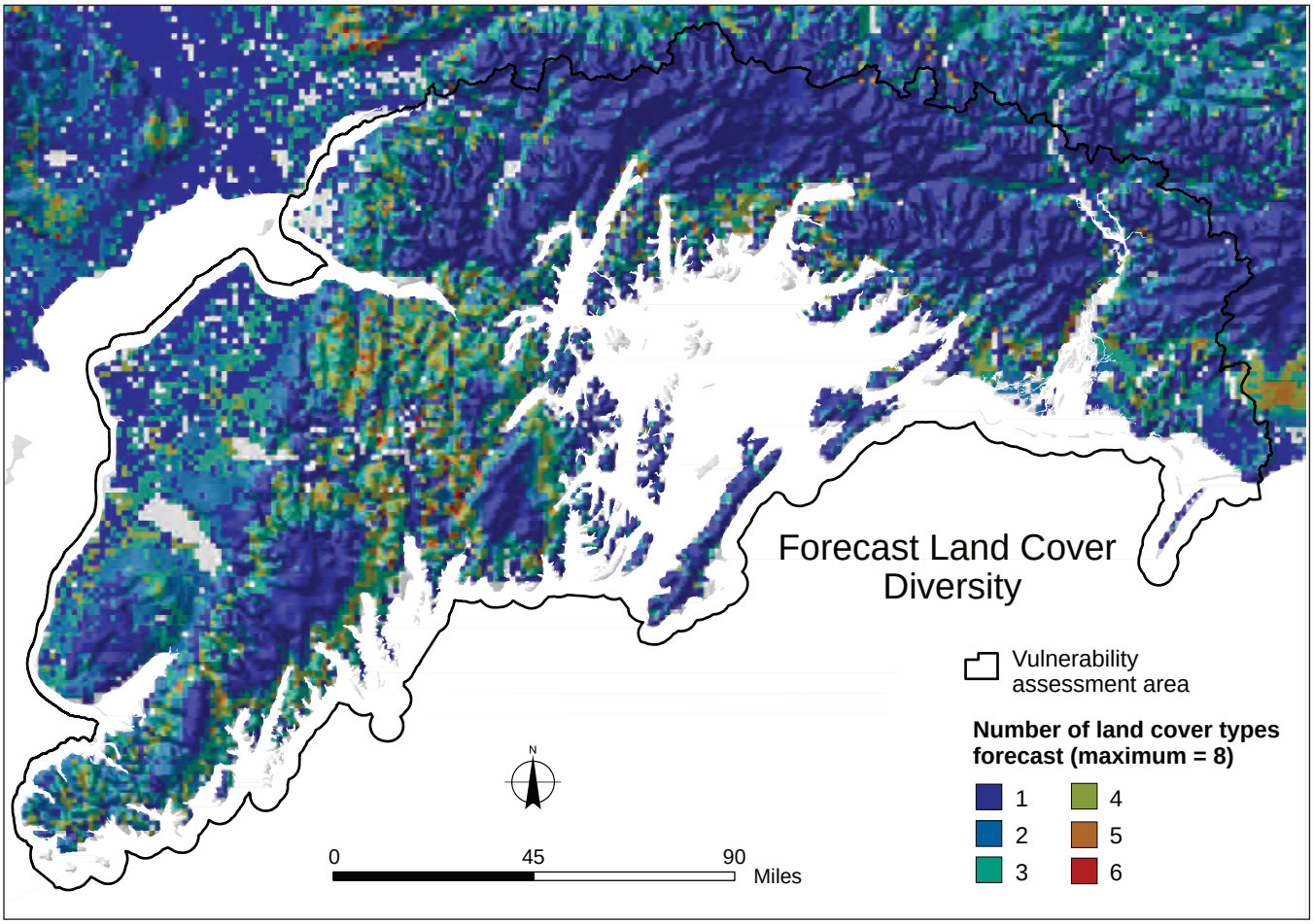


Figure 6-17—The number of different land cover types forecast in 2060–2069 across the eight climate projections representing five global climate models (GCMs) and the five-model average GCM and three emission scenarios.

Table 6-7—Pecentage of the assessment area in each land cover type calculated with LANDSAT values, a conversion threshold, and maximum index of likelihood

	Landsat	1910–1919 ecological fidelity	1910–1919 maximum value	1960–1990 ecological fidelity	1960–1990 maximum value	2060–2069 ecological fidelity
			Percent			
Barren land (rock/clay/sand)	18	18	11	19	14	13
Deciduous forest	3	4	7	4	6	6
Dwarf shrub	4	2	1	3	2	1
Emergent herbaceous wetlands	2	4	7	2	3	4
Evergreen forest	19	13	5	17	13	19
Grassland/herbaceous	0	1	3	0	1	8
Mixed forest	3	4	6	4	5	12
Perennial ice/snow	26	33	47	31	41	30
Shrub/scrub	21	15	8	15	9	4
Woody wetland	4	5	7	5	7	3

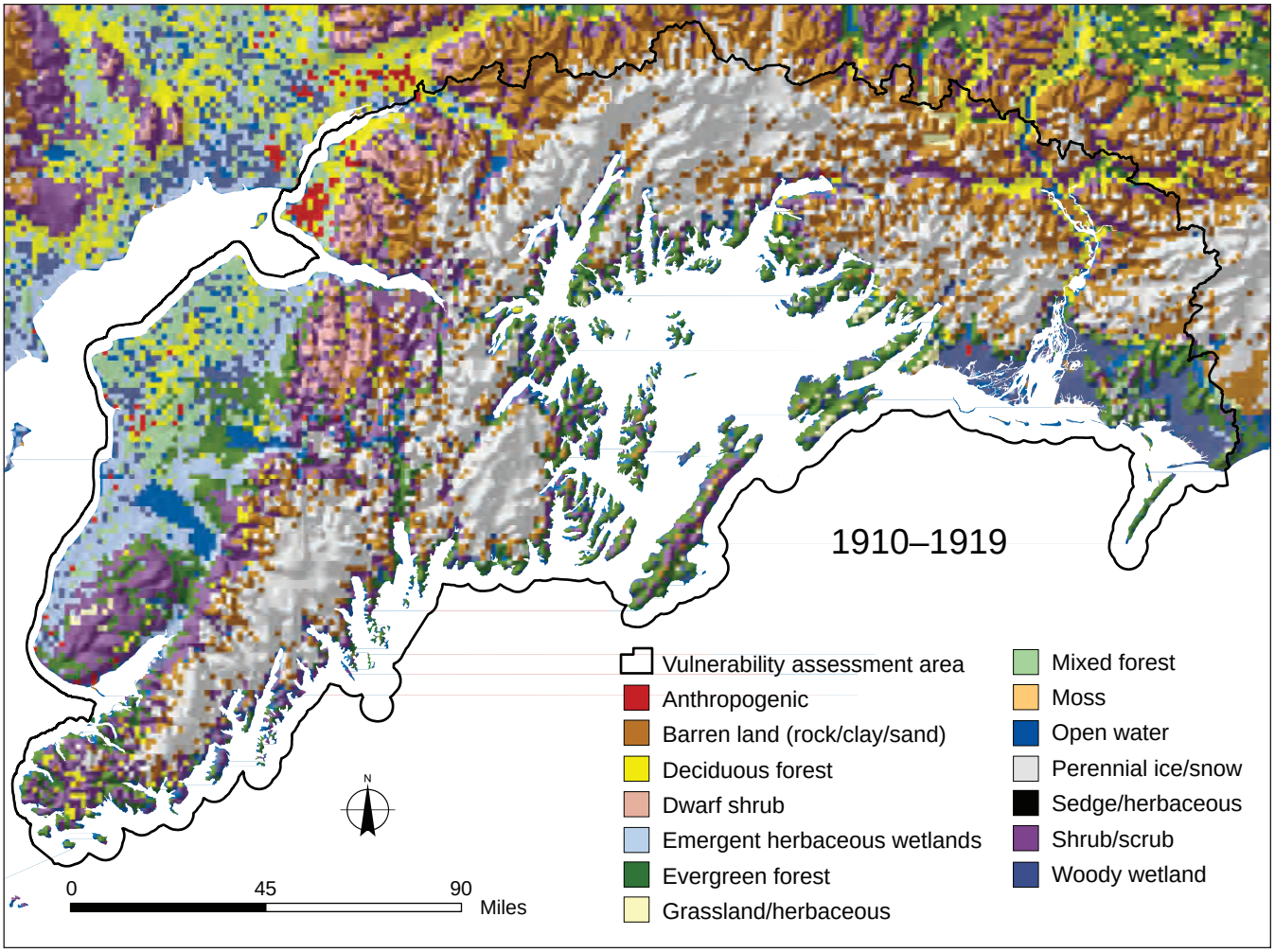


Figure 6-18—Land-cover climate niche forecast using climate data backcast to 1900–1919.

percent by 2060 in south-central Alaska in our model and when tundra was modeled as a North American biome. (Rehfeldt et al. 2012).

2. Deforestation increases, especially on the southwestern Kenai Peninsula where evergreen converted to grassland/herbaceous. Some empirical and anecdotal evidence supports current deforestation on the southwestern Kenai in the Homer area; however, other climate-envelope models provide mixed support for this trajectory (Magness and Morton n.d., Rehfeldt et al. 2012) (see "Changes in spruce distribution" on page 206). This suggests that current afforestation patterns may be a combination of direct climate factors and indirect effects of climate on disturbance regimes. The widespread bark beetle outbreak in the 1990s was linked to warmer temperatures that shortened the beetle life cycle from 2 years to 1 year (Berg et al. 2006). Warmer temperatures also increased tree mortality because the trees were drought stressed. Spruce regeneration has been severely limited by competition from *Calamagrostis canadensis* grass

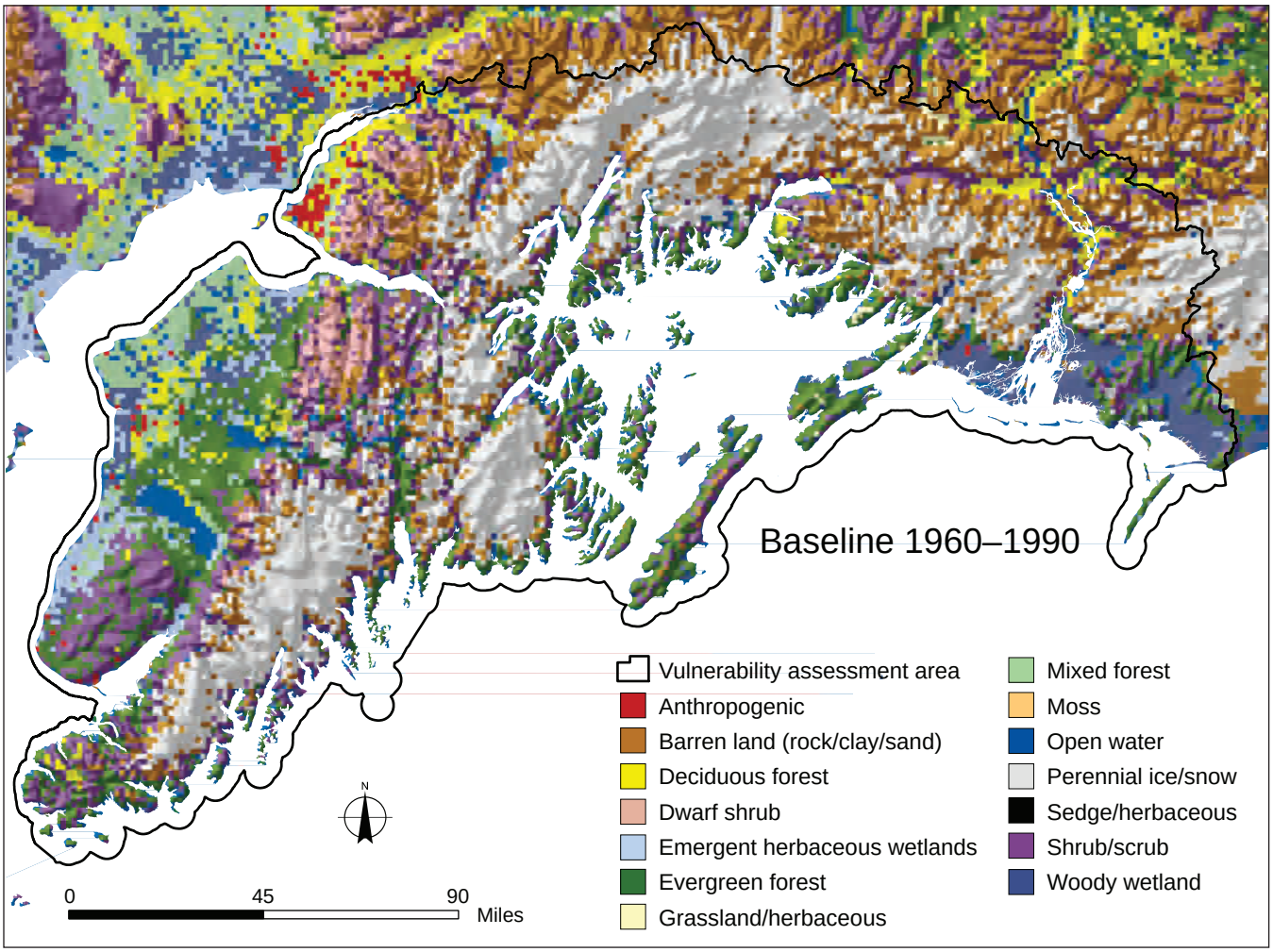


Figure 6-19—Land-cover climate niche forecast for the 1960–1990 baseline.

(Boggs et al. 2008). However, it is unclear if spruce could reestablish if the *C. canadensis* cover and spruce seed availability were actively managed.

3. Coastal rain forest remains across most of its current distribution and expands westward. Stable coastal rain forest land cover is supported by empirical evidence. Historically, the rain forest system was robust even during warm periods such as the medieval warm period (e.g. Ager et al. 2010, Gavin et al. 2003). Biome-scale and other land cover climate-envelope models also support stable coastal rain forest. Climate conditions similar to those currently associated with the coastal Pacific maritime biome remain in future climate conditions (see chapter 2). When the climate envelopes of North American biomes were considered, coastal hemlock forest was stable in 2060 (Rehfeldt et al. 2012). When more detailed land cover types were modeled using a climate-envelope approach on the Kenai Peninsula, the mixed-conifer type associated with Sitka spruce and mountain hemlock expanded (Magness and Morton n.d.).

4. Kenai Peninsula lowlands remains forested, although some areas convert to emergent herbaceous wetlands. The Kenai lowlands are a mosaic of black spruce, white spruce, and deciduous tree species. Forest type is forecast to transition to mixed forest, but the climate niches of mixed forest, evergreen, and deciduous forest types overlap. Some empirical evidence and trends support stability of Kenai lowland forest, but there is little evidence that emergent herbaceous wetlands have increased or will increase. Black spruce forest is expanding into peatlands as the climate warms and increased evapotranspiration causes drying (Klein et al 2005). The bark beetle disturbance did not cause deforestation in the Kenai lowlands. Bark beetles thinned white spruce, but black spruce and deciduous species were the primary tree canopy in which white spruce was affected (Boucher and Mead 2006). Most other climate-envelope models suggest that forest will remain stable (e.g., see "Changes in spruce distribution" below). A land cover model forecasts that the climate niche of mixed forest, deciduous forest and black spruce stands remained stable (Magness and Morton n.d.).

Changes in spruce distribution—
Potential future distribution of Sitka, black, and white spruce were examined by evaluating current climate conditions associated with established spruce forest and considering how the three spruce species would respond to climate conditions modeled in the future. We began by developing an imputation model to predict the current distribution of spruce species based on climate variables. This model effectively predicted the current species distribution, indicating that our model approach identified an appropriate set of climate features to predict current distribution of spruce in this region. Results also confirmed that Sitka, black, and white spruce occupy distinctly different climates. For instance, compared to black spruce, Sitka spruce locations averaged an extra 32 days per year during which the temperature was above 5 °C, had maximum June temperatures that were 2.7 °C cooler, had December minimum temperatures that were 8.7 °C warmer, and were found at locations with 13 cm more May precipitation. Sitka spruce is characteristic of the coastal rain forest. In contrast, white spruce and black spruce can tolerate colder winter temperatures and warmer, drier summers. White spruce and black spruce occupy similar climate conditions; however, black spruce has a greater tolerance for high water tables and nutrient-poor soils, and thus is often found in areas where white spruce cannot grow. In addition, because black spruce trees usually don't grow very large, black spruce is relatively unaffected by the spruce beetle outbreaks that substantially influence white spruce populations in this region.

Results confirmed that Sitka, black, and white spruce occupy distinctly different climates.

When projected 50 years into the future, our modeling suggests an expanding geographic distribution of suitable habitat for Sitka spruce, and decreasing habitat for white spruce (fig. 6-20B). Black spruce is less affected than white spruce, although it also shows a decrease in habitat. The geographic pattern of potential change in distribution of habitat for these three spruce species is particularly interesting. Areas of coastal rain forest at low elevations around Prince William Sound continue to support Sitka spruce habitat in the future. This result is consistent with other modeling efforts (see "Change in land cover" on page 200) and with an understanding of the relative stability of the coastal rain forest ecosystem across the Gulf of Alaska.

In contrast to the relative stability of Sitka spruce habitat around Prince William Sound, modeled climate envelopes for the three spruces suggest significant change on the Kenai Peninsula west of the major mountain spine. Currently, black and white spruce (along with Lutz spruce) are the dominant conifers throughout this area. However, the climate scenario examined in this investigation suggests a substantial expansion of potential Sitka spruce habitat across the western Kenai peninsula and associated declines in the geographic area of climate suitable for white and black spruce (fig. 6-20). Because of the association between climate envelopes for Sitka spruce and other coastal rain forest species, western hemlock and potentially cedar climate envelopes may also occur on the western Kenai by 2050.

Increased habitat for Sitka spruce makes sense in the context of warmer temperatures and increased precipitation, which is what most of the climate models predict for the assessment area. Expanded Sitka spruce (and associated conifers) is also consistent with modeling for western hemlock, which shows habitat expanding on the Kenai Peninsula and on Kodiak and Afognak Islands (Barrett et al. 2012). Future patterns of precipitation represent the factor leading to greatest uncertainty in results for Sitka spruce west of the Kenai spine. Models of future climate differ substantially in pattern of precipitation. It is possible that increased precipitation in the summer would not be enough to offset increased evapotranspiration from warmer temperatures.

The 50-year projection shows a large reduction in white spruce habitat, reducing the most suitable habitat to a small region between Ninilchik and Anchor Point. Black spruce habitat south of Tustumena Lake and along Cook Inlet also declines, as Sitka spruce habitat increases. However, the climate-envelope modeling employed does not account for soil types or wetland conditions. In regions with poor soil drainage, it is unlikely that Sitka spruce would displace black spruce. On better drained sites, both black spruce and hardwoods fared well relative to white spruce and Lutz spruce during past beetle outbreaks. If warming conditions and

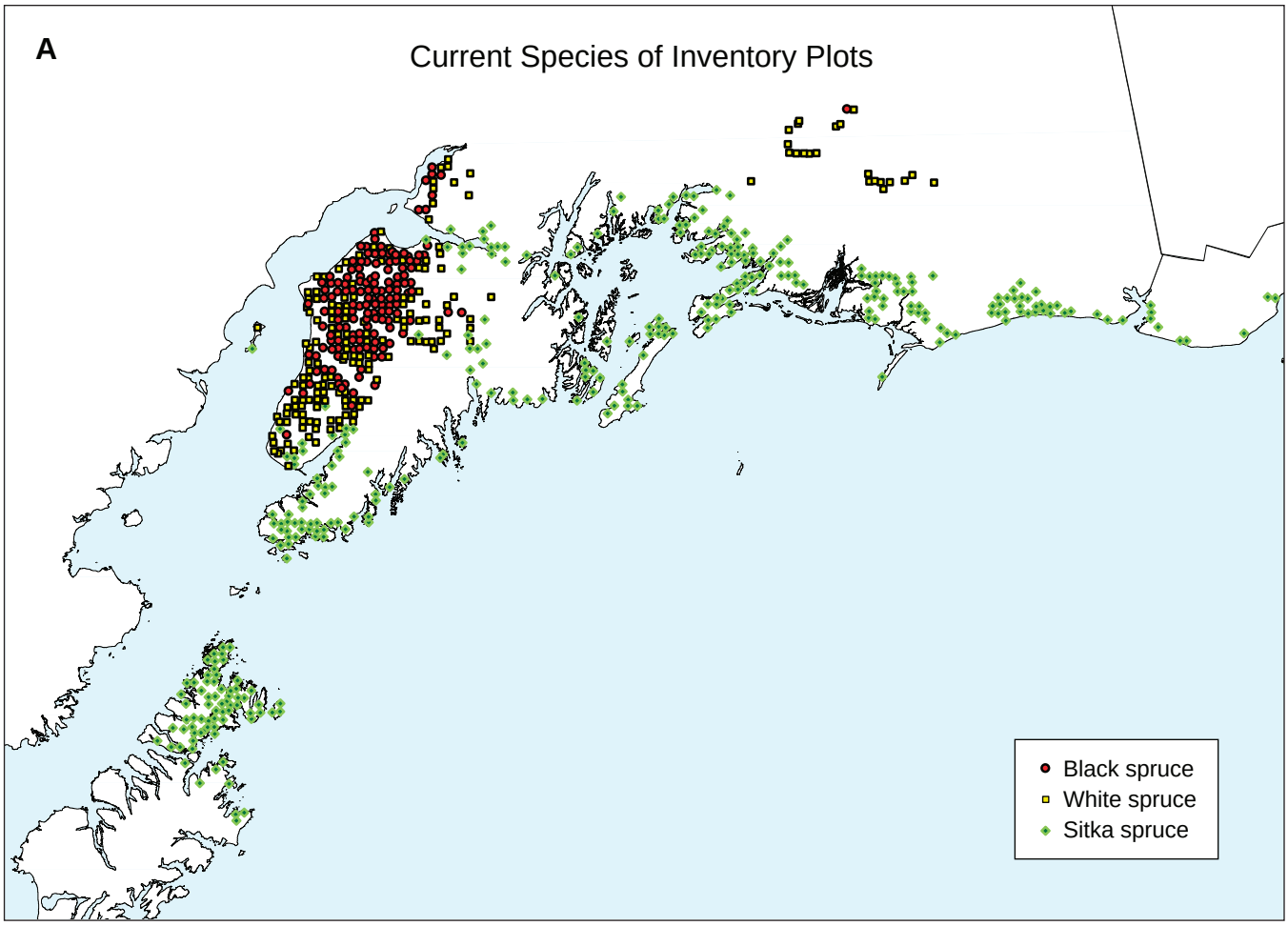


Figure 6-20—Comparison of (A) current distribution of spruce species to (B) projected habitat 50 years in the future. The figure projects Sitka spruce habitat displacing white spruce habitat on the western Kenai Peninsula.

regrowing white, Sitka, and Lutz spruce foster another large beetle outbreak, this pattern favoring black spruce is likely to continue.

In general, the impacts of shifts in spruce species distribution will influence land use patterns, economic patterns, and human values associated with disturbance events that kill trees, rather than from gradual spruce inmigration. If white spruce and black spruce are displaced by Sitka spruce through competition, then effects from this projected shift in habitat will occur slowly. If white spruce is displaced because it can no longer tolerate the climate (or becomes more susceptible to disease or insects because of changes in climate), effects will be realized much faster and over a larger areas.

Hybridization between Sitka spruce and white spruce (producing Lutz spruce) is common. Pollen is wind-dispersed, providing an opportunity for rapid hybridization. Consequently, distributional change in these conifers as a result of genetic

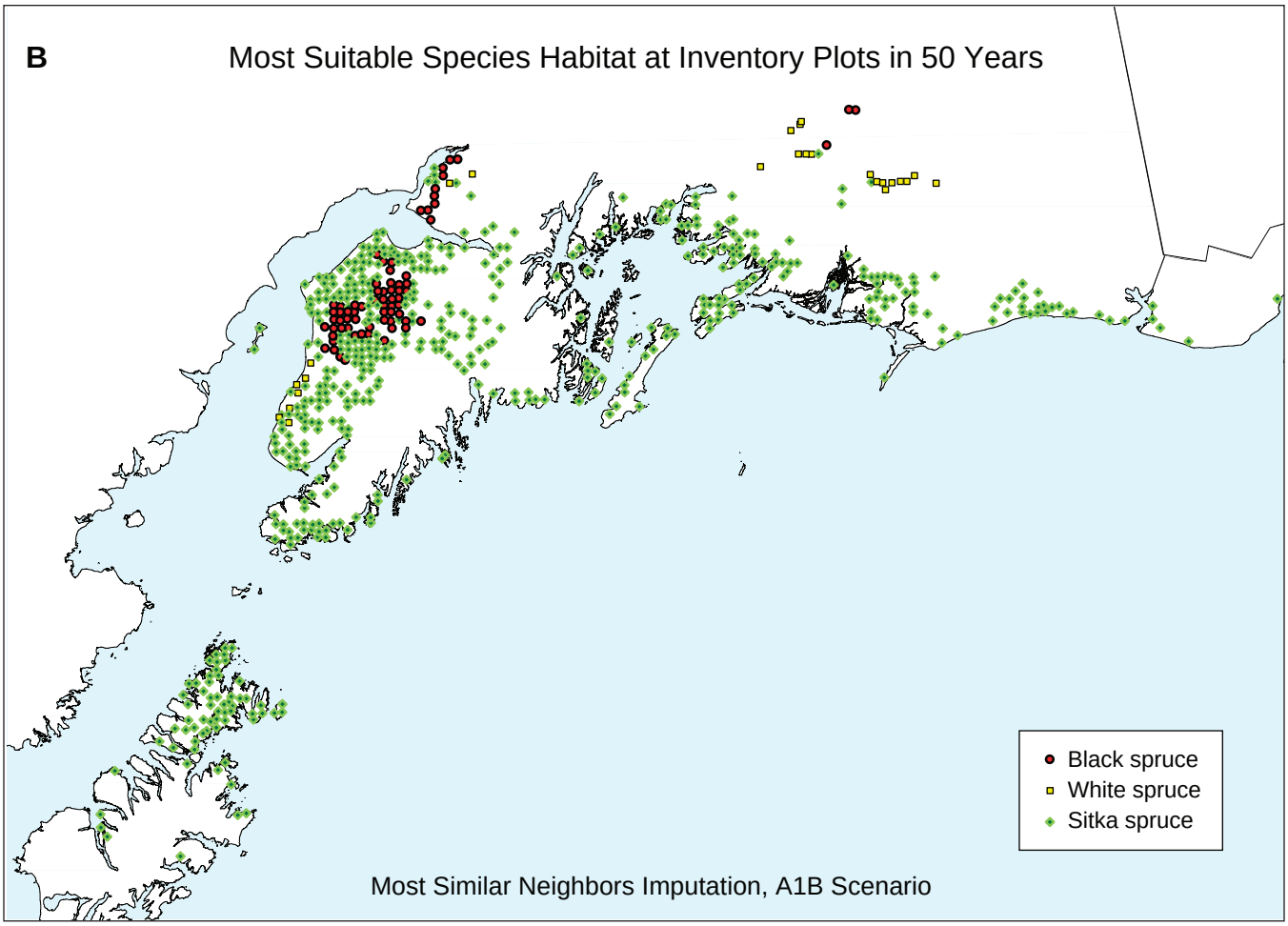


Figure 6-20—Continued.

migration could occur more rapidly than movement through seed dispersal. In contrast, there is little evidence for black spruce/white spruce hybridization.

Planting of tree species around developed areas and as a forest practice increases the potential for rapid, long-distance migration. Introduction of non-native tree species to this area of Alaska will also likely play a role in long-term shifts of species distribution. In a review of non-native trees in Alaska, Alden (2006) examined 32 sites where non-native trees had been planted on the Kenai and in the Matanuska-Susitna Valley, and concluded that potential naturalization of lodgepole pine and Siberian larch was high. These species can outgrow white spruce on productive sites, and they demonstrated successful regeneration at many older plantings. Furthermore, Alden suggested that balsam fir, another non-native, had high potential for naturalization on moister sites in the study region (see “Changes in distribution of invasive species” on page 214).

Change in habitat suitability for three rare plants—
We examined potential changes in geographic distribution of three rare herbaceous plants, whose current and future habitat suitability was explored at the statewide level previously (Carlson and Cortés-Burns 2012). Modeled outputs from *Aphragmus eschscholtzianus, Romanzoffia unalaschcensis,* and *Papaver alboroseum* were overlaid on land management boundaries and explored in greater detail here. These three species were selected from a larger pool of species because modeled outputs were of higher confidence and they represent a range of current distributions.

The overall trend within the assessment area is for a decrease in suitable habitat for *Aphragmus eschscholtzianus* and *Romanzoffia unalaschcensis* over the next 50 years and an increase in suitable habitat for *Papaver alboroseum* (figs. 6-21 and 6-22, summarized in table 6-8). Despite an overall increase in suitable habitat for *P. alboroseum,* particularly in the northwestern portion of the assessment area, our modeling results suggest that within the Chugach National Forest there will be an estimated 31 percent loss of area with habitat suitability greater than 70 percent (fig. 6-22; table 6-8). Also, of particular note is the estimated 100 percent loss of area with habitat suitability greater than 70 percent for *A. eschscholtzianus* within the Chugach.

Mean annual precipitation was the variable that explained the greatest amount of variation in distribution for all three rare plant species.

Climate variables used to develop the models included mean annual temperature, mean annual precipitation, and growing season length (number of frost-free days). Slope and elevation were also included in the models. We found that mean annual precipitation was the variable that explained the greatest amount of variation in distribution for all three rare plant species. Elevation was of secondary importance for *Aphragmus eschscholtzianus* and *Romanzoffia unalaschcensis*, with *Aphragmus eschscholtzianus* associated with intermediate elevations and *Romanzoffia unalaschcensis* associated with low elevations. Slope was the second most important explanatory variable for *Papaver alboroseum,* with populations most associated with intermediate to steep slopes. Despite the importance of precipitation, geographic patterns between current and future conditions for these three species reflects a response to temperature; suitable habitats largely shift to the north and to higher elevations for all three species.

The vulnerability of species to a rapidly changing climate encompasses two elements: (1) the degree of change in mesoscale climate means and extremes, and (2) the intrinsic sensitivity of the species (Moritz and Agudo 2013). Assessing the spatial shifts in perceived climatic envelope, as we have done, addresses only the first component of climate vulnerability. These correlative approaches have often been criticized for lacking a mechanistic underpinning and failing to capture the spatial variability in climate and other variables at finer spatial scales (Ackerly et al.

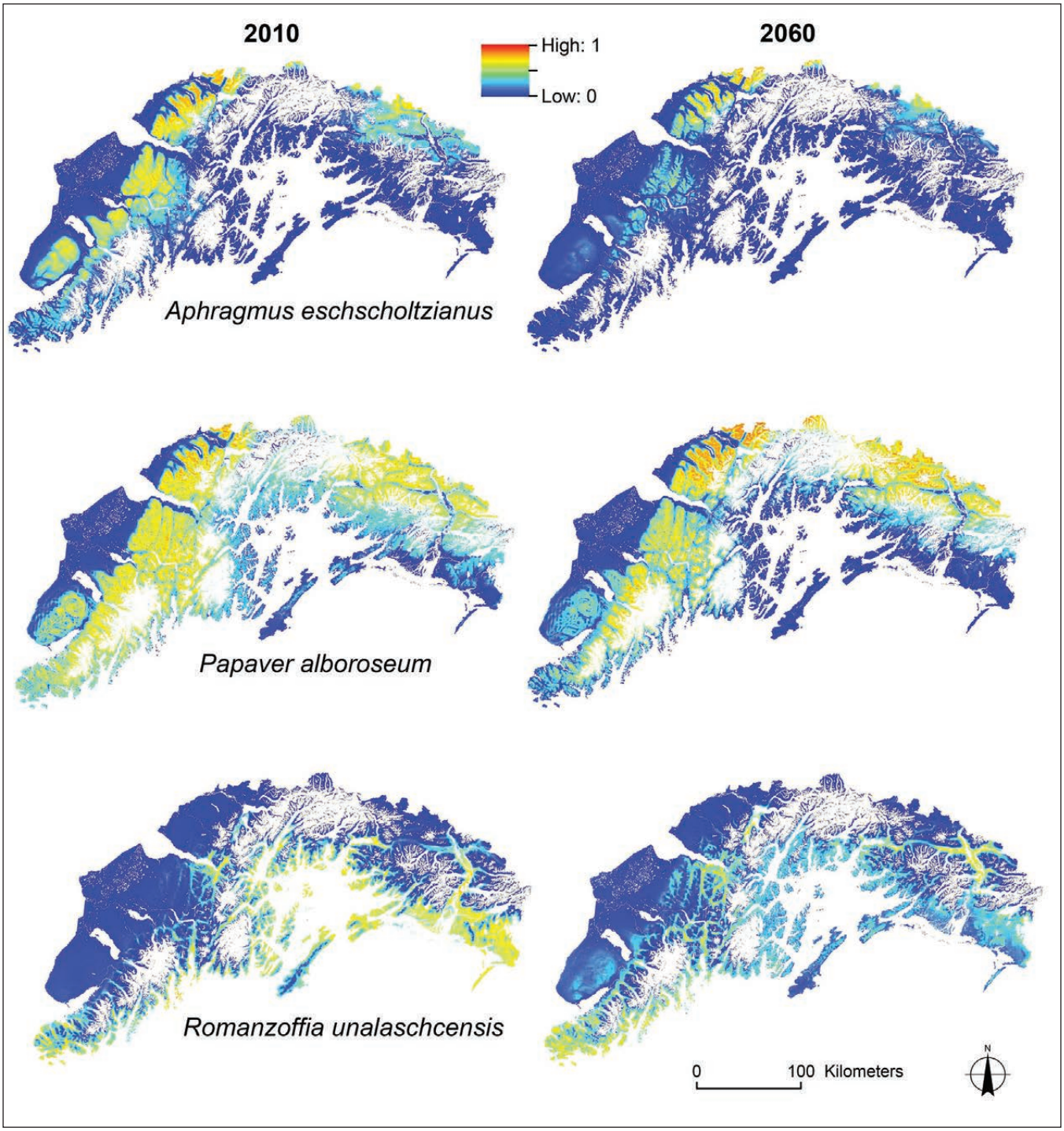


Figure 6-21—Habitat suitability for (A) *Aphragmus eschscholtzianus* (year 2010), (B) *Aphragmus eschscholtzianus* (year 2060), (C) Papaver alboroseum (year 2010), (D) *Papaver alboroseum* (year 2060), (E) *Romanzoffia unalaschcensis* (year 2010), (F) *Romanzoffia unalaschcensis* (year 2060) in the Chugach-Kenai climate vulnerability assessment area. Warm colors represent potentially suitable habitat while cool colors indicate areas in which the species is less likely to occur; the spectrum ranges from red to blue. Areas currently covered by glaciers and open water within the assessment area are shown in white. These distributions are a reflection of the environmental envelope for the species at a coarse ecological grain. The actual distribution will depend on species interactions and other ecological conditions at fine grain.

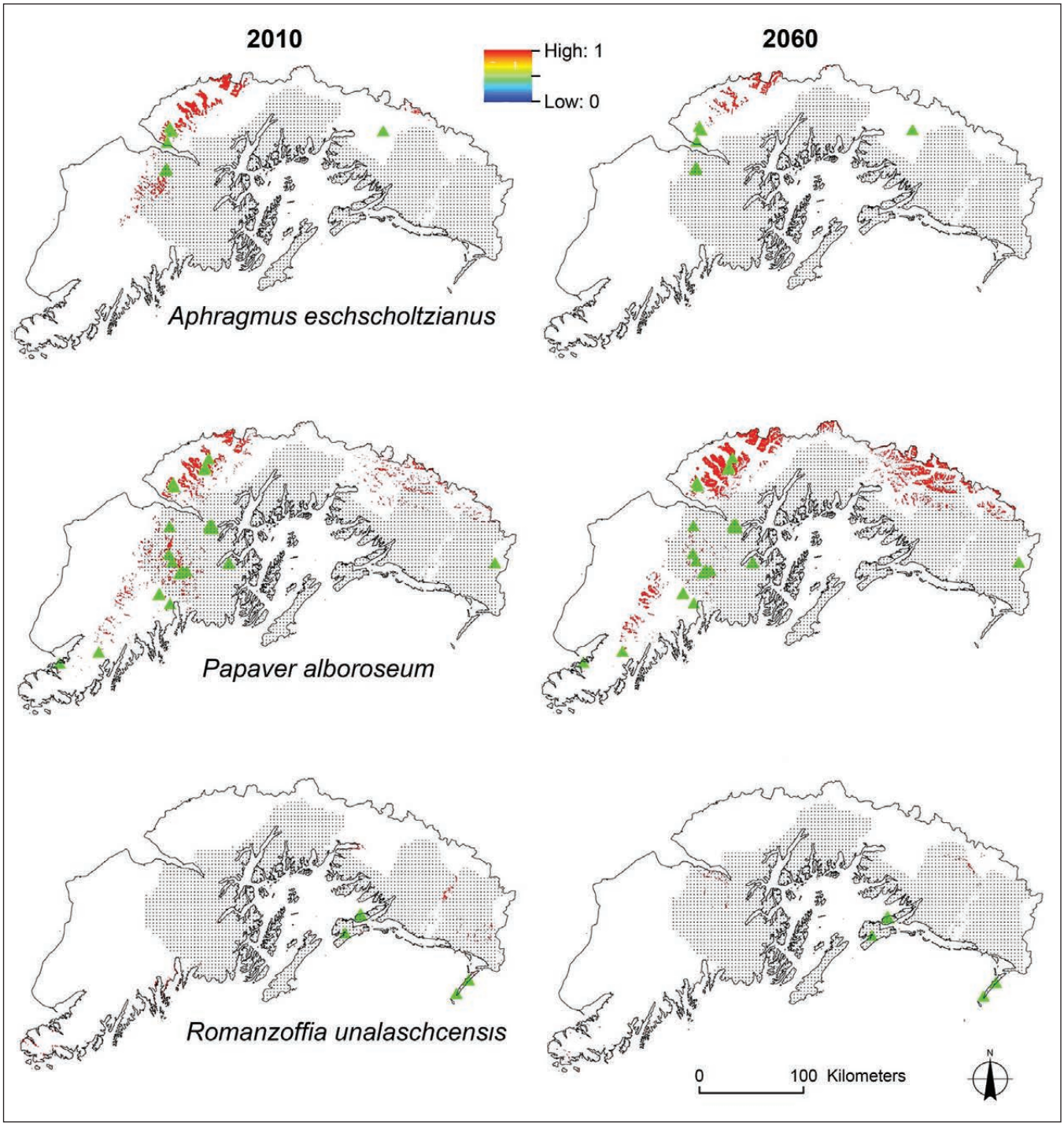


Figure 6-22—Habitat suitability ≥ 0.7 (shown in red) for (A) *Aphragmus eschscholtzianus* (year 2010), (B) *Aphragmus eschscholtzianus* (year 2060), (C) *Papaver alboroseum* (year 2010), (D) *Papaver alboroseum* (year 2060), and (E) *Romanzoffia unalaschcensis* (year 2010), (F) *Romanzoffia unalaschcensis* (year 2060) in the Chugach-Kenai climate vulnerability assessment area. The Chugach National Forest is shown in stippling. The green triangles are locations of known occurrences. Areas currently covered by glaciers and open water are excluded. These distributions are a reflection of the environmental envelope for the species at a coarse ecological grain. The actual distribution will depend on species interactions and other ecological conditions at fine grain.

Table 6-8—Acreage with habitat suitability >0.7 for APES, PAAL, and ROUN in the assessment area

	APES		PAAL		ROUN	
	Hectares	*Percent*	*Hectares*	*Percent*	*Hectares*	*Percent*
Within assessment area:						
2010	90,177	1.66	153,247	2.82	35,131	0.65
2060	34,894	0.64	272,670	5.02	11,294	0.21
Change	-55,283	-61.30	+119,423	+77.93	-23,837	-67.85
Within Chugach National Forest outer boundary:						
2010	12,602	0.49	41,076	1.61	15,455	0.60
2060	0	0	28,177	1.10	6,896	0.27
Change	-12,602	-100.00	-12,899	-31.40	-8,559	-55.38

APES = *Aphragmus eschscholtzianus* Andrz. ex DC.; PAAL = *Papaver alboroseum* Hultén; ROUN = *Romanzoffia unalaschcensis* Cham.

2010, Lenoir et al. 2013, Moritz and Agudo 2013). Substrate type and other habitat features, such as presence or absence of an overstory, are likely to be important niche space parameters for the species modeled here, but could not be included in the distribution models. Therefore, the areas delineated as "suitable habitat" encompass only the coarse climatic variables; inclusion of fine-scale surficial geology, soil moisture, etc., would likely refine the suitable habitat dramatically. Intrinsic sensitivity, such as physiological limits, degree of phenotypic plasticity, and obligate species interactions (e.g., pollinators, mycorrhizal fungi, etc.) are not known and therefore estimations of true vulnerability to climate change are limited. Autecological studies of these and other rare species in Alaska would greatly enhance our understanding of similarities and differences in vulnerability among these species of conservation concern.

Although mean annual temperature and precipitation are accepted in general to be the most important niche parameters for vascular plants (see Davis and Shaw 2001, Hughes 2000, McCarty 2001, Walther et al. 2002, Woodward 1987), it is possible that these variables are not important within the scope of the geographic region investigated. The habitat suitability outputs produced in these models represent a coarse perspective based on a limited number of predictors. Further, changes in disturbance regimes and antagonistic and mutualistic interactions, such as pollinators, herbivory, and pathogens, are likely to have equal or greater impacts on rare plant species than are the direct effects of climate (Adler et al. 2009, Davis et al. 1998, Klanderud 2005, Suttle et al. 2007). In any case, the results shown in figure 6-22 and summarized in table 6-8 suggest that some rare plant populations in the area may be vulnerable to climate change. Some of these species may have

difficulty tracking suitable habitats. For example, *Aphragmus eschscholtzianus* is found at high elevations and *Romanzoffia unalaschcensis* on islands, and both species lack clear migration corridors to track their climate envelopes under future scenarios.

Change in distribution of invasive species—
For ease of interpretation, we discuss results for four taxa (*Cirsium arvense*, *Elodea canadensis*/*E. nuttallii*, *Melilotus albus*/*M. officinalis*, and *Phalaris arundinacea*) that differ in their life histories and illustrate the variation in modeled outputs. Graphically, we display one example (*Phalaris arundinacea*) of scenarios of potential current and predicted future habitat suitability and documented populations in the assessment area with the highest elevation areas remaining unsuitable (fig. 6-23).

Modeled habitat suitability for creeping thistle (*C. arvense*) indicates high suitability in the Anchorage Bowl, southwestern Kenai Peninsula, and eastern

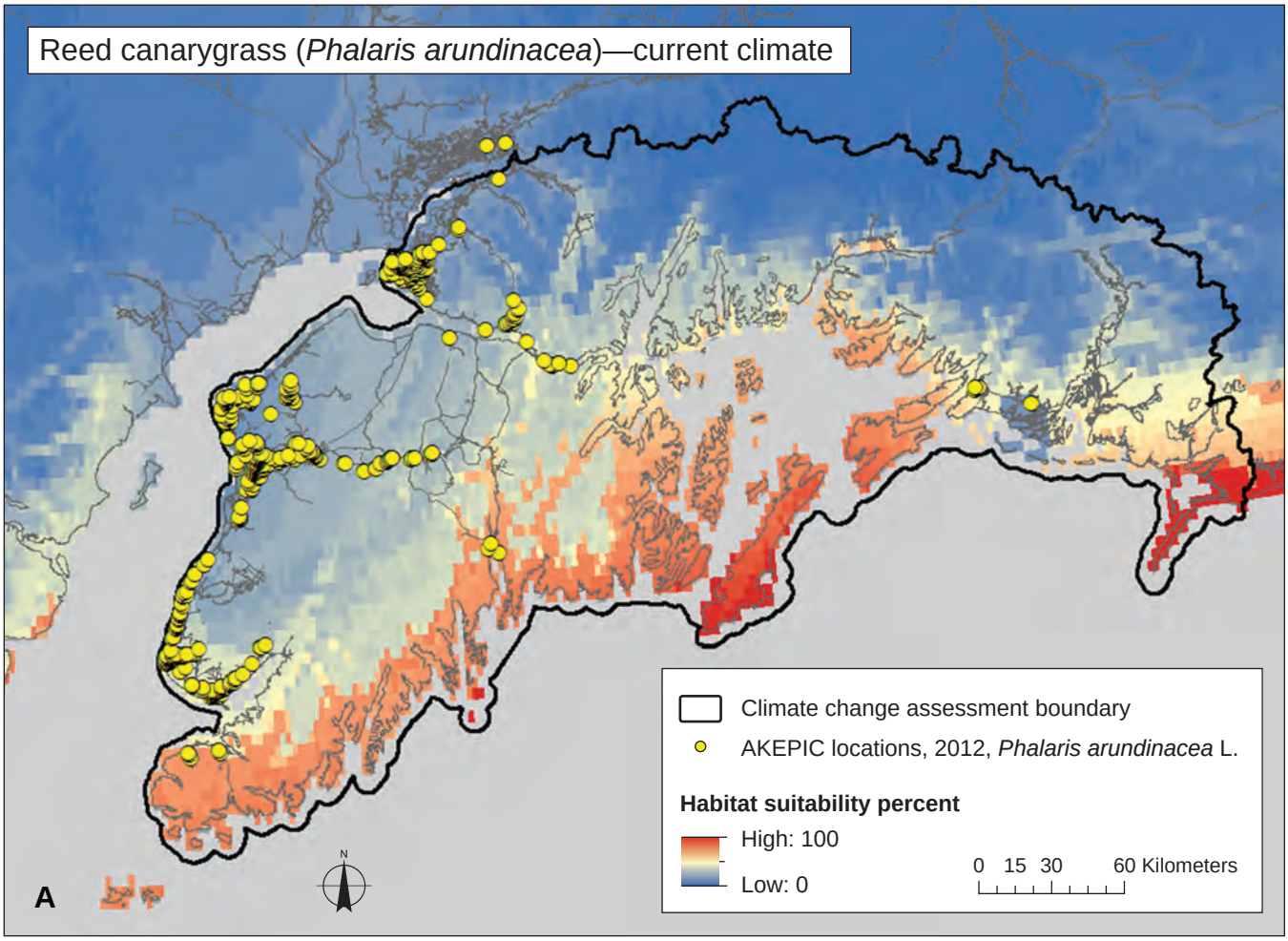


Figure 6-23—(A) Current and (B) future predicted range for reed canarygrass.

coastal Prince William Sound. By 2080, highly suitable habitat for creeping thistle is projected to move upward in elevation and become more continental. The waterweeds group of species displayed a very similar pattern to that of creeping thistle, with high current suitability along the western Kenai lowlands and Anchorage Bowl. Known locations closely matched current modeled suitable habitat. Additionally, a weak arc of mixed high and low suitability extended through the Kenai Mountains and into the Chugach Mountains to the eastern margin of Prince William Sound. By 2080, suitability was projected to decrease in the Kenai lowlands, Anchorage Bowl, and Kenai to Chugach Mountains, with the arc of mixed suitability shifting to the northern Chugach Mountains.

The model for current suitable habitat of sweetclover (*M. officinalis*) displays a moderate correspondence between known invasions and areas of high suitability. A number of invasions along the road system on the Kenai Peninsula are in areas modeled to be of low habitat suitability. This likely reflects the discontinuity

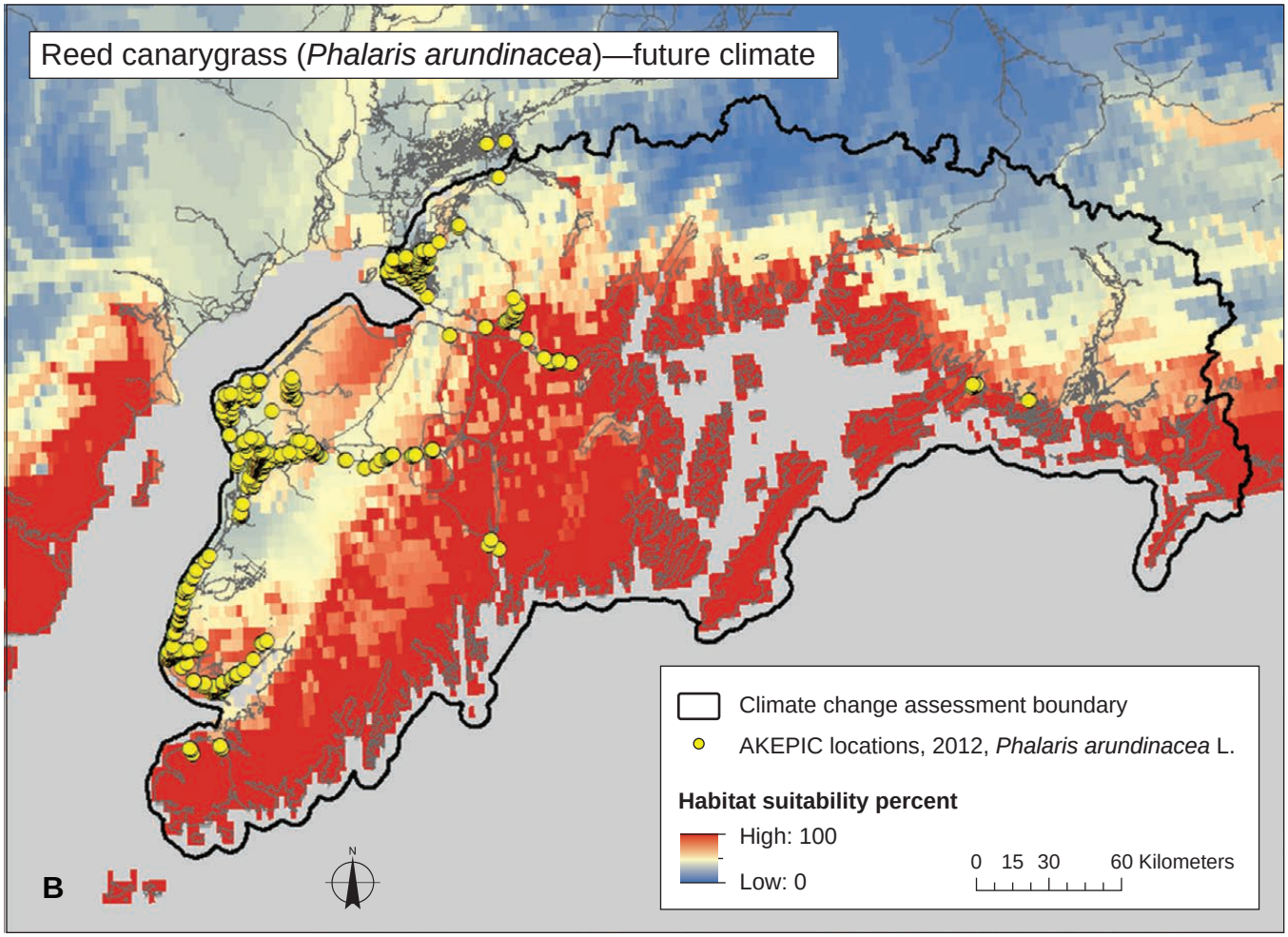


Figure 6-23—Continued.

among spatial scales, where sweetclover is established in warmer (lower elevation) microclimates that are not reflected in the coarser climate data used in the model (see Lenoir et al. 2013). Overall, areas of high current suitability are found in the Anchorage Bowl and scattered eastward through the Chugach Mountains. Isolated areas of high suitability were projected in the Kenai lowlands. The whole region is expected to increase in suitability for this species by 2080, particularly at lower elevations.

Model performance for reed canarygrass was quite poor (AUC = 0.62) and efforts to model its habitat suitability elsewhere in Alaska have been largely unsuccessful (Jarnevich et al. 2014). The lack of model performance is likely due to either lack of inclusion of climate or environmental factors that in fact determine its distribution, or that this species is a generalist that is able to grow in a very wide range of conditions. This plant is the product of a long history of plant breeding, including the crossing of North American and Eurasian cultivars (Jakubowski et al. 2013), and high ecological amplitude is therefore probable. Thus, the entire assessment area with the exception of high elevations is likely vulnerable to establishment of this grass. Particular habitats that are moist or wet and open are of greatest risk.

In addition to *Phalaris arundinacea*, a number of other taxa such as *Prunus padus*, *Linaria vulgaris*, *Hieracium* spp., *Galeopsis* spp., and *Vicia cracca* had modeled distributions with very little variation in suitability, despite the large temperature and precipitation gradients present in the region. As with many invasive species, these plants are capable of persisting in a broad range of habitats, and climate-envelope modeling at the regional scale may not offer considerable insights. Anthropogenic factors and finer-scale habitat variables are likely to be much more important in determining areas of high and low vulnerability to invasion (see Jarnevitch et al. 2014)

Currently, the highest diversity and abundance of invasive species are associated with the urban centers and travel corridors.

Currently, the highest diversity and abundance of invasive species are associated with the urban centers and travel corridors (table 6-6). Characteristic invaders of urban settings include creeping thistle, hempnettles, hawkweeds, oxeye daisy, waterweeds, butter-n-eggs, purple loosestrife, European bird cherry, common tansy, scentless false mayweed, and bird vetch (see table 6-6 for scientific names). A subset of urban species is found along road and trail corridors that act both as dispersal routes and low-competition habitats that are highly suitable for non-native plant establishment, while other non-natives frequent streamsides and appear to travel readily along waterways. *Elodea* may be transported from high-use urban lakes to more isolated lakes, such as to Alexander Lake in the Susitna Valley from an invasion in Sand Lake in Anchorage, and to waterways by floatplane or other vectors. Last, a small cohort of species has moved further from areas used heavily

by humans but likely originated from the larger established populations in urban centers and road corridors.

Certainly the majority of non-native plant populations are associated with and likely facilitated by disturbance, both anthropological and natural, if there is seed source. However, it is never easy to disentangle how much is the effect of propagule pressure, reduced competition, and germination/establishment. Future work in modeling the spread of invasive species should include examination of opportunities for invasion of non-native species following disturbance, especially facilitated by climate change. The importance of dispersal limitation may be difficult to detect for most of the species treated here that are habitat generalists, where niche barriers are fuzzy. Dispersal barriers and corridors are not readily identifiable but are likely more important in determining regional patterns of invasion (see Elith et al. 2006, Evangelista et al. 2008). Dispersal limitation may be made clearer by including additional parameters in future models that represent potential barriers such as glaciers, elevation, rivers, and human infrastructure.

Uncertainty, Economics, and Invasive-Species Management

> It is doubtful whether universal species eradication regardless of cost is even possible, or if possible, whether it holds a moral trump card over all other priorities such as our children's health and education.
>
> —*Jason F. Shogren*

There is evidence that new species are becoming established in the assessment area (see "Current Status of Non-Native Species" on page 186). Experience demonstrates that the vast majority of new species change the natural and economic system in trivial ways. A few introduced or non-native species change systems dramatically and therefore alter the ecosystem and have measurable economic consequences. These latter species are considered invasive because they have severe ecological, economic, or health consequences. On the other hand, some of these invaders can result in positive changes to primary productivity and other ecosystem measures besides their negative impacts. Mainly driven by the negative consequences, natural resource managers have developed management infrastructure focused on detection, control, and, in some cases, eradication of non-native species, but much work remains to be done to assess uncertainty related to many aspects of risk management. Current invasive species practices in Alaska are most closely described as risk assessment rather than risk management owing to the lack of explicit treatment of uncertainty and economic consequences.

Anthropogenic factors will be an important driver of ecosystem change related with non-native species causing ecological and economic change in the region. The odds of rare-species survival and invasive-species spread and associated damages depend on biological factors and climate just as much as on economic factors such as relative prices, wealth, and the extent and diversity of landownership. Yet optimal management response in part is influenced by the ability to reliably predict outcomes, both biophysical and social. As a consequence, resource managers face challenging decisions inevaluating the potential benefits of current action (or inaction) in the face of much uncertainty.

Successful invasive-species management demands an acknowledgment and willingness to work with "uncertainty." For example, sources of uncertainty in management relate to our inability to completely understand consequences and benefits of invasive species within native ecosystems, measurement error of biophysical and economic impacts, and stochasticity in environmental conditions and processes. The social sciences are inextricably linked to the invasive-species problem, providing valuable insights on optimal management under uncertainty (McNeely 2001, Perrings et al. 2002). Bioeconomics in particular can help managers improve their understanding of human drivers shaping future economic behavior through targeted incentives, optimizing investments in management actions, or estimating economic damages to assess benefits and costs to stakeholders. In addition, affected parties often have differing views on both facts and values related to management actions, obliging decisionmakers to account for a complex and challenging array of social and biophysical factors.

Integrating social and human dimensions in invasive species management—This section provides a brief overview of recent research into the integration of ecological and socioeconomic dimensions addressing invasive-species management challenges. This part also presents evidence from past invasive-species investments in Alaska relevant to the list of invasive plants examined in this report. The section concludes with a case study assessing the bioeconomics of managing *Elodea* spp., an aquatic invasive weed occurring in Cordova and the Copper River Delta, among other locations in Alaska.

Currently, statewide invasive-species management relies on invasiveness rankings; risk assessments conducted by expert groups to evaluate potential ecological impact; biological characteristics; dispersal ability; ecological amplitude; distribution; and feasibility of control (Carlson et al. 2008). The framework helps managers assess the relative threat of different non-native plants to Alaska. This ecologically

focused evaluation begins from the philosophical foundation that the consequences of invasive species are always negative. Because risk of undesirable invasive species is as much a question of economics as it is about ecology, there is a need to integrate biology with economics to better inform management aimed at risk reduction.[14] Shogren (2000) cautioned that ignoring the human dimension, particularly people's differing preferences and values, can lead to excessive expenditures on invasive-species management. He further emphasizes that risk assessment can be more effective when human dimensions are integrated, resulting in active risk management rather than passive risk assessment.

Because risk of undesirable invasive species is as much a question of economics as it is about ecology, there is a need to integrate biology with economics.

A step toward such integration is the explicit treatment and analysis of uncertainty, an important aspect of decisionmaking often overlooked within ad hoc decisionmaking processes that can lead to delay and larger damages in the long run (Leung and Steele 2013, Melillo et al. 2014, Simpson 2008). For example, agencies and lawmakers alike have the tendency to delay policy responses while gathering information on potential damages. In most situations, a "wait-and-see approach" is less than optimal, except in situations of low uncertainty. This stems largely from the potential for rapid expansion in the geographic distribution of a recent invader and therefore rapid increases in control or eradication efforts if decisions are made to take action. The following defines the main sources of uncertainty affecting a timely policy response to invasive species, including: (a) type and rate of spread, (b) policy irreversibility, (c) efficacy (treatment success), (d) economic damages, and (e) spatial considerations as outlined by Sims and Finnoff (2013) and Epanchin-Niell and Wilen (2012).[15]

When a "wait-and-see approach" is optimal—
A wait-and-see approach may be optimal if a recently detected invasive species is expected to spread slowly, with little uncertainty about the reversibility of implemented management policy. The length of the optimal delay is determined by a combination of the magnitude of uncertainty in spread rate and by policy irreversibility. Contrary to intuition, economic uncertainty about damages matters less. Also, a moderate rate of spread, with moderate uncertainty about spread, may justify a wait-and-see approach in a completely irreversible policy setting. Complete irreversibility arises when investments in biocontrol or irreversible infrastructure

[14] Risk reduction can occur through mitigation (reducing or changing the distribution of species; reducing the probability of invasion to occur) or through adaptation—the adjustment of human behavior to reduce the consequences of invasions.

[15] Currently applied invasiveness ranking could benefit from inclusion of some of the variables outlined.

are made without the option to recoup parts of the cost when policy fails in the long term (Sims and Finnoff 2013).[16]

However, species that spread quickly with large amounts of uncertainty are simply spreading too quickly and unpredictably to allow anything but an immediate response.[17] Overall, managers often have a variety of less aggressive responses available to complement those with irreversible sunk costs. Pursuing these continuous control actions may provide information on species density and spread that alleviates some of the uncertainty associated with more long-term investments. Here, a "go slow" approach may be preferred, in which less aggressive actions precede long-term commitments (Sims and Finnoff 2013). Interestingly, the decision to treat is less sensitive to uncertainty surrounding the efficacy of treatment, thus has less influence on decision outcomes (Saphores and Shogren 2005).

Estimating economic damages—
Even though significant work has been done on valuing economic damages of invasive plants in the United States, specific studies cannot readily be transferred to cases in Alaska. This issue can result in additional economic uncertainty. Often the economic effects play out differently in Alaska than in places where the economic damages were initially measured. The reasons for the discrepancy are differing economic structures and human population densities. For example, many invasive species cause measurable economic loss to agriculture by reducing forage yields to cattle ranchers (Hirsch and Leitch 1996). Because Alaska's agricultural sector is very small, and most agricultural products are imported, agricultural invasives have fairly low economic effects in Alaska on a per capita basis. In the case of spotted knapweed, for example, there are limited grazing effects, and most impacts are associated with changes to intangible nonmarket values such as wildlife forage, aesthetics, and soil and water conservation. Thus the application of many of the economic damages estimated elsewhere are difficult to apply to management situations in Alaska.

The ability to quantify economic externalities of invasive species is greatest when the invader has a direct effect on a harvestable resource, because the link between ecology and economics can easily be established, and damages can be estimated based largely on market data (Barbier 2007, Hiebert 1997). On the other

[16] On the contrary, quarantine programs, trade restrictions, and continuous control actions all can be reversed, and parts of the sunk costs can be recouped. Flexibility to cancel existing policies is also important when spread rates decline.

[17] Note that large amounts of uncertainty in the spread rate means that the invader shows a very wide range of potential spread rates. Consequently, the distribution associated with the rate of spread would be a very wide one, with a considerable variance around the mean.

hand, economic analysis is particularly challenging when there are little or no data on human preferences and use of an affected resource, or when the affected resource is not traded in the marketplace. A similar situation arises when little is known about the ecological effects of the invader, even though the affected resource may be marketed (e.g., the effects of waterweed on salmon). Despite the challenge of estimating economic damages, the past decade has seen an emergence of economic damage assessments. Transferred carefully to local cases, these examples can provide valuable insights for prioritization and decisionmaking (Frid et al. 2013).

Spatial considerations—
A look at spatial considerations shows that the size of an initial invasion matters for deciding on the optimal time to treat. Generally, it is optimal to initiate control and even eradication when initial invasions are small in size. If an invasion has already gained a significant foothold before detection, the expected damages must be large to justify eradication (Olson and Roy 2002). Rejmánek and Pitcairn (2002) present evidence that successful eradication drops off sharply with increasing initial invasion size, requiring a steep increase in management effort (fig. 6-24).

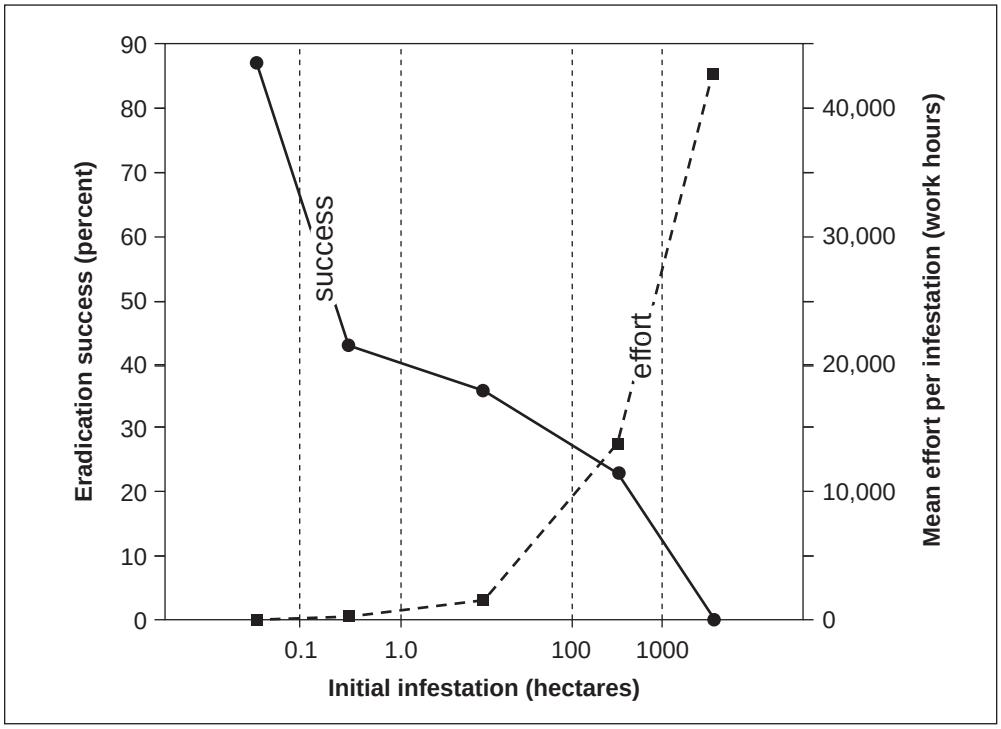


Figure 6-24—Relationship between initial infestation size, eradication success, and effort for 53 independent infestations of non-native plants in California. Source: Rejmánek and Pitcairn (2002).

For Alaska, expenses associated with management of invasions in the past suggest that management tends to be close to optimal when judged by total invasion size. Figure 6-25 presents statewide management investments from 2007–2011 for the invasive species listed in this report. Actions mainly targeted small invasions of highly invasive plants with little or nothing being spent on invasions that had already reached more than 100 ha in size (Schwörer et al. 2014). Because the current risk assessment framework does not provide information on the level of uncertainty regarding spread or potential ecological limits of these species, little can be said about optimality in policy, given other important considerations outlined in this section.

Last, recent research suggests that invasions that are of the same size can have very different optimal management policies if they differ in shape (patchy versus compact) and location (near landscape boundaries or in the center) (Epanchin-Niell and Wilen 2012).[18] Physical landscapes are not homogeneous, and the patterns and processes of invasion differ across space, particularly where glaciers, mountain ranges, or river canyons provide natural barriers to invasion processes. Where to initiate action and at what severity become difficult decisions in the spatial context, with optimal management paths over time that may not be obvious at first. Economic principles suggest that early and intensive control near the initial invasion site is better than later control elsewhere (Wilen 2007). Landscape-explicit research of invasion processes and associated long-term optimal management provide novel insights into how the topology of an invasion and the landscape itself determine the optimal policy path through time. Particularly in the context of highly valued patches (where rare species are present) and their relative location to natural boundaries, invasion location and shape and the shape of the landscape become important decision variables for optimal management.

For example, invasions in more compact landscapes warrant more control because spread is less constrained, resulting in higher damages compared to landscapes in which there are bottlenecks that constrict the spread. These features can be used to reduce long-term containment costs, highlighting the role of landscape geometry in invasion control. The occurrence of constrictions was also found to be the only feature supporting optimal delays in management action, as it physically delays spread. Concerning location, the initial invasion location being centered within a landscape generally results in higher long-term damages compared to invasions that start on a landscape edge, where control costs are lower because natural boundaries help contain the invasion. Two interesting results by Epanchin-Niell

[18] Do not account for stochastic rare long-distance dispersal events.

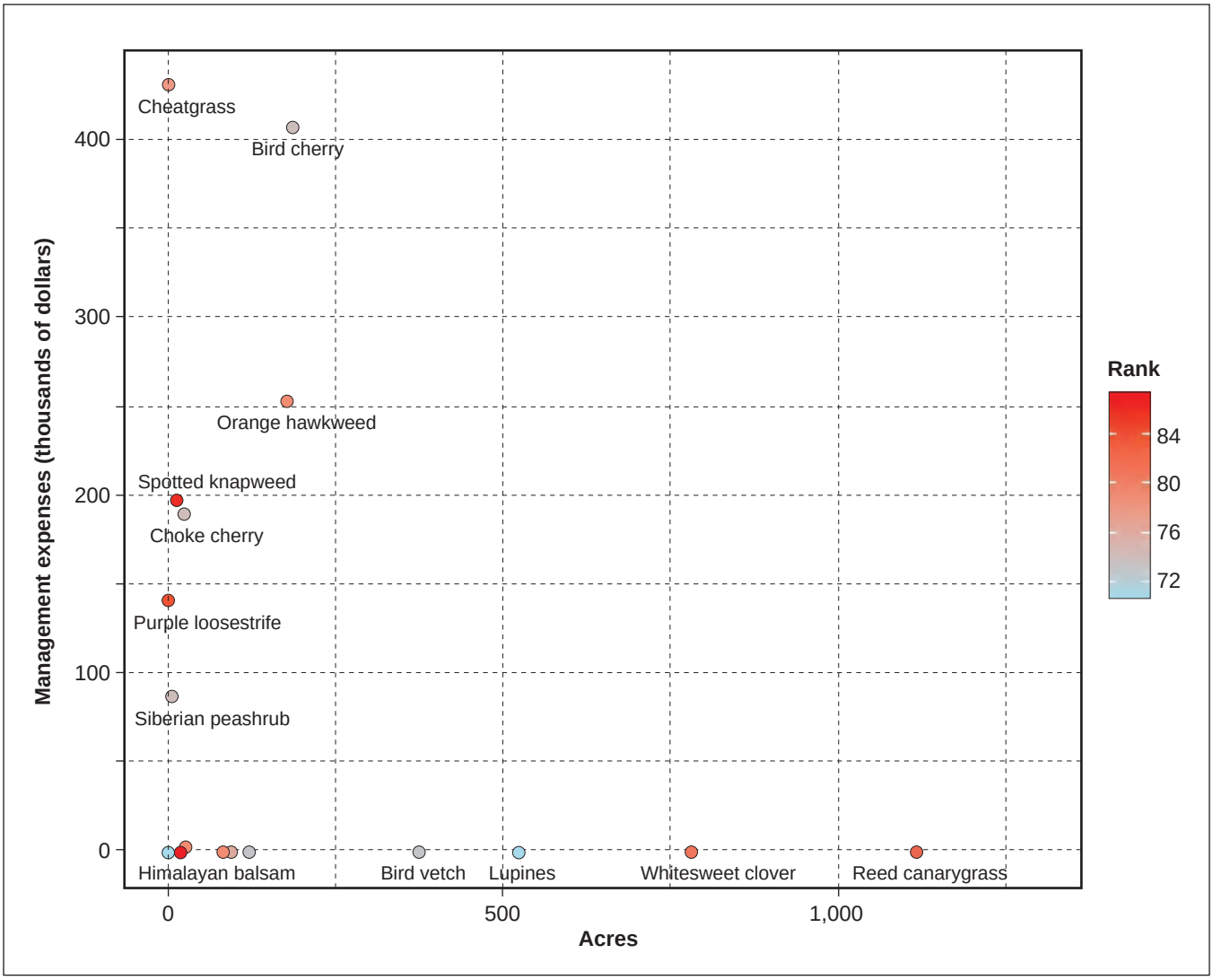


Figure 6-25—Total management expense by species for 2007–2011 by infestation size and Alaska non-native plant invasiveness ranking. Himalayan balsam represents a tight cluster of species that includes Bohemian knotweed, creeping thistle, pepper grass, *Rugosa rosa*, and field sowthistle. Figure developed using data from AKEPIC (2014) and Schwörer et al. (2014).

and Wilen (2012) are of particular importance for optimally managing multi-patch invasions:

1. Greater management expenses may be optimal for smaller satellite invasions because their eradication and containment costs are lower.[19]

2 Optimal management for each patch depends on the entire invasion and landscape. Patches cannot be considered independently, in which case a blanket

[19] This result is supported by Olson and Roy (2002), who suggested that, contrary to intuition, it may be optimal to eradicate small patches in cases where marginal cost exceeds marginal benefits for eradication.

approach to management is unlikely to be optimal. Many invasions are too widespread to justify eradication. Under some circumstances (e.g., existence of high-value/rare species patches), it is optimal to eradicate some invasive patches while leaving others to spread further. Where there is a large potential for spread, it can be optimal to slow or contain widespread invasions when eradication is not justified.

***Elodea* invasion in Fairbanks: a case study**—
Until recently, Alaska has been considered free of invasive submerged aquatic plants. The discovery of *Elodea* spp. in Fairbanks in 2010 drew attention to an established population in Eyak Lake, Cordova, Alaska, and led to the discovery of *Elodea* in 15 additional water bodies across Alaska. Eleven infested waterbodies are habitat to at least one species of Pacific salmon. Resource managers are uncertain about *Elodea*'s effect on the state's wild salmon resources. *Elodea* is native to other locations in North America at much lower latitudes. None of the literature describes the effects of *Elodea* on Pacific salmon.

None of the literature describes the effects of *Elodea* on Pacific salmon.

The invasion of Chena Slough can serve as an interesting case study owing to the availability of historical information on vegetation and the fish population pre- and post-invasion, as well as existing economic data on sport fisheries. The slough used to be an important breeding and rearing habitat for arctic grayling that produced 30 to 50 percent of arctic grayling found in the Chena River. Historically, the slough has been used recreationally by sport anglers and canoeists. The grayling sport fishery of the Chena River in 1996 was estimated to have a net annual economic value of $1.6 million (in 2011 dollars) (Duffield et al. 2001).

Being located close to Alaska's second largest city, Fairbanks, Chena Slough has experienced extensive flow modifications. A flood-prevention dike built after a large flood in 1967 resulted in flow reduction and long-term changes in the flow regime conducive to the establishment of aquatic plants. Biologists believe that, around the year 2000, the highly invasive aquatic plant *Elodea* spp. was introduced to the Slough. *Elodea* is now the most dominant vegetation found in the Slough, and has altered 30 percent of previous grayling spawning and rearing habitat into dense mats of vegetation.[20] Over the past decade, catch data indicates that grayling have significantly declined compared to a decade earlier. Based on anecdotal information, the Slough was also a popular canoeing destination. Because of the dense vegetation, canoeing is no longer enjoyable and water quality has declined.

[20] **Larsen, A.S.; Lisuzzo, N.J. [N.d.].** Changes in Arctic grayling spawning and rearing habitat in a subarctic Alaskan stream following a decade of flow modifications. Unpublished report. On file with: A.S. Larsen, National Park Service, 4175 Geist Road, Fairbanks, AK 99709. aslarsen@nps.gov.

This case study uses a bioeconomic simulation model that explicitly accounts for inventory and treatment expenditures as well as the amount of avoided damages (benefits) related to the management of invasive aquatic vegetation over a 100-year period. A benefit-cost framework was used to find the most cost effective of four potential management actions including: (a) do nothing, (b) suction dredging, (c) herbicide application with a small budget, and (d) herbicide application with a sufficiently large budget.[21] Damages were valued in terms of the loss in net economic value to production of grayling for the sport fishery in Chena River ($1.01/m^2), the estimated loss in property values ($0.46/m^2) (Zhang and Boyle 2010), and the loss in net economic value to recreational canoeists ($0.13/m^2) (Loomis 2005).

Among the three management options, the application of herbicides with a budget large enough to eradicate the vegetation results in the best management outcome, reducing much of the variation in long-term cost (fig. 6-26A). In this case, benefits of damage reduction outweigh the costs in all 1,000 cases simulated by the model. In the simulation with the least favorable outcome, benefits still outweighed costs by 1.4. In the highest case, benefits outweigh costs by more than 12 times, and on average the mean benefit-cost ratio for the herbicide option equaled 3.7. The analysis also shows that management actions without an adequate budget will not allow managers to get ahead of the invasion, resulting in higher and more uncertain long-term costs as well as lower and more uncertain long-term avoided damages (fig. 6-26B). This result clearly demonstrates that, in the early invasion stage, full eradication attempts can pay off in securing long-term avoided damages (mean annual avoided damages $750,000 after 100 years), whereas if budgets are not sufficient and eradication not successful, long-term control will be necessary, resulting in higher long-term costs (mean annual avoided damages are $350,000 after 100 years).

Potential Scenarios for Insect Populations Under a Warming Climate

Within the forests of Alaska, insects may be among the first responders to varying climatic conditions. Small body size and ectothermy make insects more exposed to changes in thermal conditions, which result in changes in physiology, development rates, and ultimately, population processes like survival, reproduction, and dispersal. The evidence is strong but mostly circumstantial for climate-driven changes to occur in the behavior and distribution of a handful of insects in Alaska that interact with important trees and shrubs. The following scenarios provide a way to consider

[21] A discount rate of 4 percent was used. For more information about the analysis, contact the author.

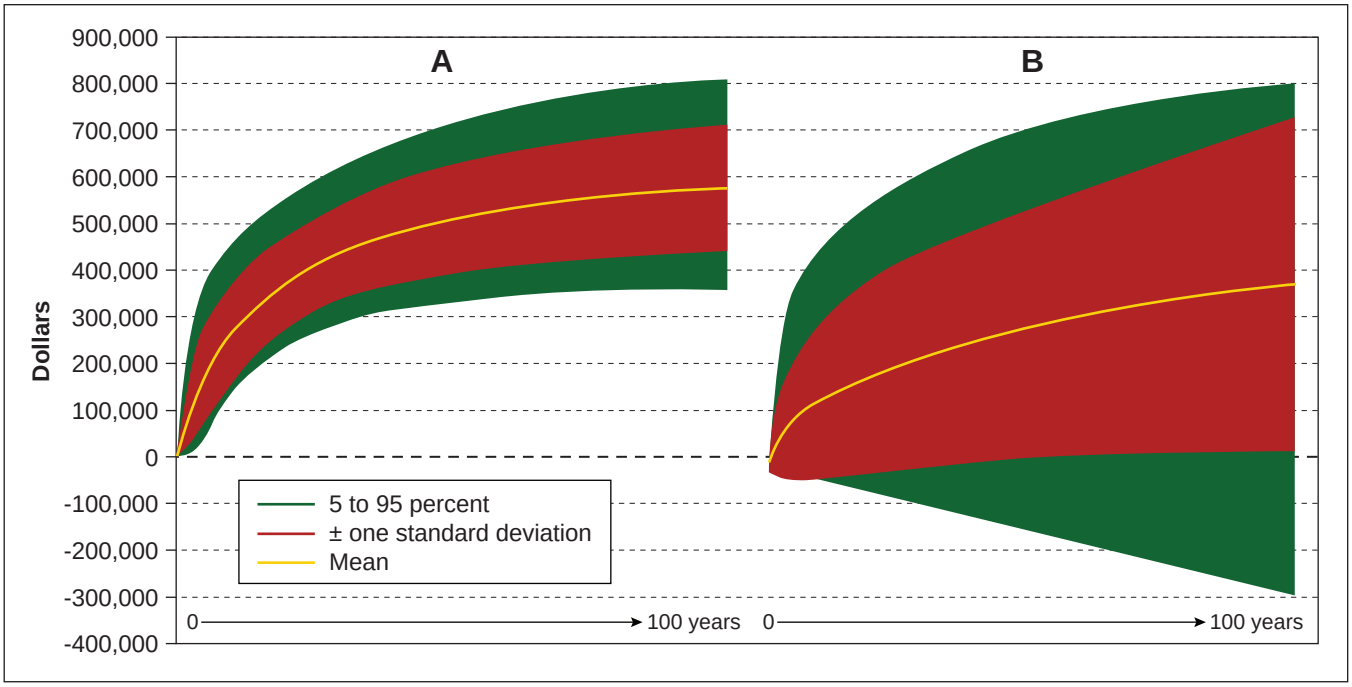


Figure 6-26—Simulation results showing the mean annual avoided damages (benefits) with 90-percent confidence interval over a 100-year period related to eradication attempt (A) and control approach (B) herbicide use in Chena Slough, Fairbanks, Alaska.

the potential influence of insect pests in Alaska's forests in the future, particularly on the Chugach National Forest as climate continues to change.

The incidence and severity of some insect pests will increase. Populations of many insects are regulated by temperature, especially in northern climates where episodes of cold temperature beyond species survival limits prevent their populations from expanding, or cause ongoing outbreaks to collapse (Bentz et al. 2008). If winter temperatures in south-central Alaska increase sufficiently, the incidence of insects whose populations are controlled by low temperatures will likely increase, provided there are sufficient host resources (Raffa et al. 2008). Warmer winters will result in an earlier advent of spring and associated insect mating activity, followed by faster larval development. As a consequence, the entire life cycle of some insect populations may shorten, leading to more generations per growing season, especially if the growing season is extended. Not only will insect populations increase, they will also have a longer period to damage trees (Berg et al. 2006, Werner and Holsten 1985, Werner 2007).

Both the frequency and extent of defoliator outbreaks may increase. Hardwood tree species in Alaska are associated with a diverse community of leaf-feeding insects. Most of these leaf feeders have distinctly cyclic population densities; relatively dense populations reoccur periodically. The frequency of high-density cycles may be correlated with seasonal temperatures. Some evidence suggests

that a wider amplitude and more frequent swings of population density will make predictions less reliable.

In addition to the direct influence of a warming climate on insect life history, climate-change-related stress on host trees may also contribute to insect-related damage to tree populations. Some tree species will experience less favorable growing conditions, especially those in environmental ecotones. The resulting reduction in vigor will increase susceptibility to attack by insects.

Forest insect pest ranges will expand northward, including new invasives. Species richness is inversely correlated with latitude and elevation (Speight 2003). During the past decade, many insect species have shown poleward shifts in range (Andrew and Hughes 2005). The distribution of insects with high population-growth potential, facultative voltinism, and absence of diapause will expand, whereas those with slow development or long life cycles are less likely to do so. In addition, nonspecialist herbivorous insects are likely to shift hosts, providing an increased potential to shift their range northward. Consequently, the total number of new species in the Arctic, including Alaska, is expected to increase as a result of range expansions under a warmer climate. Some of these species will be invasive insects that will create new forest health issues.

Pest interactions and multiple pest complexes will increase. The incidence of multiple pest complexes, in which insects interact with diseases and forest declines, will probably increase (Ayres and Lombardero 2000, Thomas et al. 2002, Valladares 2008). As a result, pathogens that currently cause little damage in Alaska forests may contribute to increased tree mortality through these new interspecies interactions.

Influence of insect pests on vegetation dynamics—
Several species of defoliators, bud and shoot insects, sap-sucking insects and mites, wood borers, seed and cone insects, and bark beetles that currently occur in the analysis area will undoubtedly be affected by future changes in climate. Few of these, however, would be able to shift the composition or abundance of existing forest vegetation. One exception is the spruce beetle (*Dendroctonus rufipennis*). We predict that as long as white spruce or Lutz spruce are major components of the forest, spruce beetle will continue to be a major catalyst for vegetation change, primarily because it is an eruptive pest that kills its host. The distribution and severity of future spruce beetle activity and how it will respond to a changing climate will depend on insect abundance and distribution, the abundance and geographic locations of vulnerable host trees, and the past disturbance history of forested areas at risk.

We predict that as long as white spruce or Lutz spruce are major components of the forest, spruce beetle will continue to be a major catalyst for vegetation change.

The effects of the 1990s spruce beetle outbreak on landscape-scale patterns of regeneration, and subsequent recovery processes have been measured and described by a range of scientists (Boggs et al. 2008; Boucher and Mead 2006; Holsten et al. 1995; Schulz 1995, 2000; van Hees 1992; Werner 1996). These studies offer a glimpse of what the vegetation landscape in the analysis area might look like in the future. Many factors can affect patterns of injury and recovery. For instance, human development in the analysis area may cause the disturbance return interval to expand (Berg et al. 2006). Under a changing environment, white spruce trees would probably become increasingly mismatched with their local environment, and increased stress will enhance their vulnerability to bark beetle attack. Under these conditions, endemic populations of spruce beetles would be sustained and would continue to kill trees that survived earlier beetle outbreaks, opening the canopy and enabling understory tree species to expand. Boucher and Mead (2006) reported that the hemlock understory was stimulated and its successional partitioning enhanced by the beetle infestation. In this scenario, spruce beetle would act as a catalyst enhancing successional partitioning and speeding up forest change. Over the analysis period, we could anticipate an increase in mountain hemlock across landscapes in the Kenai Mountains.

If Sitka spruce eventually displaces white spruce in the western Kenai, a different set of insect pests may become important. One such insect is spruce aphid, a largely coastal pest that may expand as its host expands and will probably become more common if our changing climate results in milder winters. The spruce aphid can by itself cause mortality, but additionally infested trees are stressed in ways that can make them more susceptible to bark beetles, which are more commonly the proximate cause of death. The mild winter-spruce aphid-spruce beetle interaction is a relatively simple example of multiple pest complexes that will likely become more prominent as climatic conditions continue to change.

Vulnerability to Fire in the Kenai Peninsula Wildland-Urban Interface

On May 19, 2014, a wildfire of unknown human origin started in a remote area of the Kenai Peninsula. By the time the Funny River Fire was brought under control more than 2 weeks later, it had torched nearly 81 000 ha of forest land. Because most of the burn lies within an undeveloped roadless area of the Kenai National Wildlife Refuge between Tustumena Lake and the Kenai River, damage to structures was modest. Only four cabins plus an outbuilding burned this time (NWCG 2014). Residences in subdivisions along Funny River Road were spared, although risk of future damage remained.

As it happened, the Funny River Fire caused little damage but did illustrate two important facts. The first is that fire plays a significant role in the ecology of the Kenai Peninsula. Without fire, young hardwood stands providing important forage for moose would not exist on the Kenai. Soil charcoal layers from the past 2,000 years show that the western Kenai Peninsula has experienced a mean fire interval of 400 to 600 years (Berg and Anderson 2006). Fire frequency appears to vary greatly within the region, however. Shorter fire returns of 80 to 130 years have prevailed in black spruce stands, whereas intervals lasted as long as 1,000 years in upland Lutz spruce forests (Anderson et al. 2006, DeVolder 1999).

A massive suppression response to the Funny River Fire was at times ineffective in altering its spread and combustion intensity.

A massive suppression response to the Funny River Fire, using as many as 760 firefighters, was at times ineffective in altering its spread and combustion intensity, just as it was during the previous Caribou Hills Fire in 2007, which burned more than 22 000 ha and 88 cabins or residences on the Kenai Peninsula (Jackinsky 2007, NWCG 2014, Staab 2014,Wahrenstock 2009). The fires themselves cannot be blamed on the massive spruce beetle infestation of the 1990s and early 2000s, which killed large percentages of mature spruce trees throughout the region. However, stands of beetle-killed spruce may have contributed to the rapid spread and intensity of the fires, and they undoubtedly complicated suppression efforts. The results of years of bark beetle infestation prompted fire command agencies to take a step back and essentially let the fire burn for safety reasons, according to Pete Buist of the Alaska Interagency Coordination Center (Holthaus 2014). “You can’t put people into an area where a bunch of trees have died and fallen,” Buist observed.

Berg et al. (2006) inferred from tree-ring patterns that bark beetle outbreaks have thinned spruce stands at a mean return interval of 52 years over the past 250 years; that is, much more frequently than wildfires. Despite the apparent effect on fire dynamics when fires do occur, forests in the Kenai Peninsula may have experienced 10 or more beetle outbreaks for every cycle of fire (Berg and Anderson 2006).

The second fact illustrated by the Funny River Fire is that people have largely ignored the role of fire on the Kenai Peninsula in their settlement patterns and property development choices. Public officials express dismay at the ineffectiveness of fire-suppression activities because people have placed themselves and their property at risk. Early in the 20th century, regeneration of hardwood species after several large fires created ideal habitat for moose, leading to the establishment in 1941 of the Kenai National Moose Range (renamed Kenai National Wildlife Refuge in 1980). As the population and local economy grew after the discovery of oil on the refuge in 1958, thousands of residences, commercial buildings, and

second homes were built in areas historically susceptible to fire. The pattern of fire activity also changed, with fires started by human activity greatly exceeding fire starts caused by lightning (KPBOEM 2004).

The vulnerability of human lives and property to wildfire is not unique to south-central Alaska, and has emerged as a common feature across North America in the wildland-urban interface (WUI). Looking to the future, two main factors will determine the vulnerability to wildfire in the Kenai Peninsula region. One factor is of course the pattern of development of new structures, particularly those located in more rural areas outside of established community centers (i.e., the WUI), in relation to areas most likely to experience large, destructive wildfires. The other factor is climate change, with associated effects on fire-relevant weather extremes, and potentially on vegetation and fuel production.

This study makes a preliminary assessment of the vulnerability to the combined effects of these two main forces for change. It focuses on defining and estimating property values most at risk to wildfire, and making initial long-term quantitative projections of future risks. The study combines information drawn from the Kenai Peninsula Borough's property appraisal database with information derived from the borough's community wildfire protection plans (KPBOEM 2014) to obtain a spatially explicit baseline estimate of property values at different levels of wildfire risk. It then analyzes historical patterns of property development to make a spatially explicit projection of future development over the next five decades. The development scenario provides the basis for a quantitative estimate of the future vulnerability of structures to wildfire, considering how climate change may affect wildfire risks. The results potentially raise more questions than they answer; the concluding section discusses approaches to improve future evaluations.

The Study Region

The Kenai Peninsula Borough is one of 19 organized regional governments in Alaska, incorporating 41 473 km^2, or about 4.1 million ha in south-central Alaska. Most land is owned by the federal or state governments (fig. 6-27). The Kenai Peninsula includes about 2.4 million ha between Cook Inlet and Prince William Sound. All but the easternmost reaches of the Kenai Peninsula bordering Prince William Sound lie within the Kenai Peninsula Borough. Kenai Peninsula lands outside the borough consist largely of rock and ice, with scattered pockets of coastal rain forest, no history of fire, and hardly any human residents. The study therefore focuses on the 2.2 million ha of the Kenai Peninsula that lie within the Kenai Peninsula Borough. Hereafter in this chapter, the term "Kenai Peninsula" will refer to the portion of the peninsula that lies within the borough.

The federal government dominates ownership of Kenai Peninsula lands, controlling nearly 70 percent of the land area (fig. 6-27). Most federal lands are included within three large conservation units: Chugach National Forest, Kenai National Wildlife Refuge, and Kenai Fjords National Park. The state of Alaska owns another 16 percent of Kenai Peninsula lands, and 9 percent lies in Native ownership (Alaska Native Claims Settlement Act village and regional corporation lands and individual Native Allotments). Only about 4 percent of the Kenai Peninsula consists of private property.

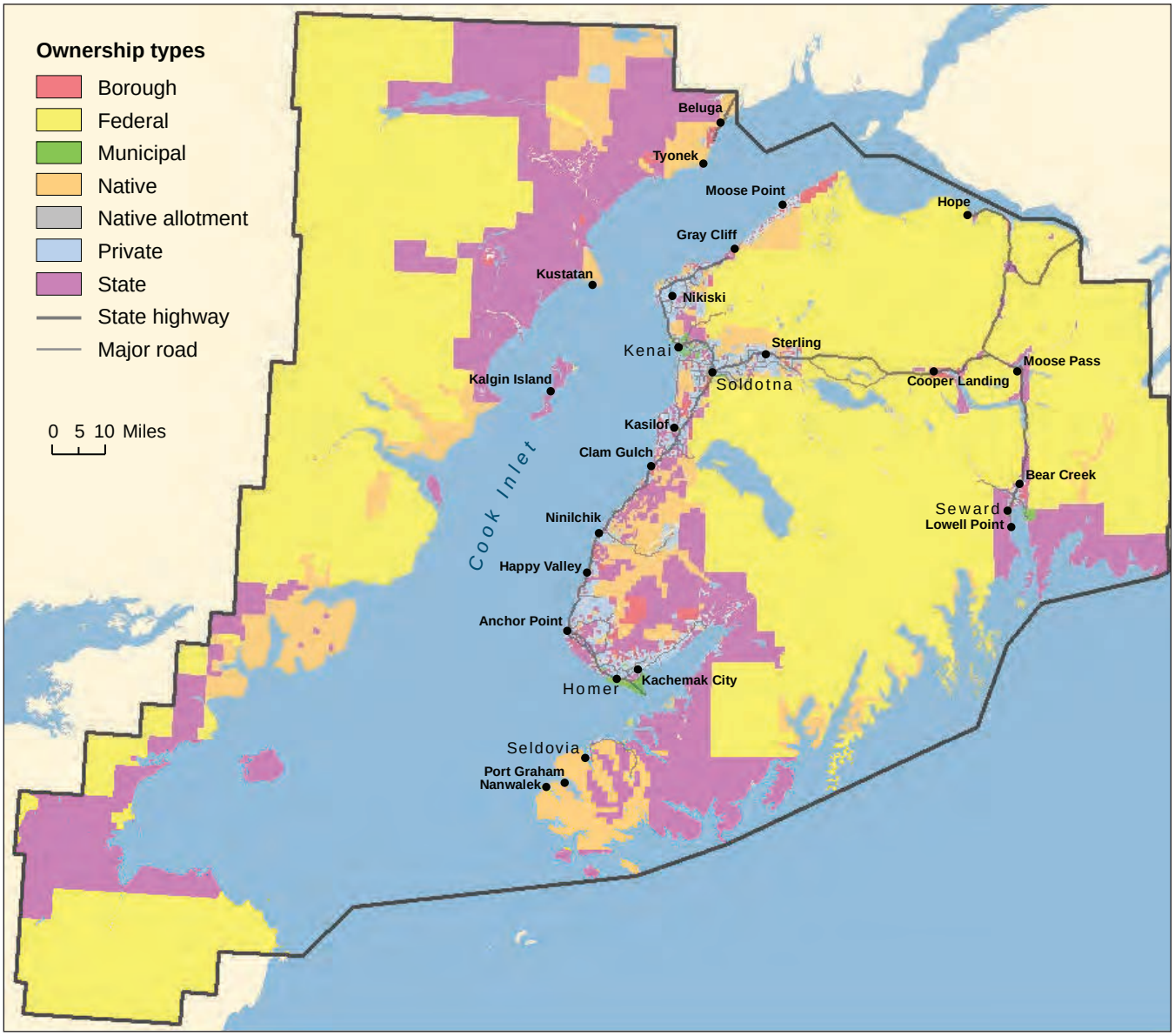


Figure 6-27—Land ownership pattern in the Kenai Peninsula Borough.

The population of the Kenai Peninsula Borough stood at 55,400 people as of the 2010 U.S. Census. Nearly all that population lives within the Kenai Peninsula study area. Considering the small amount of private property, the density of settlement is relatively high, at about 240 km^2 of private property. However, the population density is uneven. Slightly more than one-third of residents live in four towns: Kenai (pop. 7,100), Homer (pop. 5,003), Soldotna (pop. 4,163), and Seward (pop. 2,693). Table 6-9 shows that the total land area within the municipal boundaries of the four towns—about 41 000 ha—comprises less than 2 percent of Kenai Peninsula lands. Private property within town boundaries comprises only 0.3 percent of total lands.

Table 6-9—Kenai Peninsula land cover area within and outside municipal boundaries of the four largest communities (Kenai, Homer, Soldotna, and Seward)

Ownership	Within town boundaries		Outside towns	
	Acres	*Percent*	*Acres*	*Percent*
Federal	16,824	0.5	3,683,243	99.5
State	42,398	4.9	830,839	95.1
Borough	1,710	2.7	60,830	97.3
Municipal	16,924	95.7	759	4.3
Native	2,923	0.6	490,813	99.4
Private	17,002	7.1	222,442	92.9
Total	97,782	1.8	5,288,926	98.2

The remaining two-thirds of the population is spread out along the three highways in the region: the Seward, Sterling, and Hope Highways. In addition to primary residences and commercial and industrial buildings, the peninsula contains many recreational cabins and second homes, also mostly spread out along the road corridors. The greatest vulnerability to wildfire lies in these corridors of sparsely settled recreational lands outside the boundaries of the larger communities.

Current Vulnerability to Wildfire

This study concentrates on vulnerability to wildfire of the built environment on the Kenai Peninsula.

Vulnerability to wildfire could be defined in many different ways. Even if one limits the scope to consequences for people, the study could differ greatly depending on whether the focus is on threats to public safety, potential loss of ecosystem services, or damage to the economy. Given the historical and likely future pattern of wildfires, settlement patterns, and local economies, potential damage to structures stands out as a salient concern. This study, therefore, concentrates on vulnerability to wildfire of the built environment on the Kenai Peninsula.

Approach—
The Kenai Peninsula Borough's recently completed community fire plans provide the starting point for analyzing vulnerability to wildfire (KPBOEM 2014). The 19 regional plans were developed to update the earlier comprehensive 2004 study (KPBOEM 2004). Among other changes, the revised plans expand the spatial extent of the WUI to include all areas near roads, to incorporate areas potentially needing access to emergency services. The vast majority of private property lies within the expanded WUI definition, termed the Community Wildfire Protection Plan (CWPP) zone.

The community fire plans include a vegetation analysis that classifies land cover types by fire hazard. The fire hazard rating combines ignition probability, fuel load (potential intensity), and speed of spread into a single ordinal category. Fire hazard categories of various vegetation types are derived from a detailed classification of species, condition, and size for up to three dominant species, overall biomass density, and type of understory. The study maps 464 separate land cover types into a set of six hazard categories, ranging from 1 (very low) to 6 (extreme). Each land cover type has separate fire hazard ratings derived for spring and summer. The main difference between spring and summer hazards is that herbaceous land cover and understory types were assigned a lower hazard rating after green-up takes place in early summer.

To focus safety planning efforts, the community fire plans used the vegetation-based fire hazard ratings to identify relatively large planning areas where vulnerability was generally higher. Because the vegetation was mapped at a relatively fine scale, one could potentially use the hazard mapping to identify vulnerability to fire at a finer scale, down to the level of individual properties. Such a fine-scale analysis should be approached with caution, however, for a number of reasons. First, vegetation is dynamic, and could change as a result of disturbance such as fire or insect infestation, timber harvest, or natural succession. Second, homeowners may undertake activities to reduce the risk to structures on their property, such as clearing brush and trees around their homes and selecting fireproof roofing materials. Third, vegetation patterns do not in general coincide with property boundaries. Different parts of a parcel could have different vegetation, and even relatively small parcels of an acre or less might contain vegetation types with different fire hazard ratings. Spatial data available are not precise enough to determine where on a parcel structures are or will be located. Finally, a property parcel may be dominated by vegetation with a high fire hazard but surrounded by low-hazard lands, as, for example, an island in a lake. Or the reverse may be true: a low-hazard parcel may be adjacent to or even surrounded by high-hazard lands.

The appropriate spatial analysis should take advantage of the spatial detail available in the data without misleading readers by presenting results at a finer than meaningful scale. The focus of the current analysis lies not on identifying individual properties at highest risk, but rather to quantify the overall value of structures built on properties at high risk within a generalized area. The current study therefore makes use of information at the parcel level to derive an overall vulnerability at a broad spatial extent. Keeping this goal in mind, the study makes a number of simplifying assumptions. While the land cover types map to six different categories for fire hazard, the concern is mainly with the high-hazard lands. All other parcels are assigned to the lower risk category. If vegetation that yields a low fire hazard dominates a parcel, a potential public safety concern may still exist if access to the parcel is through high-hazard vegetation. However, that is an issue for public safety access; our focus is on property values. A structure on an individual parcel with low hazard vegetation that is surrounded by high-hazard vegetation could likely be defended in a wildfire.

Consequently, we define two levels of elevated risk—high and extreme—to quantify vulnerability of structures to wildfire. The structures on a parcel are designated at extreme risk if one-half or more of the parcel contains vegetation cover given an extreme (6) spring hazard rating. The parcel is designated high risk if half or more of the land has either high (5) or extreme (6) spring hazard, but the majority is not in the extreme hazard category. For example, a parcel whose vegetation is one-third high and one-third extreme spring hazard is assigned a high risk, while a parcel whose vegetation is one-sixth high hazard and one-half extreme hazard is assigned an extreme risk. The wildfire risk categories use spring rather than summer fire hazard because spring is more inclusive: land cover types with high and extreme hazards for summer all have at least as high a spring hazard.

At-risk lands—
Given this simplification, the basic measures of vulnerability follow from summarizing the land area, parcels by ownership, and value of structures in the different risk categories. To start, one should note that while most of the land area is in public ownership (fig. 6-28A), most of the individual parcels are in private ownership (fig. 6-28B). The analysis is therefore at a coarse scale for public and Alaska Native lands, but at a fine scale for private lands, which contain most of the structures. For large blocks of contiguous federal land, the Kenai Peninsula Borough property appraisal database—the source of all the property parcel data—defines the parcel as an entire township (9324 hectares).

Keeping in mind the possible coarse scale of the analysis for public lands, the results of tallying up the total land area in the three fire risk categories as defined

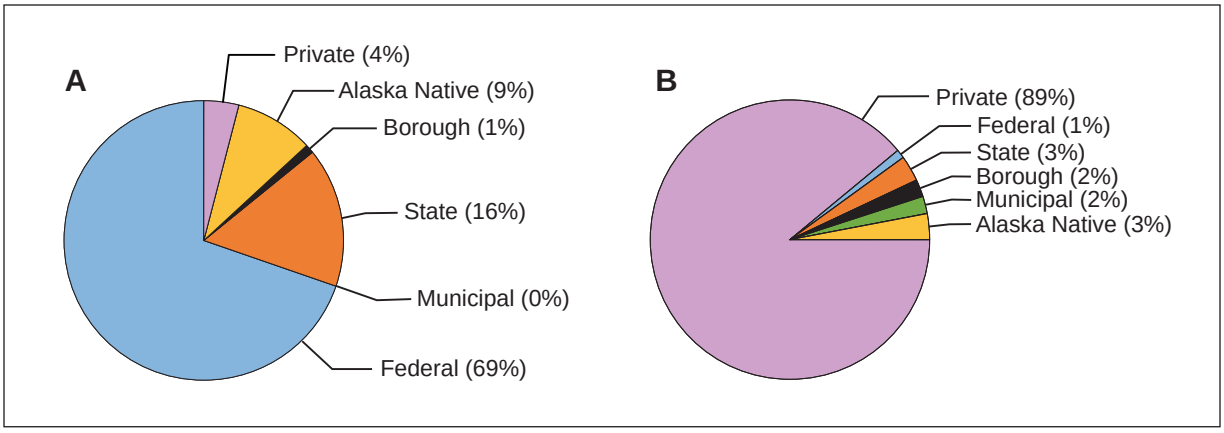


Figure 6-28—Percentage of land ownership in the Kenai Peninsula Borough (A) assessed as distribution of land ownership, and (B) assessed by number of parcels per ownership category.

above shows that nearly three-fourth of Kenai Peninsula lands are in the lower risk category. Fewer than four percent of the lands are in the extreme-risk category, and the remainder—22.6 percent—are in the high-risk category (fig. 6-29A).

However, a much greater share of the higher risk lands are in private ownership. Considering only private lands, the share in the extreme-risk category jumps to 23 percent. Another 39 percent is in the high-risk category, while only 38 percent is at lower risk (fig. 6-29B). Most private parcels in these two elevated risk categories are larger than 0.81 ha, and 86 percent are larger than 0.2 ha. Clearly, the lands most at risk to wildfire are concentrated in private ownership. The primary reason for this result is simple geography. The public lands contain mountains and rain forest as

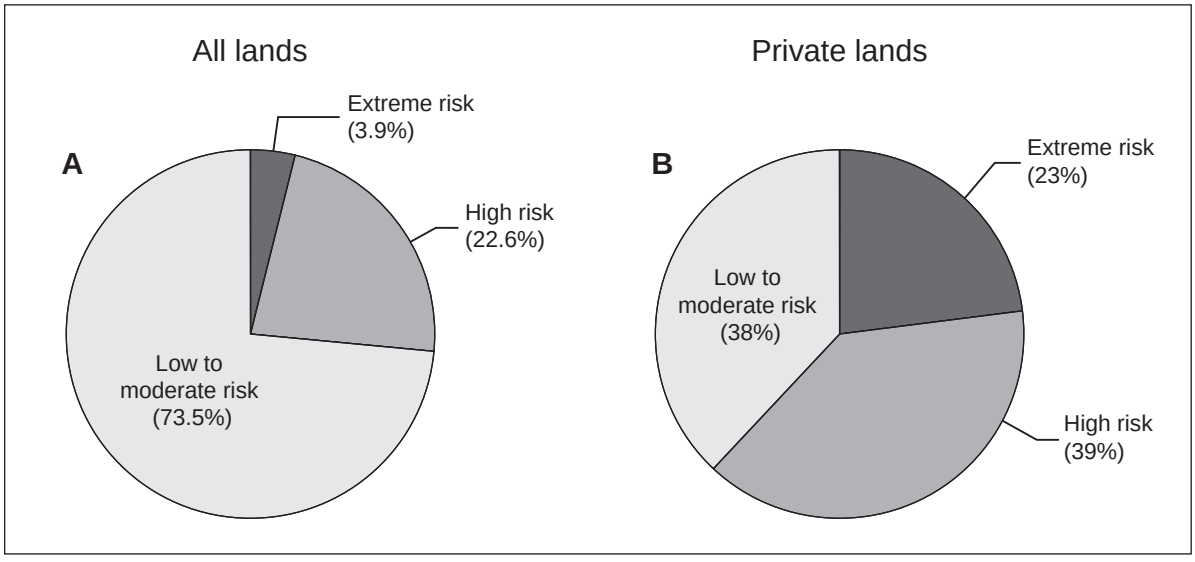


Figure 6-29—Within the Kenai Peninsula Borough, proportion of (A) all land in three fire risk categories, and (B) private land in three fire risk categories.

well as lowland areas. All the private property is located in the lowlands, which are more conducive to development, and most of the lowlands on the Kenai Peninsula are located in the drier western part of the Peninsula, where fire hazards are also highest.

Current development status—
Although more than 60 percent of the private lands in the Kenai Peninsula are located in areas at high or extreme wildfire risk (fig. 6-29b), the current risk to private property is quite a bit less. Only some of the parcels have structures, and many of those structures are small cabins or mobile home additions, and of relatively low value. As of the 2014 borough property tax assessment, 43 percent of private parcels on the peninsula are vacant, with no structures (fig. 6-30A). Another 28 percent of privately owned parcels have structures, but are located in areas with low-to-moderate wildfire risk. Most of these lower risk structures are either in the Seward area, or in the more urban parts of Kenai, Soldotna, and Homer. Twenty-nine percent of private parcels with higher wildfire risk have structures, slightly more than half of which are located on extreme-risk lands (fig. 6-30B).

Relatively few land parcels that are in government or Alaska Native ownership have structures, and most of those structures are in areas of lower wildfire risk.

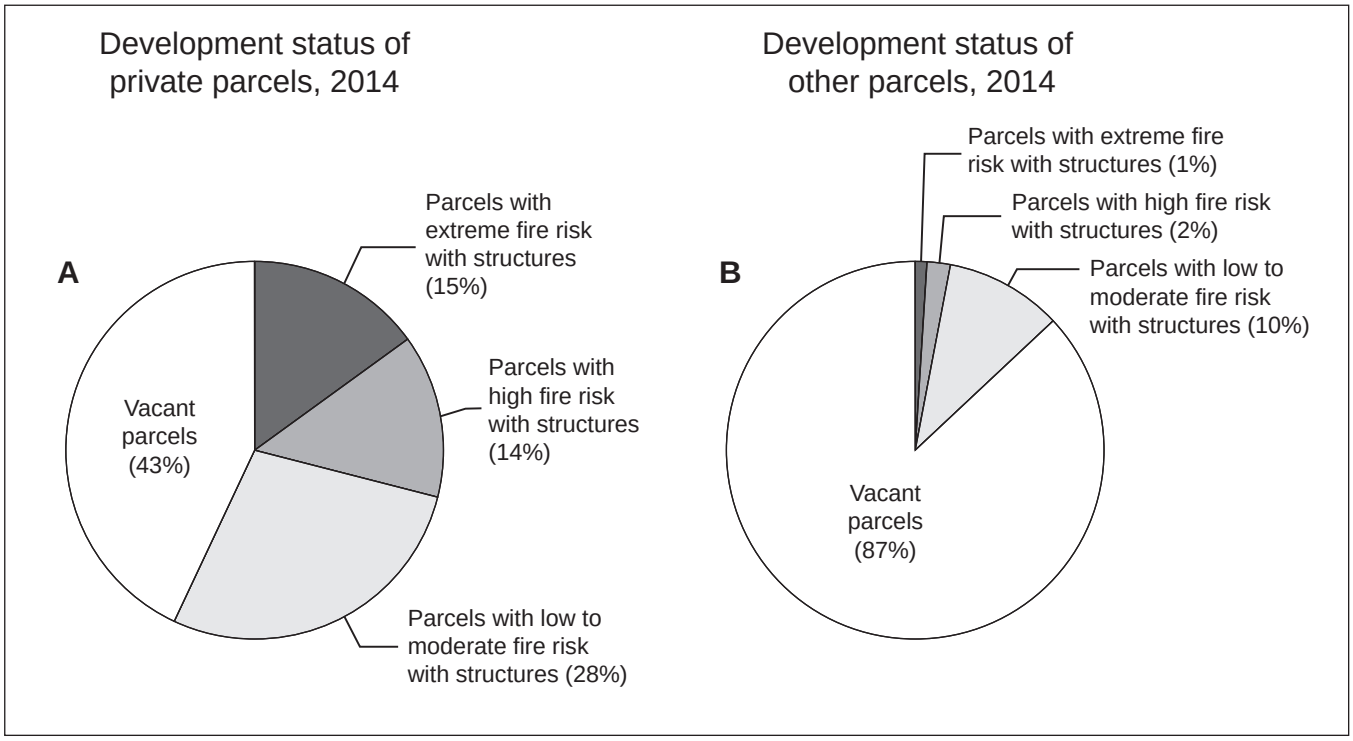


Figure 6-30—Relationship between parcel type (with or without structures) and fire risk categories in the Kenai Peninsula Borough for (A) private land, and (B) other, not privately owned land.

Only 13 percent of other parcels have structures, of which 10 percent are located on lands with low-to-moderate wildfire risk (fig. 6-30b). Structures on public and Native lands include public schools and public utilities (municipal and borough lands); post offices, visitor facilities, maintenance buildings, and offices (federal and state lands); and resort property (Native lands). Many of these structures have high appraised values, but few are located in lands with high or extreme wildfire risk.

The final step for evaluating the current vulnerability of Kenai Peninsula property to wildfire involves translating the number of parcels with structures at risk for wildfire summarized in figures 6-27 and 6-28 into property values. The Kenai Peninsula Borough's property tax appraisal database provides a potential, though imperfect, means to construct an estimate of property values at risk. The borough appraises land values and improvements separately. Improvements include driveways, utilities, and other facilities that would not necessarily be at risk of damage from a wildfire, as well as structures. Information on structures including type, value, and various characteristics such as year built is available for most, but not all properties with structures.

Table 6-10 summarizes the value of Kenai Peninsula structures by fire risk category using the information available on structures in the Kenai Peninsula Borough's 2014 property tax appraisal. The table estimates that structures worth $1.1 billion are located on parcels at extreme risk to wildfire. Another $1.3 billion worth of structures are located in areas with high wildfire risks. Eighty-seven percent of the value of these structures at risk lies on private property. On lands with low-to-moderate wildfire risk are $5.6 billion worth of Kenai Peninsula structures, of which slightly more than three-fourths are on private property.

The values in table 6-10 do not include oil and gas production and transportation property, which is assessed separately by the state, and is mostly at low risk to wildfire. They also do not include personal property such as mobile homes, boats, aircraft, recreational vehicles, and other vehicles. Some of the personal property

Table 6-10—Value of Kenai Peninsula structure by fire risk category, 2014

	Private ownership	Other ownership	Total
		Million dollars	
Extreme fire risk areas	947	175	1,121
High fire risk areas	1,189	146	1,334
Low-to-moderate fire risk areas	4,371	1,202	5,573
Total value	6,507	1,523	8,029

Source: Kenai Peninsula Borough property appraisal database.

might easily be moved if threatened by wildfire, while some might not. The values represent appraisal information and not taxable property values, because a portion of the value of structures on private lands and most of the structures on other lands are not taxed, and the values in the table do not include the value of land. Under Alaska state law, local governments are instructed to assess property at 100 percent of market value. (Alaska Statutes 29.45.110(a)). The Alaska State Assessor's office annually studies the extent to which local governments are complying. In the latest report available, for 2013, the Kenai Peninsula Borough was assessing at 93 percent of market value (Office of the State Assessor 2014: 41). In general, then, the values in table 6-10 should be considered lower-bound estimates of the potential wildfire risk.

Climate change could alter weather conditions that affect the probability of ignition, rate of spread, and intensity of wildfires.

Projecting Future Vulnerability to Wildfire

Two main factors will determine how vulnerability to wildfire in the Kenai Peninsula region will evolve over time. Climate change could alter weather conditions that affect the probability of ignition, rate of spread, and intensity of wildfires. Over the long term, vegetation may respond to changes in temperature or precipitation, with additional effects on quantity and quality of fuels. The pattern of future development could also dramatically affect vulnerability to wildfire, as new structures are built and improvements to existing structures made in areas that may experience large and potentially destructive wildfires. We first discuss effects of climate change, then consider development effects.

Effects of climate change—
Downscaled projections from climate models created by Scenarios Network for Alaska Planning (SNAP) show precipitation as well as temperature to increase steadily on the Kenai Peninsula over the next 50 years (see chapter 2). Precipitation trends are more uncertain, however, and it is not clear whether increased precipitation, if it does occur, will be sufficient to offset the drying effects of higher transpiration rates associated with temperature increases during the growing season.

The longer growing season and possibly increased rainfall could prompt changes in vegetation. Climate-envelope studies show a potential shift from white spruce to Sitka spruce or white-Sitka hybrid (Lutz spruce) on much of the western Kenai Peninsula. Stands dominated by black spruce would remain relatively stable. Additionally, large portions of the southwestern Kenai Peninsula between Homer and Ninilchik could potentially convert from forest to grassland (see "Biome shifts" and "Changes in land cover" on page 200). Actual conversion rates are likely to be very slow, however, and may not take place at all until

a large-scale disturbance. Fire is one type of disturbance that could hasten conversion of vegetation. Future bark beetle outbreaks are even more likely (Berg and Anderson 2006).

Given the uncertainties inherent in climate and vegetation projections, the information that is available suggests the following inferences for projecting the effect of climate change on wildfire hazards. First, much of the area in the southwestern Kenai Peninsula that is projected for potential conversion from forest to grassland has recently experienced high spruce mortality from bark beetle infestations. This area is currently composed of dead spruce and bluejoint grass (*Calamagrostis canadensis*) and is classified in the KPB Community Wildfire Protection Plans as being in the extreme fire hazard state. Second, the distribution of land cover types dominated by black spruce—also mostly classified as in the extreme fire hazard state—are projected to remain similar to their current distribution. Wildfire hazards in land cover types currently classified as having a high hazard—mostly white spruce and mixed forest—will likely remain at least as high as they are today over the next 50 years, even if the long-term trend is toward more Lutz and Sitka spruce.

In general, fire hazards will likely increase somewhat from today on all lands. Young et al. (2012) analyzed spatially explicit datasets of vegetation, fire occurrence between 1950 and 2010, and downscaled climate estimates between 1970 and 2000 throughout the boreal forests of Alaska. The climate-fire relationships they estimated from the data suggested that fuel drying was the main factor determining the pattern of boreal forest burning, rather than the type or amount of fuel. They projected that warmer summer temperatures projected for the next several decades would increase the frequency of drying conditions, even after considering the effect of precipitation increases. One should also note that future population growth and continued land development will almost certainly lead to more human-caused ignitions. The combination of warmer summers and increasing ignitions could create a greater fire risk in all fuel types than currently (Berg and Anderson 2006). A conservative projection of wildfire hazards on lands in the Kenai Peninsula would be to assume that future risks remain at least as high as they are currently, with the spatial variation in that risk distributed largely as it is today.

Methods for projecting effects of population growth and land development—The Alaska Department of Labor projects population in the Kenai Peninsula Borough to grow relatively slowly over the next 30 years, increasing by 16 percent from 2012 to 2042 (Howell 2014). Applying the implied annual growth rate of 0.5 percent per year for 50 years, the borough population would grow to about 73,000 by 2065—an increase of 32 percent from 2010. Given the high prevalence of

recreational homes and visitor-serving businesses in the region, however, traditional methods of projecting development based on population growth are insufficient to project future infrastructure at risk for wildfire in the borough. A reasonable projection of structures at risk requires a method that takes into account the distinction between private property and other property, the spatial dispersion of private property in relation to wildfire hazard, and forces speeding or impeding land development.

The economic forces determining land development in the region are diverse.

The economic forces determining land development in the region are diverse. Before Alaska became a state, commercial fishing dominated the local economy, and development was concentrated near the coast. During the initial years after statehood, oil and gas development became the leading driver, with greatly expanded settlement and infrastructure being built in and near the city of Kenai. In recent decades, recreation and tourism activities have come to dominate development patterns, contributing to a much more spatially dispersed infrastructure. All these historical drivers of regional development derive from forces operating at least at the state level, and for the most part at national or even global scales. That makes it difficult to predict how economic drivers will change over the next 50 years, much less how they will influence development locally on the Kenai Peninsula.

Instead of trying to predict the population and economy directly, this study opts for a scenario approach: a reasonable and informed projection of what could happen in the region based on long-term historical spatial patterns of development. The scenarios are based on an analysis of spatial patterns of land development on the Kenai Peninsula since 1960. The analysis explicitly considers location and land characteristics, including wildfire hazards, as factors that could potentially influence development. Testing whether fire hazard and other spatial characteristics influence development patterns helps clarify the current fire risk to property, as well as improve projections of spatial density of future development and associated potential future wildfire risks.

The main factors analyzed for their effect on development include land ownership status, parcel size, proximity to roads, wetland percentage of the parcel area, wildfire risk category, and whether the land lies within or outside municipal boundaries of Kenai, Homer, Soldotna, or Seward. The method produces what should be considered preliminary projections of potential vulnerability to wildfire rather than refined estimates. Its greatest value lies in demonstrating a feasible and scientifically credible approach that suggests directions for future research. The approach can and probably should be replicated, including additional data that could help articulate the spatially explicit drivers of property development and

potential subdivision and sale of land. Specifically, the analysis could consider such factors as proximity to or frontage on major rivers, lakes, and protected open space; distance to town centers and Anchorage; and additional land cover information and associated climate data. A study of the neighboring Matanuska-Susitna (Mat-Su) Borough showed that these factors did play a significant role in determining private land values, so one might infer that they could influence development patterns as well (Berman and Armagost 2013). However, in the Kenai Peninsula Borough, large expanses of protected lands in the three main federal conservation units restrict the spatial extent of development much more than in the Mat-Su Borough, making the location of private lands and road development more important as limiting factors.

To some extent, the approach taken here is similar to that employed by Hansen and Naughton (2013). They analyzed the association of spruce bark beetles, recent wildfire, and other factors with spatial property values on the Kenai Peninsula. However, Hansen and Naughton (2013) included in their study only properties with single-family homes, and ignored commercial property, vacant land, and parcels with recreational cabins or mobile homes; that is, the vast majority of land parcels. They focused on differential property values, controlling for the characteristics of structures, so most of the differences they found would be attributed to the value of land. Our focus, in contrast, is on which parcels get developed at what time, and what, if anything, gets built there.

The analysis proceeded in several steps. The first step estimated a set of survival-time equations that explained the timing and location of the first instance of a structure appearing on a parcel after 1960. If a structure currently exists on the property, or if the estimated equations predicted that it would be developed, then a panel regression model explained the value of the structure over time.

The estimated equations for survival of a parcel in an undeveloped state and the value of structures on developed parcels then formed the basis of long-term future projections of property at risk on the Kenai Peninsula. Changes in land ownership in the region since 1960, not counting transfers among private owners, have been determined primarily by the Alaska Statehood Act and the Alaska Native Claims Settlement Act (ANCSA) of 1971. Aside from decades-old state land disposals and limited transfers of borough land to private ownership in and near established communities, relatively little change has occurred in the configuration of public and private land since the Alaska National Interest Lands Conservation Act (ANILCA) in 1980 created Kenai Fjords National Park. Even less change in landownership status seems likely going forward. Therefore, it seems reasonable to assume that patterns of development that have become established on private and other lands in the region will continue.

Spatially explicit scenarios for Kenai Peninsula property development were constructed by taking random draws for the state of development (structure built or not) by 2065, based on the estimated equations for development status. Parcels presently containing structures were assumed to continue to contain structures. If the scenario included a structure on a parcel in 2065, the value was projected from the equations explaining historical patterns for that kind of property. Additions, remodeling, and replacement of buildings on parcels already developed today were also based on the established long-term trends.

Appendix 5 contains details of the modeling of land development, structure value, and scenarios, including detailed equation results. Findings are summarized below.

Results explaining historical pattern of land development—
The factor that most explained the likelihood that a structure gets built on private property was the parcel's proximity to a road. Development for a parcel that had road frontage or lay within 400 m of a road was nearly three times as likely as for a more remote parcel. Larger parcels were more likely to get developed, and those with a higher percentage of wetland were less likely to be developed. Parcels within the city limits of Kenai, Soldotna, and Homer were more likely to be developed relative to lands outside municipal boundaries, but those in Seward were less likely. Seward is older than the other communities, and the devastation suffered from the 1964 earthquake may have impeded development. Areas with high fire risk were less likely to be developed, controlling for other factors. Extreme fire risk was associated with an even lower potential for development.

Parcels of other ownership types were much more likely to be developed if lying within city limits of any of the larger towns. Road frontage increased the likelihood of development and wetlands greatly reduced it, as on private lands, but other effects differed. Parcels with high fire risk and larger parcels were much less likely to be developed, and municipal and state-owned parcels were less likely to be developed than borough, Native, and federal parcels.

On average, the results showed that structures in towns were much more valuable than those built outside city limits, with those built in Kenai and Soldotna being worth the most. The larger towns tended to have larger commercial buildings, as well as some multi-family residences. Structures on or near roads were more valuable than those built on remote parcels, which presumably tended to be recreational cabins and associated outbuildings. Structures on larger parcels were also worth more, controlling for other factors, and the value of structures built on lands with high spring fire risk or more wetland area was lower.

Structures built on public and Native lands were more diverse and therefore more difficult to explain and predict. Structures on lands within city limits of the larger towns were much more valuable than those built outside city limits, and structures on or near roads were more valuable than those built on more remote parcels. Municipal structures were worth more, which is not surprising given that city-owned buildings would include office buildings and public utility structures.

Projected Kenai Peninsula property development in 2065—
The equations provide a basis for projecting future property vulnerability to wildfire, assuming that the historical pattern of subdivision of private property continues. A number of scenarios were constructed using different random draws from the projected probability distribution for development of vacant private property and other lands. As it turned out, different sets of random draws produced essentially identical projections of property development. The only visible difference among scenarios was the location of a few relatively low-value structures projected to materialize on large tracts of public lands with a low probability of development. Consequently, the results are reported below for a single representative scenario.

The projection to 2065 included a 53-percent increase in the number of private Kenai Peninsula parcels with structures, to about 49,000. The distribution of the additional structures among areas with different wildfire risk categories changed relatively little, although the number of structures in extreme fire risk areas increased at a slightly higher rate: 56 percent (fig. 6-31A). The number of other parcels with structures increased at a faster rate—by 72 percent—but the total number of these other structures remained relatively small—fewer than 1,500—and few of these structures were built in high or extreme fire risk areas.

Projected values at risk to wildfire in 2065—
The total value of structures on private lands was projected to increase by 66 percent over the next 50 years. The value of structures on other lands would increase somewhat less: about 60 percent. The projected increase in value of structures is nearly identical for each wildfire risk category (fig. 6-31B).

Discussion

The analysis of structures potentially at risk to wildfire shows clearly that the vulnerability of the Kenai Peninsula to wildfire is high—several billion dollars—and growing (fig. 6-32). A principal reason for the high risk is the dispersed settlement pattern, which creates a large WUI.

The value of structures at risk is projected to grow by 66 percent on private lands and 60 percent for other lands between now and 2065. The growth rate in

Analysis of structures potentially at risk to wildfire shows clearly that the vulnerability of the Kenai Peninsula to wildfire is high—several billion dollars—and growing.

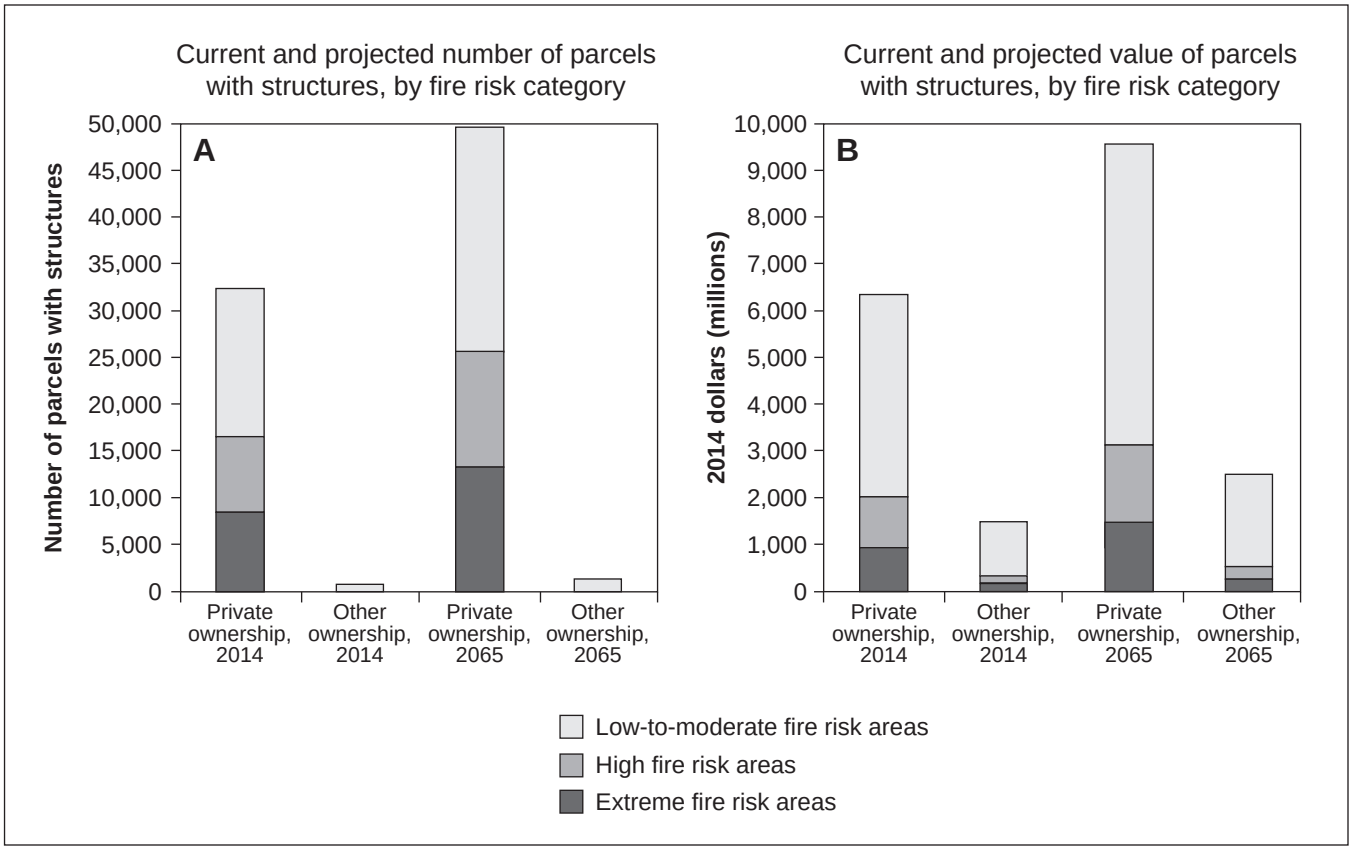


Figure 6-31—Across all three fire risk categories in the Kenai Peninsula Borough, projected change in (A) the number of parcels with structures between 2014 and 2065 and (B) value of structures between 2014 and 2065.

value at risk is twice as fast as projected for the regional population. Two factors underlie the faster projected rate of increase in value of structures than in the resident population. First, a growing share of the property on the Kenai Peninsula is recreational property and second homes. Forces primarily outside the region drive the demand for recreation property on the peninsula. These forces have produced steady growth, and there is no reason to doubt that the growth will continue. Recreational development is more spatially dispersed than that coming from population growth, more of which is within towns where the wildfire risk is lower.

The second factor underlying the more rapid growth in value of structures is that the structures that are being built are projected to be larger and more valuable than before. This is to be expected as the region matures and wealth increases. On private lands, the projected increase in the number of parcels with structures is 53 percent, while the equations project a 66-percent increase in value of structures.

The analysis assumes that the likelihood of large destructive wildfires 50 years from now will be similar to those prevailing today. In fact, the wildfire hazard

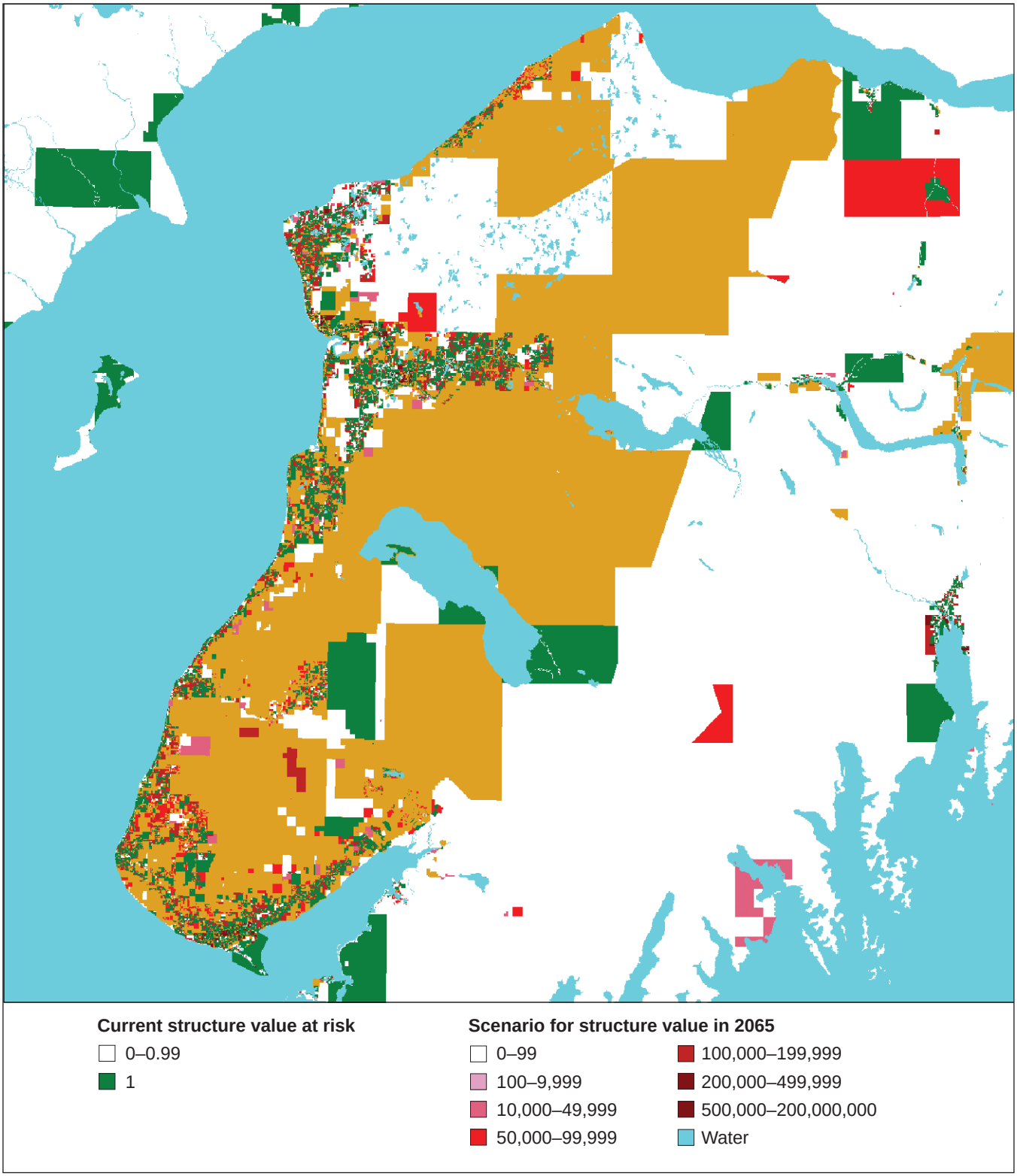


Figure 6-32—Spatial distribution of high or extreme fire risk (orange), parcels with structures in 2014 (green), and value per parcel of structures projected for 2065.

will probably increase. More property development is likely to create more human-caused ignitions. Warmer temperatures may produce drying conditions more frequently than today, even if the total amount of precipitation increases (Young et al. 2012).

One interesting finding is that areas with extreme wildfire risk, and to a lesser extent areas with high fire risk, were less likely to be developed, controlling for other factors. Hansen and Naughton (2013) found that property values were higher near previous large wildfires and recent spruce bark beetle attacks. It may appear that both these sets of empirical correlations imply some kind of preference of property owners either for or against wildfire hazards, although that is unlikely to be the case. It is more likely that these measures correlate spatially with other unobserved features that really do matter to people. For example, households seeking recreational homes may prefer riparian areas, which coincidentally have vegetation types that are less vulnerable to wildfire.

Conclusion

This study analyzed the combined effects of climate change and property development to construct a preliminary assessment of the vulnerability of Kenai Peninsula property to wildfire. It developed a method to define and estimate property values most at risk to wildfire based on information drawn from the Kenai Peninsula Borough property appraisal and community wildfire protection plans (KPBOEM 2014). It made a spatially explicit projection of future development to 2065 and projected property values at risk. The study projected a total value of $1.8 billion in 2065 for structures in extreme wildfire risk areas, with an additional nearly $2 billion for structures in high-wildfire-risk lands. Private property contains 86 percent of the value of these vulnerable structures.

This analysis is preliminary; it demonstrates a feasible method for quantitative projections of vulnerability, but leaves out many details. This analysis could be extended by including additional spatially explicit elements influencing property value, such as distance to towns and to Anchorage, additional climate and vegetation data, and proximity to lakes, streams, and protected open space. Unobserved spatial influences could be modeled with spatially correlated error terms, especially in the survival analysis for vacant land parcels. The main challenge is computational, with such a large dataset and with private property distributed across relatively narrow bands along road corridors.

Perhaps the most important element that could improve the analysis involves more complete modeling of the wildfire hazards. Detailed analysis of the projected downscaled climatology could provide insight into the changing probability of

drying conditions and fire weather that combine to produce the most destructive wildfires. Vegetation modeling could include dynamics before and after disturbance to provide a more dynamic projection of fuels and potential for ignition and wildfire spread rates. Finally, the spatial modeling of property at risk could include a formal analysis of vegetation and wildfire hazard of adjacent parcels and along critical access routes.

Examining the Effects of Vegetation Change on Recreation Infrastructure on the Chugach National Forest

The assessment area supports a diversity of recreation settings, ranging from dense rain forest to muskegs to alpine tundra, and each recreational setting presents unique challenges to managers who are providing access to recreation. For example, muskegs can typically be extensively traveled only in the wintertime, whereas alpine areas are used both in winter and summer months. This is a strong factor in determining the ease of crossing terrain and accessing destinations, and how difficult it will be for land managers to construct and maintain trails in a given area. Changes in vegetation can alter scenery, change access, and increase or decrease hazards at facilities; all these factors may influence the experience that people have at recreation facilities. Of the climate-related vegetation dynamics described in this assessment, however, three stand out as having the greatest potential to affect recreation infrastructure on the Chugach National Forest: afforestation of subalpine and alpine areas, the potential for different and more disease and insect outbreaks, and the expansion of aggressive invasive plants.

Three vegetation dynamics stand out as having the greatest potential to affect recreation infrastructure: afforestation of subalpine and alpine areas, the potential for different and more disease and insect outbreaks, and the expansion of aggressive invasive plants.

One of the key experiences that facilities and trails provide on the Chugach is accessing alpine terrain to enjoy relatively easy cross-country travel and enjoy sweeping views of the surroundings. Thus, several trails and associated trailheads across the forest, along with Palmer Creek Road on the northern Kenai Peninsula, are designed to provide recreational access to alpine and subalpine areas. If afforestation continues at current projections, infrastructure built to access alpine lands may no longer serve that purpose. However, in the short term (less than 50 years), the impacts of afforestation to recreation infrastructure should remain minimal.

Another potential impact could be through the proliferation of non-native plant species, particularly invasives, along trails and at or near facilities, undermining the scenic experience of natural landscapes. These are the locations where invasives are most likely to proliferate because the common transporters are people, domesticated animals, and equipment using this infrastructure. The assessment notes that

the coastline in Prince William Sound may be particularly susceptible to the spread of invasives in the future. The western half of Prince William Sound is managed to avoid degrading wilderness character, which includes maintaining natural conditions. Visitors to cabins in the wilderness study area may be particularly sensitive to the presence of invasives. One particularly damaging invasive is Elodea. If current rates of spread into backcountry lakes continue, this invasive has a strong potential to critically limit floatplane access to remote cabins across the Chugach.

Third, any increase in tree mortality from insect or disease outbreaks could lead to an increase in the need for logging out trails throughout the year, and increase the workload for removing dead trees that become a hazard to visitors at developed recreation sites. As with the spread of invasive plant species, high rates of tree mortality can also change the scenic qualities that people seek in forested landscapes.

Adaptive Capacity, Increased Management

Overall, it appears that vegetation on the Chugach will remain relatively stable compared to the western Kenai Peninsula, meaning that impacts to recreation infrastructure from vegetation changes are not expected to be extensive. Chugach National Forest recreation infrastructure should be resilient to changes in vegetation over the next 20 to 30 years, and these changes should not significantly affect either summer or winter use of facilities and trails. To maintain this resiliency, however, management actions may need to increase focus on avoiding the spread of invasives near facilities and along trails where most of these species are found, and must be responsive to identifying hazards at facilities and logging out trails if there is any substantial increase in tree mortality resulting from causes described in this assessment.

Interpreting the Patterns of Change

This chapter is particularly complex because of multiple scales of observation (spatial and temporal), the broad array of factors affecting vegetation distribution, and the various modeling approaches used to examine future scenarios. Through this array of models, we provide a lens for land managers, residents, and visitors to consider potential patterns of change. A simple summary of results illustrates the range of responses that may occur in vegetation during the next 50 to 60 years (table 6-11). According to our models, the distribution of coastal rain forests and Sitka spruce (the main spruce component of coastal rain forests) will be minimally affected by projected changes in climate. These two features occupy much of the

Table 6-11— Rate and direction of potential vegetation change in the assessment area

Vegetation type/species	High	Moderate	Low	Direction of change	Climatic factor(s) affecting future distribution	Factors not directly climate-related affecting future distribution
Coastal rainforest			X	+	Precipitation, air temperature	Shrubification of lowlands fire disturbance, spruce bark beetle outbreaks, competition with graminoids
Kenai lowlands		X		–		
Boreal forest		X		–		
Alpine tundra	X			–		Advancement of treeline
Sitka spruce			X	+	Precipitation, air temperature	
Black spruce		X		–		Fire disturbance
White spruce	X			–		Spruce bark beetle outbreaks
Aphragmus eschscholtzianus	X			–	Precipitation, temperature	
Romanzoffia unalaschcensis		X		–	Precipitation	
Papaver alboroseum		X		–	Precipitation, temperature	
Creeping thistle		X		+		Human spread
Waterweeds		X		+		Human spread
Sweetclover		X		+	Temperature	Human and fire disturbance
Reed canarygrass	X			+		Human spread

landscape east of the Kenai spine. Land cover types dominated by white and black spruce (western Kenai) are likely to decrease, and in particular, white spruce abundance is predicted to decrease because of climatic factors, in combination with climate-related increases in spruce bark beetle outbreaks. Of paramount concern in the assessment area is potential loss of alpine tundra and associated rare species. In contrast, it is likely that changes in climate will increase invasive/weed species—with greatest concern to generalist species like reed canarygrass.

Together, these varied results suggest a future assessment area with vegetation that differs from what is currently on the landscape. However, it is important to remember that changes in species distributions and land cover types will lag significantly behind climate. The lag will differ by life form, with long-lived species like trees potentially showing the slowest response. Furthermore, disturbances such as fire will influence rates of change in species distribution. Although land managers likely cannot mitigate the wide variety of vegetation change expected, our results aid in identifying land cover types and species most likely to change, so that response and action can be prioritized and coordinated.

These varied results suggest a future assessment area with vegetation that differs from what is currently on the landscape.

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Dan Thompson, U.S. Fish and Wildlife Service



Moose cow and calves.

Chapter 7: Moose, Caribou, and Sitka Black-Tailed Deer

John M. Morton[1] and Falk Huettmann[2]

Summary

- Current distributions of these three ungulate species on the assessment area are artifacts of glacial history, and of relatively recent translocations (moose, Sitka black-tailed deer) and reintroduction (caribou) in the 20th century.
- About 700 moose, 20 to 30 caribou, and 2,000 deer are harvested annually in the assessment area by both recreational and subsistence users.
- About 10,000 moose are well distributed throughout the assessment area, mostly on the western Kenai Peninsula and around Anchorage. Their distribution is likely to increase in the near term owing to continued post-introduction colonization of Prince William Sound, afforestation of the Kenai lowlands and alpine tundra, and increasing fires on the western Kenai Peninsula.
- About 1,000 caribou are distributed on the western side of the Kenai Peninsula in four herds. Their distribution is likely to decrease in response to afforestation of alpine tundra.
- About 20,000 black-tailed deer occur in the Sitka spruce forest along Prince William Sound. Their distribution is likely to increase because of declining snow depths along the coast and continued post-introduction dispersal onto the Kenai Peninsula.
- In the longer term, forecasting becomes uncertain because of the expected introduction of novel pathogens and their interaction with changing ecological drivers.

Introduction

Moose (*Alces alces gigas*) (Bubenik 1997, Hundertmark et al. 2006), caribou (*Rangifer tarandus granti*) (Bergerud 1978), and Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) (Wallmo 1978) are three ungulate species that will be affected by changes in the composition and distribution of vegetation, snow depth, ecological disturbances, interspecific competition, and perhaps new diseases in response to a warming climate. Moose are widely distributed over the assessment area, but their abundance varies both temporally and spatially, with the largest populations on the western Kenai Peninsula and adjacent mainland. Caribou are restricted to the Kenai

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Peninsula, currently in four herds. Sitka black-tailed deer occur on the mainland and on islands in Prince William Sound. Extant distributions of all three species are partially artifacts of glacial history, barriers to movement after the last glaciers receded (Klein 1965), and translocations and reintroductions in the 20th century (Paul 2009).

Moose, caribou, and black-tailed deer are harvested for both subsistence and recreational purposes in the assessment area. Population abundance and composition are manipulated primarily through harvest regulations in game management units (GMUs) designated by the Alaska Department of Fish and Game. GMUs 15 and 7 are on the Kenai Peninsula, GMU 14C is on the mainland adjacent to the peninsula, and GMU 6 stretches from Prince William Sound through the eastern extent of the Copper River Delta (fig. 7-1). Fire management also plays an important role in the distribution and abundance of moose on the western Kenai Peninsula.

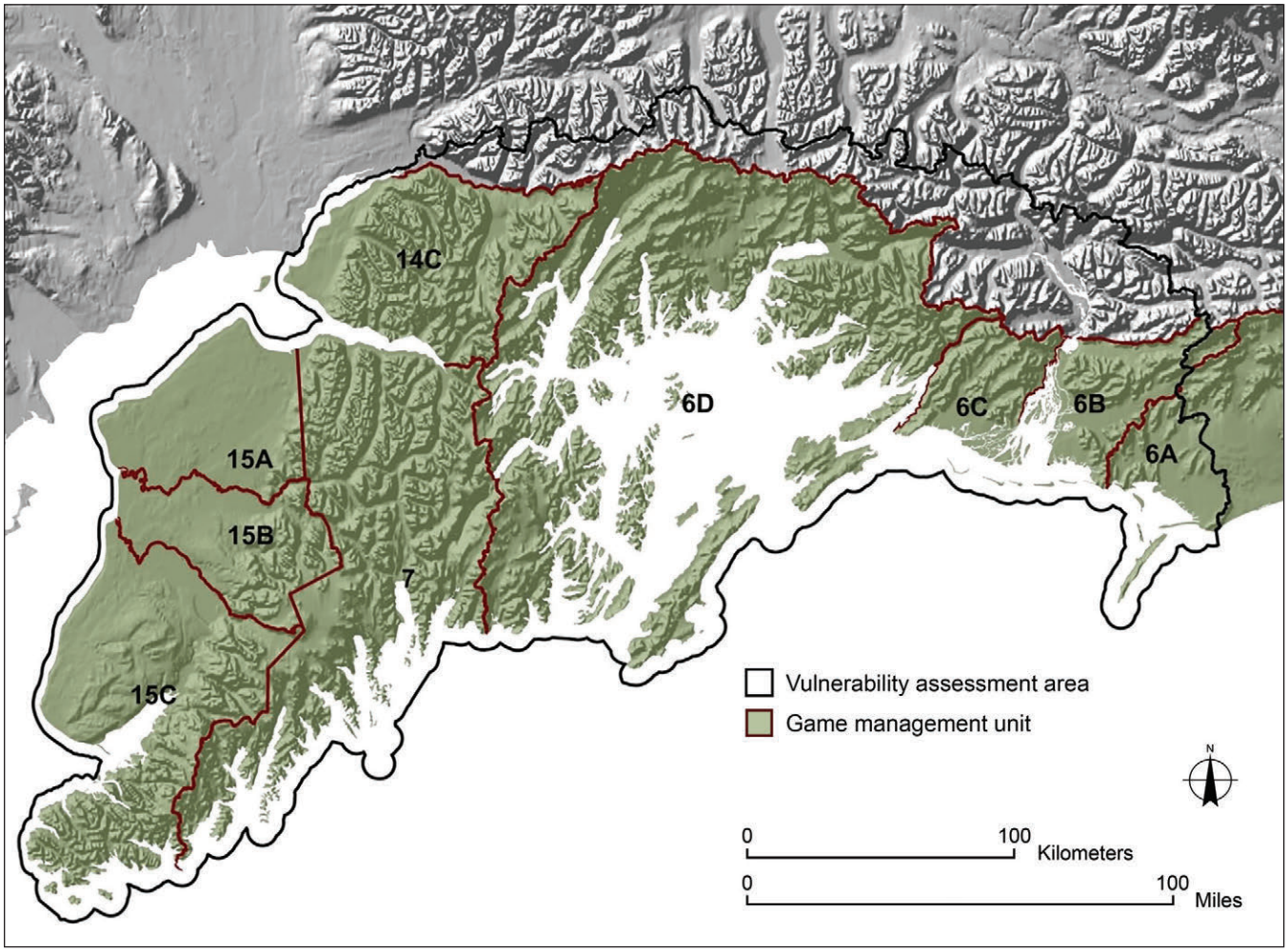


Figure 7-1—Game management units designated by the Alaska Department of Fish and Game for managing moose, caribou, and Sitka black-tailed deer populations in the assessment area.

Moose: Current and Historical Distribution

Moose have been present in Alaska since mid- to late-Pleistocene times (11,000–14,000 years BP) (Hundertmark et al. 2003, 2006). They likely survived in relatively small disjunct groups wherever suitable habitat could be found throughout this period, when a tundra-steppe community dominated much of Alaska refugia (LeResche et al. 1974). With the close of the glacial period and proliferation of shrub and forest communities, moose spread via river valleys throughout 90 percent of contemporary Alaska (LeResche et al. 1974, Lutz 1960). Very recent extensions of moose distribution have occurred in the geographic extremes of Alaska; most relevantly in southeast Alaska, where glacial recessions have allowed moose to colonize coastal forests (Darimont et al. 2005, Hundertmark et al. 2006, Klein 1965, LeResche et al. 1974) as well as by deliberate translocations to the Copper River Delta near Cordova (Paul 2009). LeResche et al. (1974) concluded that, in most of Alaska, moose numbers have varied dramatically in local areas over the past two centuries, largely in response to fire and subsequent forest succession. Historical accounts that moose were absent from a particular locale within its range most likely reflected only a period of very low moose numbers resulting from a prolonged absence of fires in that area (LeResche et al. 1974), which is likely the case for the Kenai Peninsula through most of the 19th century (Lutz 1960).

The Alaska-Yukon race of moose is widely but patchily distributed in the assessment area, consistent with the distribution of vegetation, and, to a lesser extent, glaciation. Currently, about 10,000 moose populate the assessment area, of which almost 60 percent are on the western side of the Kenai Peninsula (GMU 15). Moose do not occur on the extreme southern Kenai Peninsula, and are patchily distributed along Prince William Sound, presumably because suitable habitats are restricted to a few sizable areas where the vegetation is still in the early stages of succession, and which occur only in the larger river valleys of the mainland and on the terminal moraines of glaciers that have recently receded (Klein 1965).

Currently, about 10,000 moose populate the assessment area, of which almost 60 percent are on the western side of the Kenai Peninsula

Moose are most abundant on the western Kenai Peninsula, where a drier climate and an active fire regime produce hardwood browse and less snow, which are critical and interacting components for overwinter survival (Peek 1998). Moose occur in relatively low densities on the eastern Kenai Peninsula, where the mountainous terrain, paucity of hardwood habitats (and browse), and deep snow are limiting. Moose are absent from much of the southern coast of the peninsula, which is isolated by the Kenai Mountains, the Harding lcefield, and the Wosnesenski-Grewingk Glacier complex. Although there is anecdotal evidence that moose may have colonized the Kenai Peninsula in the late 1800s, Lutz (1960) provides references that indicate that moose were on the peninsula since the early 1800s and were

present in archaeological sites dating to circa 750 BCE. Moose are abundant on the mainland immediately north of the Kenai Peninsula, specifically in the Anchorage Bowl, where they take advantage of high-quality browse growing in the wildland-urban interface and adjacent military reservation. Genetic evidence suggests that populations on the Kenai Peninsula are semi-isolated from the adjacent mainland, presumably because of natural and human barriers in and around the 16-km-wide isthmus (Wilson et al. 2015).

Moose are sparse over much of the Sitka spruce (*Picea sitchensis*)-dominated landscape adjacent to Prince William Sound. Moose were effectively isolated from Prince William Sound by glaciation in the Chugach Mountains and by Miles Canyon on the Copper River (Klein 1965). In southeast Alaska, anecdotal evidence suggests that moose colonized the lower Stikine River valley at the end of the 19th century and the Yakutat-Dry Bay area from 1925 to 1935 in response to relatively recent deglaciation (Klein 1965); genetic evidence suggests that these populations may originate from the Western moose (*Alces alces andersoni*) (Colson et al. 2014),[3] although Hundertmark et al. (2006) suggested that the dividing line is further south (58° 45′ N). The extant population on the Copper River Delta (and Berners Bay) (Klein 1965) was established by a series of calf transplants between 1948 and 1958 from the Kenai Peninsula (Burris 1965, Paul 2009) and so belong to the Alaska-Yukon race (Hundertmark et al. 2006). The moose population on the western Copper River Delta has responded favorably to uplift and vegetation growth since the 1964 earthquake, which help sustain a small population on Hinchinbrook Island.[4] A few moose inhabit the Valdez area, occasionally reaching western Prince William Sound at Kings Bay via the Nellie Juan River (LeResche et al. 1974).

Kenai Peninsula (GMU 15)—
Moose populations on the western Kenai Peninsula are managed in three subunits (fig. 7-1). GMU 15A includes all of the Kenai lowlands and other habitats north of the Kenai River. GMU 15B includes the subalpine shrubs on the Tustumena Benchlands and forested habitats between the Kenai and Kasilof Rivers. GMU 15C includes the Caribou Hills and other forested areas south of the Kasilof River.

On the Kenai Peninsula, moose population fluctuations have been historically linked to fires and winter browse availability (Franzmann and Schwartz 1998,

[3] **Colson, K.; White, K.S.; Hundertmark, K. 2014.** Population boundaries and the subspecific divide in southeastern Alaskan moose. Presented at 48th North American Moose Conference and Workshop, Girdwood, Alaska.

[4] **Burcham, M. 2016.** Personal communication. Wildlife biologist, U.S. Department of Agriculture, Forest Service, Chugach National Forest, Cordova Ranger District, Cordova, AK 99574.

Loranger et al. 1991, Oldemeyer et al. 1977, Spencer and Hakala 1964). Moose populations typically peak 15 to 25 years post-fire (Loranger et al. 1991, Spencer and Hakala 1964), but fires must be severe enough that mineral soil is exposed to get maximum regeneration of hardwood browse (Miner 2000). The moose population in GMU 15 probably peaked in 1925 and declined somewhat by 1950 in the aftermath of large human-caused fires in 1871, 1891, and 1910 (Chatelain 1952; cited in LeResche et al. 1974), which burned much of the Tustumena Benchlands (GMU 15B). In the aftermath of these fires, which replaced mature spruce with early successional hardwood, wintering habitat for moose was created while destroying that of caribou (see "Caribou: Current and Historical Distribution" on page 273). Declining moose populations on the western Kenai Peninsula in the early 1900s helped justify establishing the Kenai National Moose Range in 1941, later to become the Kenai National Wildlife Refuge in 1980.

The 125 500 ha Kenai Fire in 1947 and the 32 000 ha Swanson River Fire in 1969, both accidentally caused by humans, set the stage for abundant hardwood browse (Oldemeyer et al. 1977) and moose (Loranger et al. 1991) in the Kenai lowlands (GMU 15A) in the 1960s through 1980s. Populations in this area peaked at 5,300 moose in 1971, with densities as high as 4.4 moose/km^2 (Loranger et al. 1991), but browse quality declined thereafter (Oldemeyer et al. 1977). The moose population in GMU 15A is now less than 1,600, a consequence of no significant fires for more than 40 years until the 3600 ha Card Street Fire in 2015.

After the 1969 fire, the U.S. Fish and Wildlife Service and subsequently the Alaska Department of Fish and Game used three 40-ton LeTourneau tree crushers in efforts to create moose browse in GMU 15A (fig. 7-2). From 1970 to 1988, young spruce on more than 6500 ha were crushed with limited success and at high financial cost (Miner 2000). The Kenai National Wildlife Refuge initiated a prescribed fire program in 1986 to increase the likelihood of softwood being converted to hardwood (Miner 2000), but fewer than 2400 ha were successfully burned before that program was terminated in the early 2000s.

Since 1985, moose populations have fluctuated on the western Kenai Peninsula (GMU 15A, 15B, 15C) between 5,000 and 6,000 animals. This variation, however, has not been uniform in distribution. Moose populations have decreased in GMU 15A, remained stable in GMU 15B, and increased in GMU 15C (Wilson et al. 2015). These differences can be attributed to changes in the habitat conditions in each subunit. Mostly black spruce (*Picea mariana*) forests within GMU 15A have experienced few fires in the last four decades and have continued to mature since the last big wildfire in 1969, producing less browse as forest succession has progressed. GMU 15B has seen little increase in moose habitat, as there have been

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Figure 7-2—Three LeTourneau tree crushers were used to create 16,000 ac of early successional hardwood on the Kenai National Moose Range (now the Kenai National Wildlife Refuge) during the 1970s. This approach to managing large-scale winter moose habitat was eventually abandoned in favor of more strategic management of wildfire.

no significant fires until very recently. The 2800 ha 2004 Glacier Creek Fire was an intense fire on the northeast shoreline of Tustumena Lake, and the 2014 Funny River Fire spanned a 80 000 ha fire perimeter of which about 65 percent was actually burned, much of it black spruce and beetle-killed white (*Picea glauca*) spruce.

In GMU 15C, most white and Lutz (*Picea* × *lutzii*) spruce forests had not burned in the past 600 years (Berg and Anderson 2006). In the past two decades, however, white and Lutz spruce forests that coincidentally experienced high mortality rates resulting from spruce bark beetle attacks during the late 1980s through the 1990s have burned. Until the most recent Funny River Fire in 2014, about 57 000 ha burned on the Kenai Peninsula since the 1100-ha Windy Point Fire in 1994, two-thirds of that south of Tustumena Lake in GMU15C. Not surprisingly, moose have increased in GMU 15C from 2,000 in 1992 to 3,200 in 2013.

Annual harvests in GMU 15 have averaged >500 moose over the past three decades, ranging from a high of 884 in 1983 to a low of 388 in 1999. Over this same

period, moose-vehicle collisions on the Kenai Peninsula, mostly along the Sterling Highway, have averaged 244 per year, translating to more than 7,100 moose killed by vehicles since 1980. Currently, about a third (30 percent) of moose killed by humans every year in GMU 15 is a result of vehicle collisions (Morton 2012).

Kenai Peninsula (GMU 7)—
The moose population on the eastern side of the Kenai Peninsula is managed in GMU 7, which includes drainages flowing into the Gulf of Alaska and upper Turnagain Arm, and the Kenai River upstream from the Russian River. Moose densities are low relative to GMU 15 on the Kenai Peninsula and are expected to remain so unless significant habitat alteration occurs. Widespread spruce bark beetle infestations that began in the 1990s have affected more than 500 000 ha of spruce forests on the Kenai Peninsula. Since 2001, infestation rates have decreased as the number of uninfected trees becomes scarce (Schulz 2003). The impact of spruce mortality and salvage logging efforts will affect the quality of moose habitat over a large area, but the nature of the effect remains uncertain, particularly in the Sitka-spruce dominated GMU 7, where wildfire has historically not been an ecological driver.[5] Although a complete population survey has never been completed, the Alaska Department of Fish and Game has assumed that fewer than 1,000 moose reside in GMU 7; over the past 20 years, this game management unit has provided about 10 percent of the annual moose harvest on the Kenai Peninsula.

Prince William Sound area (GMU 6)—
Moose populations on the northern coast of the Gulf of Alaska and throughout Prince William Sound are managed in four subunits of GMU 6 (fig. 7-1). GMU 6A encompasses the Gulf of Alaska drainages east of Katalla, including Kanak, Wingham, and Kayak Islands. GMU 6B encompasses the Gulf of Alaska and Copper River basin drainages west of Katalla and east of the Copper River. GMU 6C includes the drainages west of the Copper River and east of the Rude River. GMU 6D includes all other drainages flowing into Prince William Sound from Cordova to Valdez to Whittier.

Moose populations in most of GMU 6 originated from translocations of calves from the Kenai Peninsula, Anchorage, and Matanuska-Susitna areas.

Moose populations in most of GMU 6 originated from translocations of calves from the Kenai Peninsula, Anchorage, and Matanuska-Susitna areas (Burris and McKnight 1973, Paul 2009). During 1949–1958, Cordova residents successfully raised 24 captive moose calves and released them on the western Copper River Delta in GMU 6C. This small population grew rapidly and expanded eastward into

[5] **Potkin, M. 1997.** Fire history disturbance study of the Kenai Peninsula mountainous portion of the Chugach National Forest. Unpublished report. 75 p. On file with: Chugach National Forest, 161 East 1st Ave., Door 8 Anchorage, AK 99501.

GMU 6B by the early 1960s. Eastward expansion continued into GMU 6A to the Bering River area by the late 1960s, and to Cape Yakataga by the mid-1970s. The population reached a record high of approximately 1,600 in 1988 (Griese 1990), then declined to 1,227 by 1994 as part of a planned reduction (Nowlin 1998). The only moose indigenous to GMU 6 are small populations in the Lowe River drainage and Kings Bay, numbering about 40 animals total. The current population in GMU 6 is estimated to be 1,250 moose, and is stable in most areas, but is increasing in GMU 6C near Cordova.

Hunting of the introduced population in 6C began with 25 bulls harvested in 1960. Harvest began in 6B and 6A during 1965 and 1971, respectively. Moose in 6A were divided into two populations (east and west of Suckling Hills) during 1977 and have been managed separately since then. Hunters have harvested 3,800 moose during 1965–1998 in GMUs 6A, 6B and 6C. In contrast, total hunting mortality of the indigenous moose population in GMU 6D during the same period was about 40 moose.

Anchorage area (GMU 14C)—

Part of the assessment area includes a subunit of GMU 14, which encompasses drainages north of Turnagain Arm to the Knik River and Knik Glacier and includes the Anchorage area. Moose were uncommon in this area before the 1940s. They increased in the late 1940s as brushy regrowth replaced mature forests cut or burned during the development of Anchorage and the Fort Richardson Military Reservation. Numbers increased considerably during the early 1950s, and by the late 1950s and early 1960s moose were abundant and have remained so during the past four decades because of continued production of browse. Open-canopied, second-growth willow (*Salix* spp.), birch (*Betula neoalaskana*), and aspen (*Populus tremuloides*) occur on burned-over military lands and on several hundred acres of military lands that have been rehabilitated during the past two decades. Extensive moose browse occurs in the parks, greenbelts, residential areas, riparian areas, and most south-facing slopes in the Anchorage Bowl. Consequently, moose mortality from vehicle collisions is high, particularly along the Glenn Highway. From 1994 to 1999, annual moose-vehicle collisions averaged 156 in the Anchorage Bowl (Garrett and Conway 1999), although the annual rate has exceeded 200 in recent years.

Nearly 2,000 moose are currently estimated in GMU 14C, including the Placer and Portage River drainages. A record harvest of nearly 500 moose (50 percent females) occurred in 1965, but hunters harvested only 18 moose in 1978. Annual harvests increased steadily during the late 1980s and early 1990s but began to decline in 1992. The mean annual harvest in the past 5 years was fewer than 90 moose, most of which were taken on military reservations.

Annual harvest from all GMUs currently approximates 700 moose out of an estimated population of 10,000 moose in the assessment area. Collisions with vehicles kill more than 400 moose annually in the assessment area.

Caribou: Current and Historical Distribution

Caribou have not penetrated into the southern coastal region of Alaska except on the Alaska and Kenai Peninsulas, where they have been restricted almost exclusively to the dryer western sides (Klein 1965). The only caribou in the assessment area are on the Kenai Peninsula. The peninsula historically supported an endemic caribou subspecies (*Rangifer stonei*) (Porter 1893, Seton-Karr 1887) that, by all accounts, functioned as a woodland population.[6] The indigenous caribou were extirpated circa 1912, when Andrew Berg shot 13 caribou near Ptarmigan Head in the Caribou Hills, the last authenticated report of caribou on the peninsula. This extirpation has been attributed to large-scale habitat change brought about by both human-caused fires and overharvest by miners and trophy hunters in the 19th century, but Davis and Franzmann (1979) believed the latter was a "more proximate cause of extermination" than the former (also see Collins et al. 2011).

The only caribou in the assessment area are on the Kenai Peninsula.

By the early 1950s, biologists from the Kenai National Moose Range (now the Kenai National Wildlife Refuge) and the Alaska Game Commission (now the Department of Fish and Game) were considering the introduction of caribou to the peninsula. The first 15 caribou were captured from the Nelchina herd near Glenallen and released at an airstrip near the Chickaloon River in 1965 (Paul 2009). Another 29 caribou were inadvertently released at Watson Lake on the East Fork of the Moose River in 1966 after the transport vehicle broke down. These two translocations resulted in the establishment of the Kenai Mountain and Kenai Lowland herds, respectively. Additional releases of 80 caribou in 1985 and 1986 at Emma Lake, Green Lake, Tustumena Glacier Flats, and Caribou Lake eventually became the Killey (Twin Lakes) and Fox River herds (Paul 2009) (fig. 7-3).

The Kenai Mountain Herd ranges from 200 to 400 animals and currently numbers about 300. This herd occupies 907 km^2 in the Chickaloon River and Big Indian Creek drainages on the Kenai National Wildlife Refuge (GMU 15), and Resurrection Creek drainages on the Chugach National Forest east of the Sterling Highway (GMU 7).

The Killey River Herd currently numbers about 250 animals and occupies 778 km^2 in the upper Killey, Funny, and Skilak River drainages on the Kenai National

[6] **Palmer, L.J. 1938.** Management of moose on the Kenai Peninsula. Research Project Report, March, April, May 1938. Unpublished manuscript. On file with: Kenai National Wildlife Refuge, 1 Skihill Road, Soldotna, AK 99669. 40 p.

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Figure 7-3—Caribou were reintroduced to the Kenai Peninsula from the Nelchina herd in the 1960s and 1980s by the Alaska Department of Fish and Game and the U.S. Fish and Wildlife Service. The endemic Stone's caribou was extirpated from the peninsula circa 1912 by overharvesting and loss of habitat resulting from human-caused fires.

Wildlife Refuge (GMU 15). This herd once numbered more than 700 animals until three avalanches killed about 200 caribou during two winters in 2001–2003, representing about 20 percent of the caribou population on the Kenai Peninsula at that time.[7]

The Fox River Herd contains between 50 and 75 caribou. It occupies 130 km^2 south of the Tustumena Glacier in the Upper Fox River and Truli Creek drainages on the Kenai National Wildlife Refuge (GMU 15). This herd appears to be expanding its range eastward into the ice fields of Kenai Fjords National Park; small groups have been seen above Exit Glacier in recent years.

The Kenai Lowland herd numbers between 130 and 150 animals. This herd occupies 1425 km^2 in and around the communities of Kenai, Soldotna, and Sterling on the western side of the Kenai Peninsula (GMU 15). Of the four caribou herds

[7] **Ernst, R.D.; Spraker, T.; Hall, J.; Selinger, J. 2004.** Caribou killed by "unexpected predator"—avalanches. Presented at 10th North American Caribou Conference, Girdwood, Alaska.

recognized on the Kenai Peninsula, the Kenai Lowland herd is the only one that does not spend time feeding on lichens above treeline in the Kenai Mountains. Instead, this herd winters east of the Moose River, feeding on arboreal lichens that have regenerated in the spruce forests since the 1947 fire that burned 125 000 ha. In the latter part of May, cows from this herd calve near the Cook Inlet, from the Kenai Airport through the Kenai Flats and south toward Kasilof along Kalifornsky Beach Road. Domestic dogs and vehicle collisions are looming problems as the Kenai-Soldotna area becomes urbanized. As many as five caribou have been killed in a single vehicle incident on Bridge Access Road (Morton 2007).

The fewer than 1,000 caribou on the Kenai Peninsula continue to redistribute themselves. After the last releases of caribou in the 1980s, five distinct herds were established. By 2003, wildlife managers recognized that the Twin Lakes herd was comingling with the Killey River herd, and the two herds were combined for management purposes. In recent years, caribou groups have been observed more frequently in the Exit Glacier area of Kenai Fjords National Park, presumably from the Killey River herd. Also, in 2013, caribou groups were seen near Carter Lake and east of the Seward Highway in Turnagain Pass, presumably from the Kenai Mountain herd. Collectively, these observations suggest that caribou are continuing to spread eastward on the Kenai Peninsula, occupying (or re-occupying) alpine habitat, likely seeking new lichen forage.

The Kenai Mountain, Killey River, and Fox River herds are open to public hunting through the drawing system. The Kenai Mountain herd is also open to federal subsistence harvest. The Kenai Lowland herd has been closed to hunting since 1993. Current annual harvest from all three hunted herds is 20 to 30 animals.

Sitka Black-Tailed Deer: Current and Historical Distribution

Sitka black-tailed deer (fig. 7-4) are closely related to the larger Columbia black-tailed deer (*Odocoileus hemionus columbianus*) of the Pacific Northwest, and both are considered subspecies of the even larger mule deer (*Odocoileus hemionus*) of the American West (Wallmo 1978). Sitka black-tailed deer are native to the wet coastal rain forests of southeast Alaska and north-coastal British Columbia, from latitude 53° N to 58° N. They swim well and are found on all southeast islands except remote Forrester Island. An estimated 200,000 deer occupy southeast Alaska,[8] where deep snow keeps the number of deer on the mainland lower than on adjacent islands that generally accumulate lower snowpack (Klein 1965).

Sitka black-tailed deer are native to the wet coastal rain forests of southeast Alaska and north-coastal British Columbia, from latitude 53° N to 58° N.

[8] **Merriam, H.R. 1970.** Deer fluctuations in Alaska. Presented at Northwest Section of The Wildlife Society. Spokane, WA: 5 p.

Milo Burcham



Figure 7-4—Sitka black-tailed deer are not native to the assessment area. They were initially introduced to Prince William Sound from southeast Alaska by the Cordova Chamber of Commerce in 1916–1923. They are now harvested for both subsistence and recreational purposes in Game Management Unit 6, mostly on the Chugach National Forest. Deer have continued to expand their distribution and are likely to colonize the eastern Kenai Peninsula in coming years.

Sitka black-tailed deer densities on winter ranges have been estimated as high as 25 to 75 deer per square kilometer (Hanley 1984); population densities are highest in high-volume old-growth forest. Deer populations tend to fluctuate primarily in response to winter weather and to wolf and bear predation. During winter, the distribution of deer is influenced by changing snow depth. During extreme snow accumulation, deer congregate in old-growth forest stands with high canopy cover at lower elevations, and on beaches, where they consume intertidal species.

Deer have inhabited northern southeast Alaska since their migration from southern refugia following the Pleistocene (Klein 1965). The oldest deer bone in southeast Alaska was found on the west side of Heceta Island, dated at more than 8,000 years old (ADFG 2015). Deer likely moved northward up the coast as the glaciers receded and forest became established. Deer have occupied all islands of the Alexander Archipelago capable of supporting them, with the exception of remote Forrester Island, and occur on the mainland northwest of Juneau. The absence of

deer, except through human introduction, on the Queen Charlotte Islands likely results from the effectiveness of Hecate Strait as a dispersal barrier. Their access to favorable habitat in Prince William Sound and on Kodiak Island has been blocked by the exposed coastal area north of Cross Sound, where conditions are not suitable for their survival (Klein 1965).

Sitka black-tailed deer were introduced into the assessment area, where they have continued to disperse. The Cordova Chamber of Commerce introduced deer to Prince William Sound and North Gulf Coast (GMU 6), specifically 24 deer to Hawkins and Hinchinbrook Islands during 1916–1923 (Paul 2009) (fig. 7-1). Deer were introduced to Kodiak Island (GMU 8) in three transplants, totaling 25 deer, during 1924–1934. In 1930, two more deer were captured from Prince of Wales Island and released on Long Island. There was little natural movement from Long Island to Kodiak, so, in 1934, nine deer were captured in the Rocky Pass area near Petersburg and released on Kodiak. Deer were introduced to the Yakutat area in 1934 (Paul 2009).

The original 24 deer transplanted to Hinchinbrook and Hawkins Islands survived and flourished. Being good swimmers, Sitka black-tailed deer spread from these islands to the mainland and to other islands in Prince William Sound. Black-tailed deer now occupy most of GMU 6 (Harper 2013) with a population estimated to be about 20,000 animals in 2012 (Gibbins 2012). Legal hunting began in 1935 and, currently, about 2,000 deer are harvested annually in the Prince William Sound area (Harper 2013).

Although Hinchinbrook and Hawkins Islands are about 240 air kilometers from Anchorage, separated by mountain ranges, glaciers, rivers, inlets, and bays, the Alaska Department of Fish and Game received reports of deer in mountain passes during the 1990s. Since 2002, a few deer, including both bucks and does, are seen in Anchorage, in the Portage and Placer river drainages, and along Turnagain Arm (Peninsula Clarion 2003). In recent years, black-tailed deer have also been seen infrequently on the Kenai Peninsula near Seward.

Future Distributions

Over the next 50 years, moose, caribou and Sitka black-tailed deer populations will persist in the assessment area, although their distributions and abundance will vary in response to changing vegetation, fire regimes, and snow dynamics. The most salient of the anticipated long-term impacts include afforestation of alpine tundra, primarily by mountain hemlock (*Tsuga mertensiana*); deforestation of the southwestern Kenai Peninsula (see chapter 6); and afforestation and reduced snow depth along the Prince William Sound coastline (chapter 3). In general, deer and

moose should respond favorably to predicted changes along Prince William Sound. Black-tailed deer in particular will likely continue their westward colonization onto the Kenai Peninsula, with contemporary climate warming (including reduced snowfall) only accelerating that dispersal. Moose distribution will likely decline in response to grassland conversion on the southern Kenai Peninsula, but their abundance will likely increase in the near term as black spruce forests in the Kenai lowlands approach the historical mean fire-return interval. The Kenai Peninsula has already lost about 121 000 ha of alpine tundra over the past 50 years to treeline rise (derived from Dial et al. 2007). Consequently, the abundance of caribou will almost certainly decline and their genetic diversity likely reduced (Yannic et al. 2013) over the long term in response to alpine afforestation. These changes in land cover and snow dynamics are incorporated into the following climate envelope modeling used to develop scenarios for future distributions of the three ungulate species.

The abundance of caribou will almost certainly decline and their genetic diversity likely reduced.

Regional Ecological Niche Models for 2009 Versus 2069 (Decades)

This model effort predicts the potential ecological niche for moose, caribou, and Sitka black-tailed deer on the assessment area. This niche is modeled from the best publicly available distribution data for each species in Alaska. The algorithms used are from the machine learning family, which are high-performing models for visualizing relationships (TreeNet; i.e., boosting) and for prediction of species distribution (RandomForest; i.e., bagging) (Craig and Huettmann 2009, Lawler et al. 2011).

Distribution data for all three ungulate species were generally of poor quality or spatially incomplete within the assessment area. Consequently, models were based on statewide distributions and then clipped for the assessment area. For moose, we compared the year-round presence points from the Gap Analysis Program (GAP) (http://akgap.uaa.alaska.edu/) with pseudo-absence points for all of Alaska (fig. 7-5A). For caribou, we used the year-round presence polygons in Alaska, and subsampled them for presence points (in polygons) and absence points (outside of the polygons; fig. 7-6A). For Sitka black-tailed deer, we used the known year-round range maps from the Alaska GAP, and subsampled them for presence points (inside of the polygons) and absence points (outside of the polygons) in the study area (fig. 7-7A). For all three species models, we chose to average data by decade to increase the robustness of the climate signal.

The key elements of this approach are the use of available species location data in Alaska (1971–2000), high-resolution environmental GIS layers (table 7-1), and high-performance modeling algorithms, resulting in model predictions for species

Table 7-1—Environmental predictors used as geographic information system layers in ArcGIS™ for modeling current and future potential distributions of moose, caribou and Sitka black-tailed deer

Data set number	Dataset name	Units	Time period (decadal)	Pixel size	Source
1	Elevation	Meters	Constant	60 m	AK GAP
2	Slope	Degrees	Constant	60 m	AK GAP
3	Aspect	Degrees	Constant	60 m	AK GAP
4	Temperature July	Degrees Celsius	2010, 2069 (A2)	2 km	SNAP PRISM
5	Temperature January	Degrees Celsius	2010, 2069 (A2)	2 km	SNAP PRISM
6	Precipitation July	Millimeters	2010, 2069 (A2)	2 km	SNAP PRISM
7	Precipitation January	Millimeters	2010, 2069 (A2)	2 km	SNAP PRISM
8	Distance to coast	Meters	Constant	60 km	AK GAP
9	Maximum 1 April snow equivalent	Index of snow depth	2010, 2049 (A2)	2 km	J. Little
10	NLDC (rescaled)	Landcover class	2010, 2069 (A2)	2 km	D. Magness

distributions for the present (2000–2009) and future (2060–2069). Despite good model performance, the models are limited in several important ways: spatially incomplete location data, particularly for the assessment area, to inform, train and test the models; lack of relevant high-quality environmental GIS layers for the assessment area such as fine-grain vegetation layers; and poor snow-cover data for Alaska.

However, the models illustrating current distribution appear to adequately explain general trends, and reflect the potential ecological niche for the three ungulates (figs. 7-5 through 7-7). These models show a high prediction accuracy (AUC >92 percent) based on the potential ecological niche. As expected, the potential niches of Sitka black-tailed deer and moose in the assessment area were much greater than extant distributions. As discussed earlier, the historical (natural) distributions of both species were constrained by topographic and glacial barriers in the post-Pleistocene landscape, whereas the current distributions are an artifact of translocations by humans and subsequent dispersal. Consequently, the realized distributions of both species are geographically small subsets of their potential distributions.

At broad spatial extents, caribou and black-tailed deer do not overlap in either realized or potential distributions; caribou are constrained to the western side of the Kenai Peninsula, whereas black-tailed deer tend to occupy all other areas of the assessment area. At finer grains, more characteristic of habitats, caribou tend to prefer alpine tundra, whereas black-tailed deer prefer forests, although the former will feed on arboreal lichens within mature forests during winter. Moose are widely but patchily distributed over the assessment area, sympatric with deer in coastal areas and with caribou on the western Kenai Peninsula.

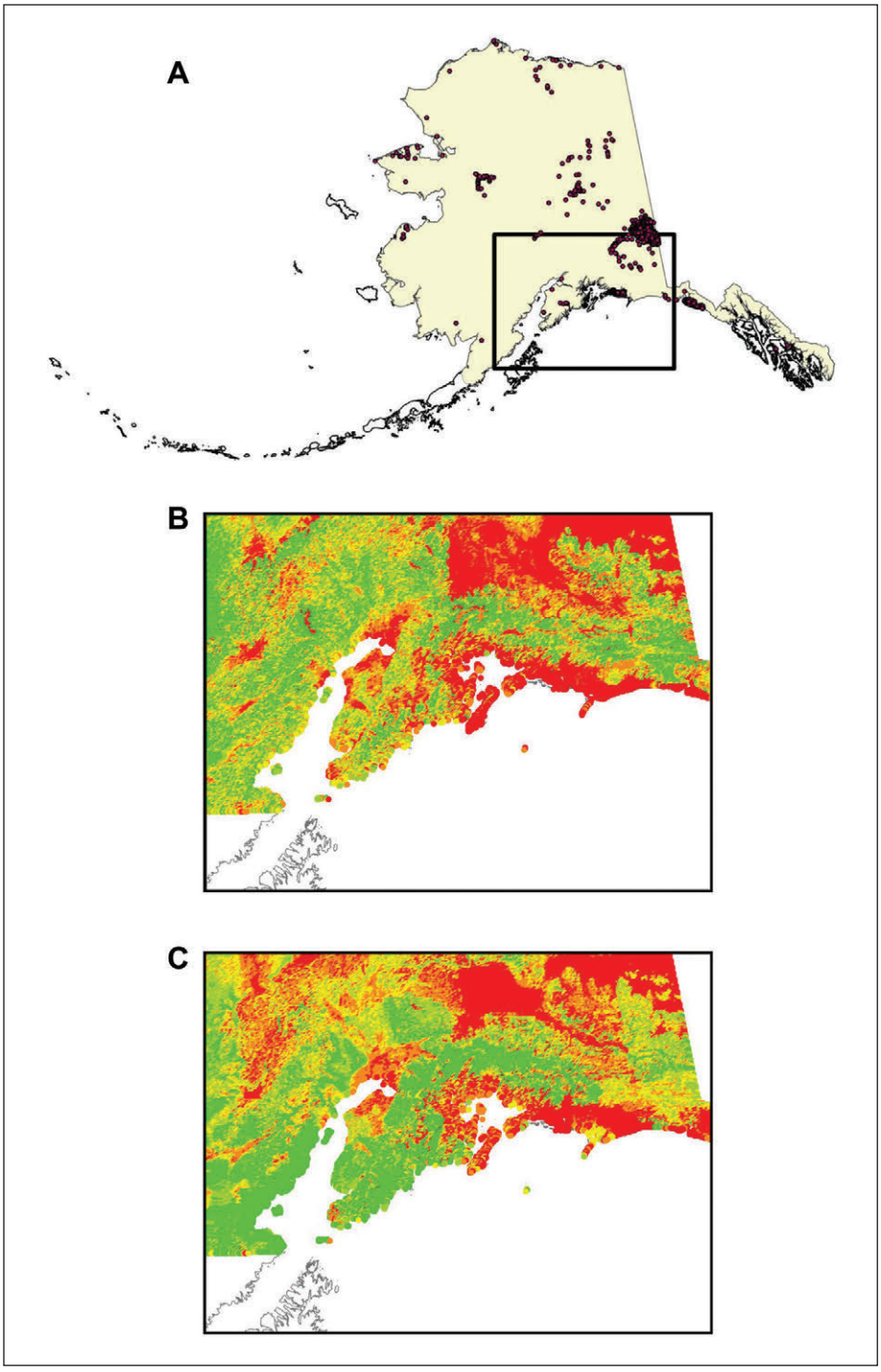


Figure 7-5—Current and future distributions of moose: (A) Training data for statewide distribution of moose from the Alaska Gap Analysis Program (http://akgap.uaa.alaska.edu), (B) modeled potential moose distribution on the assessment area in 2000–2009, and (C) modeled potential moose distribution of the assessment area in 2060–2069. Colors reflect the likelihood of occurrence (0–1) ranging from green (absent) to yellow to orange to red (present) as generated by Random Forest™ for the decadal means.

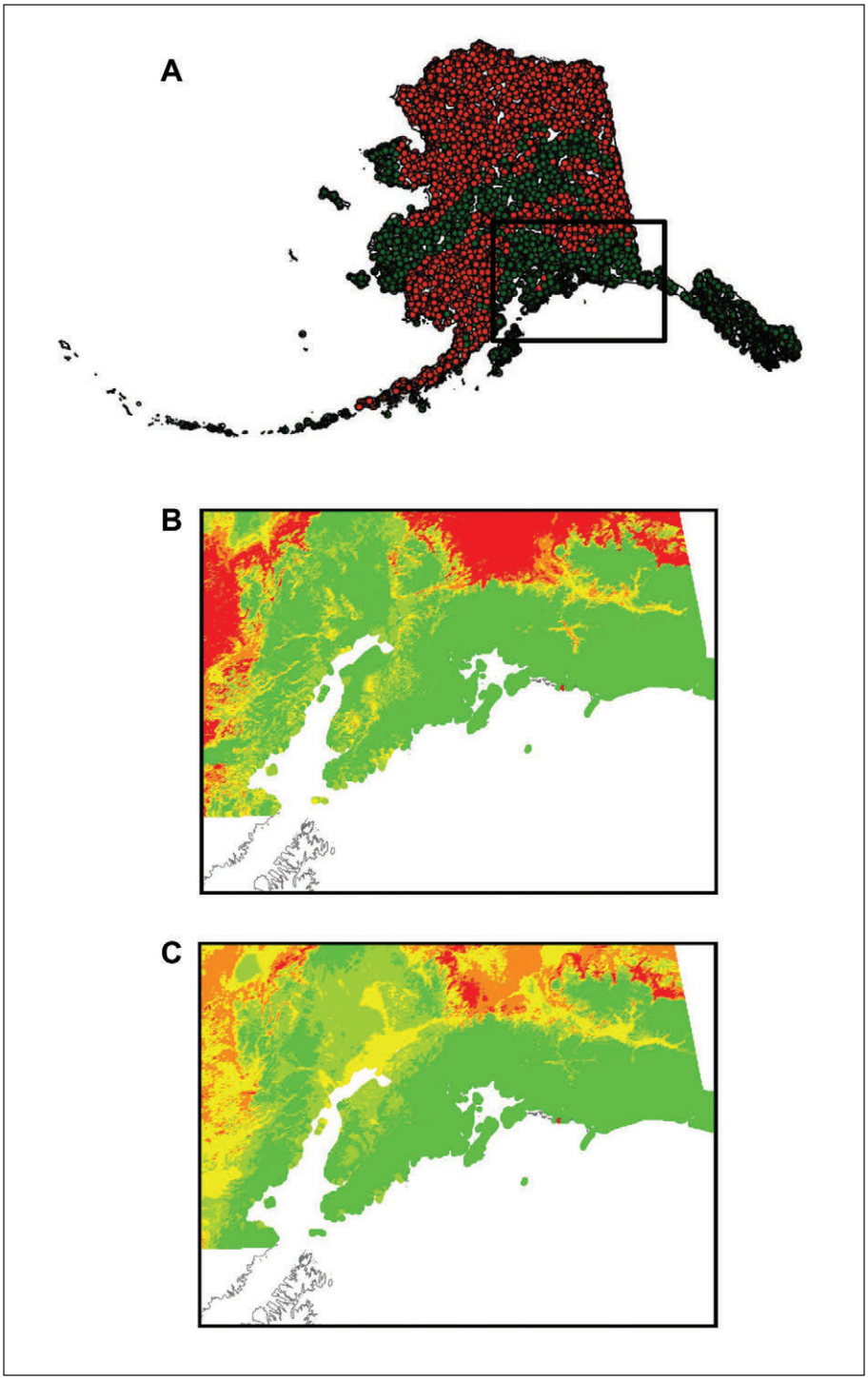


Figure 7-6—Current and future distributions of caribou: (A) Training data for statewide distribution of caribou from the Alaska Gap Analysis Program (http://akgap.uaa.alaska.edu), (B) modeled potential caribou distribution on the assessment area in 2000–2009, and (C) modeled potential caribou distribution of the assessment area in 2060–2069. Colors reflect the likelihood of occurrence (0–1) ranging from green (absent) to yellow to orange to red (present) as generated by Random Forest™ for the decadal means.

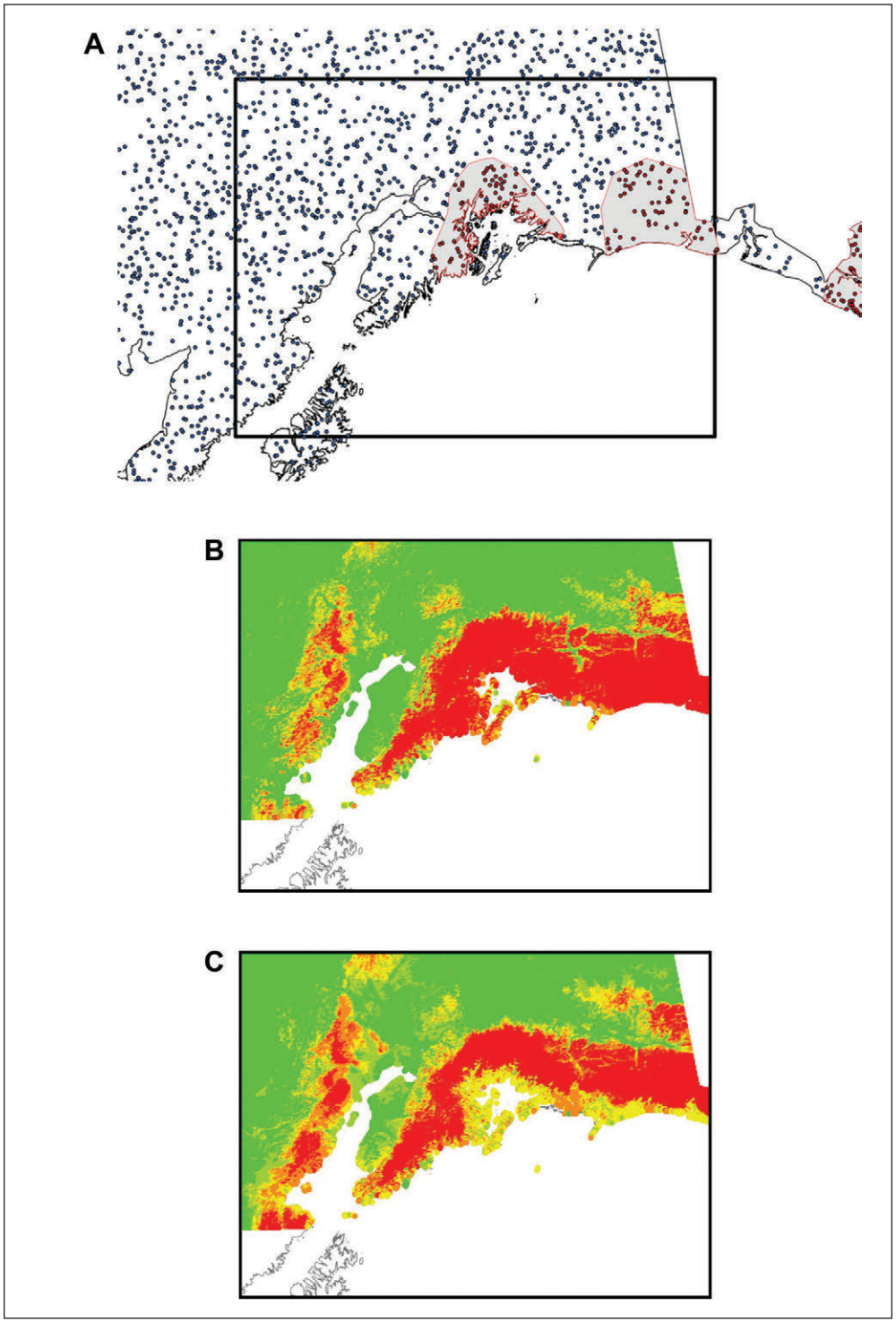


Figure 7-7—Current and future distributions of Sitka black-tailed deer: (A) Training data for regional distribution of deer from the Alaska Gap Analysis Program (http://akgap.uaa.alaska.edu), (B) modeled potential Sitka black-tailed deer distribution on the assessment area in 2000–2009, and (C) modeled potential Sitka black-tailed deer distribution of the assessment area in 2060–2069. Colors reflect the likelihood of occurrence (0–1) ranging from green (absent) to yellow to orange to red (present) as generated by Random Forest™ for the decadal means.

Five decades from now (circa 2069), these climate envelope models generally suggest diminishing ecological niches within the assessment area, resulting in range shifts for all three species, usually northward and toward higher elevations. This redistribution pattern translates to shifts inland, away from the coast, particularly for moose and deer. Despite modeling that suggests diminishing potential distributions resulting from contemporary climate warming, it seems likely that the realized distributions of moose and deer will be more sympatric in the future owing to their continued dispersal in the aftermath of 20th-century introductions to Prince William Sound.

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Proximate Drivers of Future Distributions

Future distributions of moose, caribou, and Sitka black-tailed deer, and particularly their local-scale population abundances, will be mediated by mechanistic ecological interactions involving vegetation disturbance, predators, competitors, and disease. For example, ecological disturbances (e.g., fire and insects; table 7-2) will influence forage, cover, and predation. Also, as these three species continue to disperse and more fully occupy the assessment area (i.e., their realized distribution), competitive interactions are likely between moose and deer, and between moose and caribou. Diseases transmitted among species or moving northward could also influence populations.

Moose—
Moose distribution is likely to expand in response to forecasted afforestation of coastal areas and alpine tundra in the assessment area, as these will be early successional, albeit not necessarily hardwood. LeResche et al. (1974) suggested that four macrohabitats were used by moose in Alaska: climax communities dominated by upland willow or birch; lowland bog; and seral communities created by fire and by glacial or fluvial actions. Fires that are hot enough to burn to mineral soil in boreal Alaska, such as on the western Kenai Peninsula where black and white spruce predominate, generally convert conifer stands to hardwood (Miner 2000). Good moose habitat occurs for 15 to 25 years after these mineral soil-exposing fires (Miner 2000). Hundertmark (2007) found that, between 40° and 60° N latitude, mean sizes of winter and summer home ranges of moose in 13 studies remained relatively stable at 51 $km^{2.}$ However, in the Yakutat forest in southeast Alaska, mean annual home range size was 76 km^2 for females and 125 km^2 for males (Oehlers et al. 2011), presumably because of relatively poorer browse availability in the coastal rain forest than in fire-dominated boreal systems. Future moose abundance in the assessment area will likely be driven by the distribution of these habitats and their interaction with changing rates of fire and other disturbances.

Anticipated changes in climate are likely to increase the frequency and extent of fire on the western Kenai Peninsula (see chapter 6), at least in the near term. The official start of the Alaska fire season was changed in 2006 from May 1 to April 1, largely because of the increasing threat of "pre-green up" grassland fires in the aftermath of the spruce bark beetle outbreak on the Kenai Peninsula combined with earlier snowmelt. The year before, in 2005, the Tracy Avenue Fire near Homer started on April 29, burning 2185 ha in what was described by the Division of Forestry's director as the "earliest large complex fire in the state's history." This and other spring fires since then were human-caused, and were started in grasslands composed primarily of bluejoint (*Calamagrostis canadensis*). This is a significant departure from fire records kept over the previous half century that show mostly lightning-caused fires started in spruce forests in mid or late summer. Radiocarbon-dated soil charcoal and tree-ring counts show that not all spruce on the western Kenai Peninsula burns with the same frequency (Berg and Anderson 2006). On the Kenai lowlands, where black spruce predominates, a given acre has historically burned every 80 years, a statistic called the mean fire-return interval (MRI). In the southern part of the Kenai National Wildlife Refuge, where white and Lutz spruce predominate, the MRI is 400 to 600 years. The MRI for white and black spruce stands mixed with hardwood is 130 years. Sitka spruce, on the eastern side of the peninsula, has essentially no MRI because of the wet climate there.

Understanding the MRI helps us understand the distribution of moose populations. Spruce stands convert to hardwood when fires are hot enough to burn to mineral soil, and moose favor these stands for winter browse 15 to 25 years post-fire. But fires and the vegetation response to fires are changing. Roughly 50 percent of every acre burned in spruce on the western Kenai Peninsula has been converted to hardwood in the past century. However, in the aftermath of the longest spruce bark beetle outbreak in North America, not all spruce is regenerating back to spruce or converting to hardwood. Much of what was mature white and Lutz spruce forest on the southern peninsula is now bluejoint grasslands with few spruce seedlings. This has prompted federal, state, and local fire management agencies in the Kenai Peninsula Borough to evaluate different treatments for reducing bluejoint in the wildland-urban interface (Oja et al. 2004). Consistent with climate-envelope models that suggest deforestation on parts of the Kenai (see chapter 6), these spring fires may be a mechanism by which a novel grassland ecosystem is maintained in what was previously transitional boreal forest. The long-term consequence will likely be reduced moose densities.

Under future warming scenarios, moose in the assessment area may also experience physiological stress. For example, moose in boreal Minnesota, on the extreme

southern edge of this species' range in central North America, have declined since their numbers peaked in 1984, coinciding with increased temperatures in September and March that resulted in lower reproductive rates and poorer body condition owing to heat stress (Murray et al. 2006). Murray et al. (2006) concluded that in areas where climate and habitat conditions are marginal, especially where deer act as hosts for parasites, moose populations will likely not persist; these are conditions that may occur on the assessment area in the future (see discussion below on disease).

Caribou—
Caribou habitat in the assessment area is anticipated to decrease, primarily in response to treeline encroachment into alpine tundra. This rate of treeline rise is expected to exceed land exposed from deglaciation (and its subsequent colonization by lichens). The distribution of caribou is ultimately constrained by the need for animals to escape or find relief from flying insects in the summer and to find food through deep snow or in old forest in the winter (Bergerud 1978). The winter survival of caribou populations living in subarctic or northern taiga areas depends on the availability of lichen, mostly reindeer lichen (*Cladina* spp.), which is their preferred forage (Bergerud 1978, Helle and Aspi 1983, Paez 1991). Lichen forage is constrained by its slow growth rate and by snow that may reduce its availability. The only other large mammal that may compete with caribou on the Kenai Peninsula is the Dall sheep (*Ovis dalli dalli*), though the latter prefers graminoids rather than lichens.

There is some anecdotal evidence to suggest that the Kenai Mountain and Killey River herds may be dispersing further eastward in the Kenai Mountains, but likely in response to declining lichen forage. Although warmer winter temperatures and reduced snow depths may benefit caribou, the former will likely increase avalanche rates. Three avalanches over a 2-year period in 2002–2003 killed about 200 caribou in the Killey River herd, representing 20 percent of all caribou on the Kenai Peninsula at that time; this may have been random chance or a harbinger of winters to come (Ernst et al. 2004).

Sitka black-tailed deer—
Even without invoking contemporary climate change, Sitka black-tailed deer are likely to continue expanding their range throughout the Sitka-spruce-dominated coastal rain forest. The introduction of deer to Prince William Sound by humans in contemporary times appears to have accelerated what would have been its "natural" northward expansion from southeast Alaska post-Pleistocene. Recent reports of deer near Seward suggest that they are likely to spread throughout the eastern Kenai Peninsula.

Even without invoking contemporary climate change, Sitka black-tailed deer are likely to continue expanding their range throughout the Sitka-spruce-dominated coastal rain forest.

Snow depth and its interaction with canopy cover appear to be the ultimate driver of Sitka black-tailed deer distribution in the assessment area (Parker et al. 1999). Moose and deer are not likely to be direct competitors, as the former is adapted to deep snow and the latter is constrained by deep snow during winter. Moose appear to be better adapted to foraging on hardwood and woody shrub browse during winter. In contrast, black-tailed deer forage on evergreen forbs and arboreal lichens during winter, and only switch to woody browse such as blueberry (*Vaccinium* spp.) and hemlock when snow is deep (Hanley et al. 2012). This browse alone, however, offers inadequate nutrition, and deer rapidly deplete their energy reserves when restricted to such a limited diet. Unlike grazers such as Dall sheep, black-tail deer rarely eat grass. Reductions in snow cover and expansion of snow-free periods at low elevations will generally favor improved deer habitat (see chapter 3 for snow patterns) contributing to expansion of deer distribution, certainly along Prince William Sound.

Climate Effects on Wildlife Diseases

In general, climate affects the health of animals either directly (e.g., thermal-neutral zone, heat stress) or, more often, indirectly by influencing the agents, vectors, and ecosystems with which animals live and interact (Greifenhagen and Noland 2003, Hueffer et al. 2013, Kutz et al. 2012, Murray et al. 2006). The responses of disease agents to specific climate changes are difficult to predict. Multiple, differential population changes may be reflected in changing biotic-abiotic interactions; i.e., a change in the organization of the ecosystem itself. Many disease agents, indeed most of concern under conditions of climate change, are protean, meaning they can infect multiple species (Greifenhagen and Noland 2003).

Wildlife diseases can be transmitted directly from animal to animal, or indirectly through vectors. Diseases that are directly transmitted include influenza, rabies, canine distemper, tuberculosis, brucellosis, and chronic wasting disease. The latter two diseases are of particular concern to moose, caribou, and Sitka black-tailed deer, particularly as their distributions expand over the assessment area. Darimont et al. (2005), in discussing range expansion by moose into coastal areas of British Columbia, suggested that there may be ecological consequences such as transmission of disease to native black-tailed deer. Clearly the reverse is possible as well: Sitka black-tailed deer that were introduced to Prince William Sound continue to expand into habitats currently occupied by both indigenous and introduced moose populations.

Brucellosis is a bacterial disease that can be spread from contact with livestock, and can cause weight loss, loss of young, infertility, and lameness in wild cervids.

In Alaska, *Brucella suis* is known to occur in both caribou and moose populations (Heffer et al. 2013), but is still not known to occur on the Kenai Peninsula.[9] However, horses, llamas, alpacas, and even goats have been used by humans in recent years to pack gear into the backcountry on the Kenai Peninsula, thereby providing a mechanism to spread *Brucella abortus* and *B. melitensis* known to occur in livestock. Hueffer et al. (2013) reported that brucellosis in humans has been linked to the consumption or processing of raw caribou meat, and infection has been shown to be endemic in many caribou and reindeer herds across Alaska and northern Canada. They suggest that a warming climate may increase the likelihood that Brucella spp. will be transmitted to subsistence user groups in Alaska.

Chronic wasting disease (CWD) is caused by prions (nonliving protein infectious particles). The most obvious and consistent clinical sign of CWD is weight loss over time, hence the name "chronic wasting." Behavioral changes also occur in most cases, including listlessness, lowering of the head, droopy ears, stumbling or tremors, and a smell like rotting meat. Once an animal starts manifesting signs of CWD, it may be only weeks or months before death. This disease was first documented in captive mule deer at a Colorado research facility in 1967, but, by 1981, it was detected in free-ranging mule deer and elk (*Cervus canadensis*) populations in nearby Rocky Mountain National Park. By 2002, CWD had moved eastward to white-tailed deer (*Odocoileus virginianus*) in Wisconsin; by 2011, it was detected on the east coast. It is now known to infect wild populations of elk, mule deer, white-tailed deer, black-tailed deer, and moose. Currently, CWD does not occur in Alaska; however, CWD was confirmed in a road-killed moose from southern Alberta in 2013, the first time that moose tested positive for CWD in Canada.

Vectorborne diseases possess a vector stage, usually associated with an insect, acarid, mollusk, or crustacean. Each of these is poikilothermic (cold-blooded) and is therefore especially sensitive to changes in climatic variables, especially temperature and humidity. Disease-causing agents and their vectors are strongly affected by weather. Many adult insect vectors and the agents they carry are killed by low winter temperatures, so that cycles of disease transmission are interrupted and need to be restarted in spring (Greifenhagen and Noland 2003). Consequently, warmer winters can increase survivorship and therefore range expansion of insect vectors, particularly those that cause arboviral infections. These include mosquitoes (responsible for western equine encephalitis, snowshoe hare virus, and West Nile virus); Culicoides or biting midges (bluetongue virus and epizootic hemorrhagic

[9] **Butler, E.A. 2006.** Diseases found on the Kenai National Wildlife Refuge with recommendations for screening and investigations. Unpublished report. 98 p. On file with: Kenai National Wildlife Refuge, 1 Ski Hill Rd., Soldotna, AK 99669-2139.

disease virus); and ticks. The most likely novel insect vectors for vectorborne diseases with the potential to kill ungulates in the near term are winter tick (*Dermacentor albipictus*) and meningeal worm (*Parelaphostrongylus tenuis*).

Winter ticks feed on ungulates, including moose and caribou. In more severe cases, associated with substantial blood and hair loss and distraction from eating, animals starve to death, especially in winter. Winter tick survival rather than moose density is probably the major determining factor for outbreaks of severe disease. Adult tick survival is enhanced by warm temperatures, low precipitation, and absence of snow cover in April. Although winter ticks have not been found in Alaska, increasing temperatures associated with a warming climate and the occurrence of winter ticks in the Yukon Territory beginning in the 1980s and in the Northwest Territories in the 2000s suggest that introduction of this ectoparasite to the assessment area is likely.

Moose have declined in many parts of the eastern United States because of meningeal worm, a neurological disease that can be fatal in moose. The white-tailed deer is the usual host of this parasitic nematode, and neither is currently known to occur in Alaska. Adult meningeal worms live as long threadlike worms in the veins and venous sinuses of the cranial meninges of white-tailed deer. Eggs pass to the heart and then lungs, then are coughed up, swallowed, and passed into the environment. Larvae are picked up by slugs and snails, and deer become reinfected when they incidentally ingest gastropods while foraging. Although meningeal worms do not cause serious disease in deer, they can cause severe neurological illness in some species such as moose. Moose sickness (meningeal worm infection) has been associated with severe moose population declines in New Brunswick, Nova Scotia, Maine, and Minnesota (Murray et al. 2006). Warmer summers and lengthening of the frost-free period in autumn will likely result in more infections and higher doses of worms per infection. Moose and deer can co-exist sympatrically, albeit at lower densities (Schmitz and Nudds 1994). In contrast, Murray et al. (2006) cautioned that moose will be extirpated where climate and habitat conditions are marginal and where deer are abundant and act as reservoir hosts for parasites. The concern for ungulates in the assessment area is that meningeal worm may ultimately spread to Sitka black-tailed deer. A different species of meningeal worm, *P. odocoilei*, has been found in Columbia black-tailed deer in Oregon, as well as in woodland caribou, mountain goat (*Oreamnos americanus*) and Dall sheep in Alaska and Canada (Mortenson et al. 2006).

Other diseases known to exist in the assessment area that could affect moose populations include hemorrhagic disease (the result of bluetongue virus or epizootic hemorrhagic virus), bovine viral diarrhea virus, infectious bovine rhinotracheitis,

parainfluenza virus, contagious ecthyma virus, *Coxiella burnetii*, *Leptospira interrogans*, *Echinococcosis* sp., and malignant catarrhal fever virus (Butler 2006).

Conclusion

Moose and Sitka black-tailed deer occur in much of the assessment area as a result of human introductions into Prince William Sound over the past century. Similarly, caribou were re-introduced to the Kenai Peninsula during this same period after being extirpated at the start of the 20th century (circa 1913) (Paul 2009). Assuming no significant change in proximate drivers (table 7-2), caribou populations are expected to persist in the Kenai Mountains, albeit with a decrease in distribution and abundance in the foreseeable future. Moose and black-tailed deer are expected to continue colonizing the assessment area regardless of contemporary climate change. A warming climate is expected to accelerate this process in the near term, but the expected introduction of novel pathogens hosted by both species is likely to negatively affect moose abundance. Indeed, in the longer term, anticipating the demographics of these three species becomes highly problematic because of the uncertainty of how ecological drivers and landscape change may interact in the future (table 7-2).

In the longer term, anticipating the demographics of these three species becomes highly problematic because of the uncertainty of how ecological drivers and landscape change may interact in the future.

Table 7-2—Likely responses of three ungulate species to anticipated changes on the Chugach-Kenai Peninsula assessment area over the next 50 years

	Moose (n ~ 10,000)		Caribou (n ~ 1,000)		Sitka black-tailed deer (n ~ 20,000)	
Change	**Distribution**	**Abundance**	**Distribution**	**Abundance**	**Distribution**	**Abundance**
Best guess (assumes no unexpected change in mechanistic drivers)	-	+	-	-	+	+
Higher temperatures	?	?	?	?	?	?
Glacial retreat	0	0	+	0	0	-
Decreased snow depth (particularly at lower elevations)	-	-	0	+	+	+
Increased fire frequency and intensity on western Kenai Peninsula	+	+	0	-	0	0
Increased activity of spruce bark beetle and other forest defoliators	?	?	0	-	?	?
Afforestation of alpine tundra	+	+	-	-	+	0
Deforestation of southwest Kenai Peninsula	-	-	0	0	0	0
Afforestation of coastline	+	?	0	0	+	+
Increased richness and abundance of terrestrial exotic invasive plants	?	?	0	-	?	?
New wildlife diseases (brucellosis, chronic wasting disease, winter tick, meningeal worm)	0	-	0	-	0	-

Responses: + = increase; - = decrease; ? = uncertain; 0 = no change.

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Greg Hayward



A backcountry skier enjoys stark vistas and the winter light of January in the high mountains of south-central Alaska.

Chapter 8: Conclusion

Gregory D. Hayward[1]

This assessment highlights a subset of changes in socioeconomic and biophysical conditions expected to occur in the Chugach National Forest/Kenai Peninsula region as a consequence of a warming climate. Accordingly, we provide scenarios to stimulate consideration of these future conditions, so that resource users and managers can imagine new ecological and social conditions and prepare to adapt. However, the assessment also demonstrates several broader principles independent of the specific ecological and social trajectories of south-central Alaska. These broad messages emerge from other assessments but are worthy of note because they provide a useful generalized framework for evaluating climate change. This framework may be valuable when one is considering resource management and other social responses. First, this assessment illustrates the relationship between global patterns of climate change and local responses; it demonstrates that context matters. Second, the assessment shows the value of taming the firehose of information on climate change by considering a subset of resource conditions. To help set priorities for action, it acknowledges the limitations of human focus and the value of narrowing the conversation. Finally, by evaluating potential changes in the short term and honestly acknowledging the significant uncertainty in long-term scenarios, the assessment indirectly highlights the ultimate value of reducing the driver of climate change—emissions of greenhouse gasses—to address long-term risks.

Context Matters

Rapid directional climate change resulting from human activities is a global phenomenon (chapter 1). Scientific analyses and public media both provide a continuous stream of examples illustrating the consequences of a warming planet on social systems, culture, and the environment. Thoughtful evaluations of future social, economic, and environmental conditions describe unsettling challenges (e.g., Bergoglio 2015, IPCC 2014). Sea-level rise, dramatic changes in native vegetation, shifts in the distribution of flora and fauna, and changes in major disturbance agents such as floods, hurricanes, and wildfire all appear to be universal outcomes that many people recognize as global consequences of climate change. Awareness is growing that, in the desert southwest, a combination of invasive species and altered disturbance regimes are converting old pinyon-pine forests to annual grasslands (Romme et al 2012, Spotts 2013), and that sea-level rise in coastal regions of Virginia and Florida threatens highly productive estuaries as well as the infrastructure of cities

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and military installations (Gillis 2014). Alaska is recognized as experiencing some of the most dramatic environmental change. Readers of the New York Times and other media hear of permafrost melting and the resulting damage to buildings, of coastal erosion threatening villages, and of increased peatland fires (e.g., Gillis 2011, Hirschfeld Davis 2015).

Just as resource management is geographically, ecologically, and socially context-specific, the scenarios described in this report demonstrate the importance of place.

Although broad awareness and alarm has developed regarding climate-induced global challenges, our assessment communicates a humble but important message: through example, it demonstrates the critical importance of context in determining the local outcomes of climate change. Just as resource management is geographically, ecologically, and socially context-specific, the scenarios described in this report demonstrate the importance of place. They show how the unique characteristics of the Chugach/Kenai region will result in social and biophysical outcomes that differ significantly from other locations in Alaska and across the globe.

Many of the catastrophic changes to ecological and social systems expected in other regions during the next 30 years are not anticipated in the assessment area. Although sea-level rise across the globe alters ecological systems and threatens economies, the effective sea level in the assessment area will change little because of isostatic rebound—the uplifting of the land following the melting of glaciers (see chapters 1 and 4). Although shrub systems are invading large portions of the Arctic (Sturm 2001), and desertification in North Africa robs large populations of food crops (Verdin 2005), the vast coastal rain forest in the assessment area will likely support productive rain forest far into the future. Although salmon stocks in the Columbia River basin are experiencing multiple threats from climate change (e.g., Isaak 2012), freshwater systems that support salmon reproduction in the assessment area are currently intact and diverse. Their significant resilience will likely continue to support the freshwater life history of robust salmon populations.

Local conditions that buffer the negative consequences of changing climate for certain biophysical and social features also contribute to potential negative consequences—again, local context matters. Anchorage, the largest city in Alaska, is located in the northwest corner of the assessment area, and for decades the Kenai Peninsula has experienced some of Alaska's highest rates of population increase. Tourism and recreation are major features of the regional economy, including summer cruise ship traffic and winter sports that exploit what once was a dependably deep snowpack. The rugged Chugach and Kenai Mountains attract summer visitors viewing dramatic glacier-centered vistas, as well as heli-skiers in winter. Snowmachine enthusiasts and others enjoy miles of alpine and subalpine snow-covered mountain slopes. Both the glaciers and snowpack, features intimately associated with the region's tourism and recreation, are changing rapidly in response to a

warming climate (see chapter 3, "Snow and Ice"). Cancellation of the ceremonial start of the Iditarod dogsled race in 2015 for lack of snow, and ubiquitous photos of glaciers in cruise ship advertisements, demonstrate the importance of glaciers and snowpack but also the vulnerability of local economies and social activities to changes in these physical features (O'Neel et al. 2015). The coastal location of the assessment area, in a region that often experiences winter temperatures near freezing, results in high vulnerability of the snowpack. The context of the assessment area—its geography (e.g., a wet coastal climate with high mountains) and its social environment (high human population oriented toward snow and glacier tourism)—result in particular vulnerabilities described in previous chapters.

While local conditions (social, physical, ecological) will largely determine the outcomes from a changing climate, changes in neighboring regions and global conditions will also be important for some elements of the assessment area. Salmon provide a striking example. Although glacier systems and mountain environments (which include high-elevation snowpack) will buffer changes in many freshwater systems of the region, salmon populations will also respond to changes in ocean conditions across extensive portions of the north Pacific. Ocean surface temperatures, pH, and food webs will determine growth and survival of adult salmon and the characteristics of stocks returning to the assessment area's largely intact freshwater systems (e.g., Abdul-Aziz et al. 2011, Mathis et al. 2014). Likewise, global fish markets and global tourism (sport fishing) will influence local salmon harvest and demand for local fish, with cascading consequences for salmon populations and the economic role of salmon in the region. Similarly, interregional and global processes influence coastal environments in the assessment area, demonstrating the interaction of local and global conditions. Freshwater input from glaciers in southeast Alaska is largely responsible for the Alaska Coastal Current, which interacts with Prince William Sound to affect marine chemistry and biota (e.g., O'Neel et al. 2014). The vast migration of waterfowl using the Copper River Delta and other stopover spots throughout the assessment area is supported by processes in the Arctic and subarctic breeding grounds and distant wintering areas (chapter 4). These represent just a few of the many interactions between local and global conditions that determine outcomes experienced in the Chugach/Kenai assessment area. Hence, while local context is critical for envisioning potential futures, regional and local processes must be integrated into scenarios for some elements as demonstrated by our assessment.

Ultimately, this vulnerability assessment and the scenarios offered represent a set of potential futures offered to stimulate deeper consideration of the consequences of climate change for social, cultural, and environmental systems in the

The value of this assessment rests in the extent to which it provides vision and opens the imagination to potential change.

Chugach/Kenai region. None of the scenarios offered here—climatic, social or biophysical—is likely to be experienced as described in the assessment. This is not a failing of the assessment but rather the reality of characterizing an exceptionally complex future. The value of the assessment rests in the extent to which it provides vision and opens the imagination to potential change. The assessment serves its purpose if it stimulates resource users, policymakers, and resource professionals to begin carefully considering actions that are appropriate in light of rapidly changing climate. The assessment highlights topics motivating grave concern in other locations that need not motivate immediate action in the short-term in this region, such as significant changes in coastal rain forest or sea-level rise. It also highlights elements of the system that invite attention—changes in snowpack, alpine environments, or fire in the western Kenai, to name just three.

Taming the Firehose

Vulnerability assessments provide a mechanism to manage the abundance of information regarding climate change for a particular region and focus attention on a subset of the plethora of changes taking place globally. The flood of information on climate change is drowning policymakers, resource management practitioners, and the public. A vulnerability assessment focuses attention and synthesizes current understanding. If considered carefully, the synthesis can be used to begin setting priorities for adaptation and create a common language among partners crafting adaptation actions. Multi-organization collaborations should begin by deciding what actions not to pursue and where to focus common attention. We suggest that this assessment be employed to initiate that collaborative process.

Adaptation and Greenhouse-Gas Emissions

In response to the opportunity for prioritizing management actions toward various social or biophysical elements affected by climate change that are motivated by this assessment, I wish to highlight an emergent message. Doing so requires brief consideration of the temporal scope of the assessment, which examines relatively short-term futures. We chose not to consider a longer time horizon for three reasons. First, to provide a focused treatment of the most important current management considerations, the scope was purposefully limited to a small set of topics. In that spirit, we also chose to limit the temporal extent. Second, the assessment was motivated, in part, by forest plan revision on the Chugach National Forest. Examining change in the next 30 to 50 years served that effort. Finally, and more importantly, careful consideration of uncertainty further confirmed consideration of

a 30- to 50-year climatology rather than longer term scenarios. Considering long-term change requires a projection window that extends beyond 2060, when uncertainty regarding emissions scenarios (release of greenhouse gasses) exceeds model uncertainty, and potential biophysical consequences become highly uncertain.

The resulting short-term scope of the assessment provides an opportunity to motivate constructive dialogue to establish priorities for climate change adaptation actions. The shorter temporal scope avoids the less tractable characterization of multiple, divergent long-term scenarios, and acknowledges that planning near-term adaptation actions based on long-term (uncertain) scenarios will largely lead to "no-regrets" decisions that benefit little from specific scenarios. Furthermore, a more direct response to risk involves initiating adaptation actions in response to short-term scenarios with reasonable certainty while focusing long-term actions on the more compelling task of mitigation. Without a radical change in emission levels, the long-term trajectory for climate is known—substantial warming will occur. Reduction in emissions of greenhouse gases addresses the threat directly and therefore reduces risk regardless of the specifics of long-term scenarios. The Chugach/Kenai assessment illustrates that short-term consequences of a warming climate are unlikely to shatter the social, cultural, or ecological systems of the Chugach/Kenai region. Over longer time frames, the changes that occur in such features as coastal rain forest and the marine environment are highly uncertain, therefore are begging for adaptation actions. The approach to mitigation—a reduction of emissions—can be effectively applied while an informed public and enlightened managers make short-term, climate-smart adaptation decisions.

Without a radical change in emission levels, the long-term trajectory for climate is known—substantial warming will occur.

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English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	1.61	Miles
Hectares (ha)	2.47	Acres
Square meters (m^2)	10.76	Square feet
Square kilometers (km^2)	0.386	Square miles
Cubic kilometers (km^3)	0.2399	Cubic miles
Kilograms (kg)	2.205	Pounds
Degrees Celsius (°C)	1.8 °C + 32	

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	.305	Meters
Miles (mi)	1.609	Kilometers
Square miles (mi^2)	2.59	Square kilometers
Acres (ac)	0.405	Hectares
Gigatons (Gt)	0.907	Gigatonnes
Degrees Fahrenheit (°F)	.56(°F – 32)	Degrees Celsius

Appendix 1: Common and Scientific Names

Common name	Scientific name
Plants:	
Alder	*Alnus* Mill.
Alaska bellheather	*Harrimanella stelleriana* (Pall.) Coville
Alaska hollyfern	*Polystichum setigerum* (C. Presl) C. Presl
Alaska mistmaiden	*Romanzoffia unalaschcensis* Cham.
Aleutian mountainheath	*Phyllodoce aleutica* (Spreng.) A. Heller
Alpine azalea	*Loiseleuria procumbens* (L.) Desv.
Alpine sweetgrass	*Hierochloe alpin*a (Sw. ex Willd.) Roem. & Schult.
Alpine timothy	*Phleum alpinum* L.
American dunegrass	*Leymus mollis* (Trin.) Pilg.
Annual bluegrass	*Poa annua* L.
Beach strawberry	*Fragaria chiloensis* (L.) Mill.
Black cottonwood	*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw
Black crowberry	*Empetrum nigrum* L.
Black spruce	*Picea mariana* (Mill.) Britton, Sterns & Poggenb.
Blueberry	*Vaccinium* spp.
Bluejoint	*Calamagrostis canadensis* (Michx.) P. Beauv.
Bog birch	*Betula glandulosa* Michx.
Bog blueberry	*Vaccinium uliginosum* L.
Bog rosemary	*Andromeda polifolia* L.
Boreal sagebrush	*Artemisia arctica* Less.
Boreal yarrow	*Achillea millefolium* L. var. *borealis* (Bong.) Farw.
Canadian waterweed	*Elodea canadensis* Michx.
Common dandelion	*Taraxacum officinale* F.H. Wigg.
Common plantain	*Plantago major* L.
Canada thistle	*Cirsium arvense* (L.) Scop.
Crowberry	*Empetrum* L.
Dwarf birch	*Betula nana* L.
Disc mayweed	*Matricaria discoidea* DC.
Eelgrass	*Zostera marina* L.
Fireweed	*Chamerion angustifolium* (L.) Holub
Fourpart dwarf gentian	*Gentianella propinqu*a (Richardson) J.M. Gillett ssp. *aleutica* (Cham. & Schltdl.) J.M. Gillett
Grasses:	Poaceae
Harold's milkvetch	*Astragalus robbinsii* var. *harringtonii*
Kenai birch	*Betula papyrifera* Marshall var. *kenaica* (W.H. Evans) A. Henry
Kentucky bluegrass	*Poa pratensis* L. ssp. *pratensis*
Lutz spruce	*Picea* × *lutzii* Little [*glauca* × *sitchensis*]
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carrière
Mud sedge	*Carex limosa* L.
Nootka lupine	*Lupinus nootkatensis* Donn ex Sims

Common name	Scientific name
Orange hawkweed	*Hieracium aurantiacum* L.
Pacific buttercup	*Ranunculus pacificus* (Hultén) L.D. Benson
Paper birch	*Betula papyrifera* Marshall
Pyrenean sedge	*Carex pyrenaica* Wahlenb.
Quaking aspen	*Populus tremuloides* Michx.
Reed canarygrass	*Phalaris arundinacea* L.
Reindeer lichen	*Cladina* (Nyl.) Nyl.
Resin birch	*Betula neoalaskana* Sarg.
Sagebrush	*Artemisia* L.
Salmonberry	*Rubus spectabilis* Pursh
Sessileleaf scurvygrass	*Cochlearia sessilifolia* Rollins
Sitka alder	*Alnus viridis* (Chaix) DC. ssp. *sinuata* (Regel) Á. Löve & D. Löve
Sitka spruce	*Picea sitchensis* (Bong.) Carrière
Sphagnum	*Sphagnum fuscum* (Schimp.) Klinggr.
Tall cottonbrush	*Eriophorum angustifolium* Honck.
Tufted bulrush	*Trichophorum cespitosum* (L.) Hartm.
White sweetclover	*Melilotus albus* (L.) Lam.
Western waterweed	*Elodea nuttallii* (Planch.) H. St. John
Western fescue	*Festuca occidentalis* Hook.
Western hemlock	*Tsuga heterophyll*a (Raf.) Sarg.
White spruce	*Picea glauca* (Moench) Voss
Willow	*Salix* spp.
Yellow-cedar	*Callitropsis nootkatensis* (D. Don) Oerst. ex D.P. Little
Yellow sweetclover	*Melilotus officinalis* (L.) Lam.
Diseases:	
Bovine brucellosis	*Brucella abortus*
Ovine brucellosis	*Brucella melitensis*
Swine brucellosis	*Brucella suis*
Animals:	
Alaska-Yukon race of moose	*Alces alces gigas*
Biting midges	*Culicoides*
Black oystercatcher	*Haematopus bachmani*
Black turnstones	*Arenaria melanocephala*
Caribou	*Rangifer tarandus granti*
Chinook salmon	*Oncorhynchus tshawytscha*
Chum salmon	*Oncorhynchus keta*
Coho salmon	*Oncorhynchus kisutch*
Columbian black-tailed deer	*Odocoileus hemionus columbianus*
Cutthroat trout	*Oncorhynchus clarkii*
Dall sheep	*Ovis dalli dalli*
Dolly Varden trout	*Salvelinus malma*
Dunlin	*Calidris alpina*

Common name	Scientific name
Dusky Canada goose	*Branta canadensis occidentalis*
Elk	*Cervus canadensis*
Glaucous-winged gull	*Larus glaucescens*
Meningeal worm species #1	*Parelaphostrongylus tenuis*
Meningeal worm species #2	*Parelaphostrongylus odocoilei*
Mountain goat	*Oreamnos americanus*
Mule deer	*Odocoileus hemionus*
Northwestern moose	*Alces alces andersoni*
Pink salmon	*Oncorhynchus gorbuscha*
Rainbow trout	*Oncorhynchus mykiss*
Red knot (Pacific coast population)	*Calidris canutus roselaari*
Red-necked phalarope	*Phalaropus lobatus*
Sitka black-tailed deer	*Odocoileus hemionus sitkensis*
Sockeye salmon	*Oncorhynchus nerka*
Spruce bark beetle	*Dendroctonus rufipennis*
Stone's caribou	*Rangifer tarandus stonei*
Surfbird	*Calidris virgata*
Western moose	*Alces alces andersoni*
Western sandpiper	*Calidris mauri*
White-tailed deer	*Odocoileus virginianus*
Winter tick	*Dermacentor albipictus*

Appendix 2: Modeling Climate Change

Purposes of This Appendix

The Scenarios Network for Alaska and Arctic Planning (SNAP) provided objective projections of potential climate futures, or scenarios, based on downscaled climate models to form the foundation for this assessment. Subsets of the extensive SNAP library of climate models were used in different portions of the assessment depending on the climate feature of interest and the geographic or temporal scale of interest. In many cases, climate scenarios from the SNAP library were used in conjunction with other data or models to provide the appropriate set of climate variables to characterize potential future conditions.

SNAP data, models, methods, and results are described, in brief, in each section of the report in which they are used. This appendix offers expanded background and additional maps illustrating outputs examined for this project.

More extensive detail regarding the climate models is available from SNAP's website at http://www.snap.uaf.edu.

This appendix offers expanded background and additional maps illustrating outputs examined for this project.

What Is SNAP?

SNAP is a research, modeling, and outreach program centered within the University of Alaska's International Arctic Research Center. The collaborative network includes the University of Alaska; state, federal, and local agencies; nongovernmental organizations; and industry partners. The network provides downscaled climate projections and other data to craft scenarios of future conditions in Alaska and other Arctic regions for more effective planning by communities, industry, and land managers. The network meets stakeholders' requests for specific information by applying new or existing research results, integrating and analyzing data, and communicating information and assumptions to stakeholders. SNAP's goal is to assist in informed decisionmaking.

What Information Does SNAP Offer?

Downscaled climate models and associated date delivered by SNAP cover Alaska, Alaska–western Canada, polar regions, and other regions spanning the mid 1800s to 2100. Datasets include observed historical data, modeled historical data, and modeled downscaled projected data out to 2100.

SNAP climate projections are based on downscaled regional global climate models (GCMs) from the Intergovernmental Panel on Climate Change (IPCC). The IPCC used 15 different GCMs when preparing its fourth assessment report, released in 2007. SNAP researchers analyzed how well each model predicted

monthly mean values for three different climate variables over four overlapping northern regions for the period from 1958 to 2000, and selected the top five.

Each set of SNAP-projected climate data files originates from one of these five top ranked GCMs, or is calculated as a five-model average. Each set of files also represents one of three greenhouse-gas emission scenarios (B1, A1B, A2), as defined by the IPCC.

SNAP datasets include derived products such as monthly decadal averages or specific seasonal averages. Basic monthly outputs have also been interpolated or interpreted to produce datasets such as mean date of freeze and mean date of thaw (representing days on which temperatures are projected to cross the freezing point) and snow-day fraction (SDF) (temperature-based projections of the percentage of days in a given month in which precipitation, were it to fall, would arrive as snow).

Model Downscaling

GCMs generally provide only broad-scale output, with grid cells typically 1 to 5° latitude and longitude. SNAP bias-corrects and downscales these files via the delta method by using parameter-elevation regressions on independent slopes model (PRISM) baseline gridded climate data (Daly et al. 2008). These grids represent mean monthly values for precipitation and temperature. PRISM uses historical data from climate stations, a digital elevation model, and other spatial datasets to generate gridded estimates of monthly, yearly, and event-based climatic parameters, such as precipitation, temperature, and dew point. PRISM baselines represent the years 1961–1990 for SNAP's 2-km-resolution Alaska and Western Canada data, or 1971–2000 for SNAP's 771-m Alaska data.

SNAP models have been assessed using back-casting and comparison to historical conditions, and have proven to be robust in predicting overall climate trends for the portions of Alaska addressed in this assessment.

Model Uncertainty

Greenhouse-gas-driven climate change represents a response to the radiative forcing associated with increases in carbon dioxide, methane, water vapor, and other gases, as well as associated changes in cloudiness. The projected response varies widely among GCMs because climate forcing is strongly modified by feedbacks involving clouds, the cryosphere (ice and snow), water vapor, and other features whose effects are not well understood. The ability of a model to accurately replicate seasonal radiative forcing is a good test of its ability to predict changes in radiative forcing associated with increasing greenhouse gases. SNAP models have been assessed using back-casting and comparison to historical conditions, and have proven to be robust in predicting overall climate trends for the portions of Alaska addressed in this assessment.

Model projections are presented as monthly average values. Although trends are relatively clear, precise values for any one year or month for any single model cannot be considered reliable weather forecasts. Each model incorporates the variability found in normal weather patterns. The downscaling process introduces further uncertainty. Although PRISM offers the best available algorithms for linking climate variability to weather station interpolation and digital elevation maps (DEMs), the connection incorporates considerable uncertainty. Weather stations are sparse in Alaska, which tends to lower model reliability. Even when climate trends are directional and consistent, the dominant trend can be obscured by normal ups and downs in weather patterns that take place on a monthly, annual, or decadal scale. For example, the Pacific Decadal Oscillation (PDO) can temporarily mask or exacerbate climate trends (Bieniek et al. 2014, Walsh et al. 2011). GCM outputs simulate this normal variability, mimicking an appropriate degree of variability across time scales, but the variations cannot be expected to match actual swings. Overall, model validation has shown that SNAP projections are more robust for temperature than for precipitation.

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Some variability introduced by factors such as the PDO can be dampened by using average values across time, space, and GCMs. All three kinds of averaging have been used in SNAP downscale models. Averaging increases the reliability of projections over temporal scales such as decades, but makes it difficult to make predictions about extreme events such as storms or floods.

Results presented below use model projections averaged across five GCMs. However, examining the variability between these five models sheds light on model uncertainty. Given this variability, projected fine-scale changes in temperature cannot be considered highly significant if they are less than approximately 2.5 °C (36.5 °F). This should be kept in mind when interpreting the maps presented in this appendix. Precipitation data carry an even higher level of uncertainty. Thus, although trends are clear, estimated dates for variables such as freeze, thaw, season length, and snowfall should be viewed as approximate and considered over a series of years rather than in a single year.

Models Specific to This Project

For this assessment, SNAP used mean (composite) outputs from five GCMs, and examined outputs based on midrange (A1B) and more pessimistic (A2) predictions of greenhouse gas emissions. Outputs from the A2 scenario, now considered the most realistic, were the primary focus in the body of the text, but both A1B and A2 outputs are shown below.

The projections used in this project were for a range of modeled data. Basic climate outputs examined in the introduction reference a baseline time period (1971–2000), the current decade (2010s), and future decades (2020s, 2040s, and 2060s). For the introduction, SNAP provided data on the effects of climate change on the following environmental factors: mean and extreme July and January temperature; mean and extreme July and January precipitation; timing of thaw and freeze; length of unfrozen season; and estimated SDF and snowline.

Model Results: Temperature and Precipitation

Temperature and precipitation values are expressed as monthly means for decadal time periods. For example, July temperature for the A1B emissions scenario for the 2020s represents the average of 50 SNAP data files (five models × 10 years in the decade). This averaging smooths the data, facilitating comparison between decades. If examined annually, any of the climate features would exhibit normal variability, with some years and seasons being hotter, colder, wetter, or drier than others owing to the vagaries of weather, rather than the driving force imposed by increases in greenhouse gases. Some variability will occur at a decadal or multidecadal scale, owing to the influence of the Pacific Decadal Oscillation.

January and July data were selected for illustration of patterns in temperature and precipitation to highlight changes in the most extreme months of winter and summer.

January and July data were selected for illustration of patterns in temperature and precipitation to highlight changes in the most extreme months of winter and summer. Changes in shoulder season characteristics are also biologically and culturally important, and are captured via assessment of freeze and thaw dates.

Figure A2-1 shows temperature projections for the current decade. Because consequences of the two emissions scenarios have had little time to diverge, A1B and A2 outputs are similar. Mean temperatures in the coldest month of the year range from approximately -20 °C in the mountains to slightly above freezing along the coastline south of Cordova and Valdez. In July, the hottest temperatures (15 °C) are found in the Anchorage and Wasilla region, outside the core study area, while the coolest temperatures are again found at the mountain peaks, where averages are well below freezing (-7 °C).

These temperature profiles are expected to change over time. Summer warming trends can be seen in figure A2-2, which compares July temperatures for the current decade with those projected for the 2020s, 2040s, and 2060s, all for the A1B emissions scenario. Figure A2-3 offers the same comparison using data from the more pessimistic A2 scenario. Both scenarios show a similar pattern across the landscape, with all areas warming by about 2 °C (A1B) or 3 °C (A2) in the next 50 years.

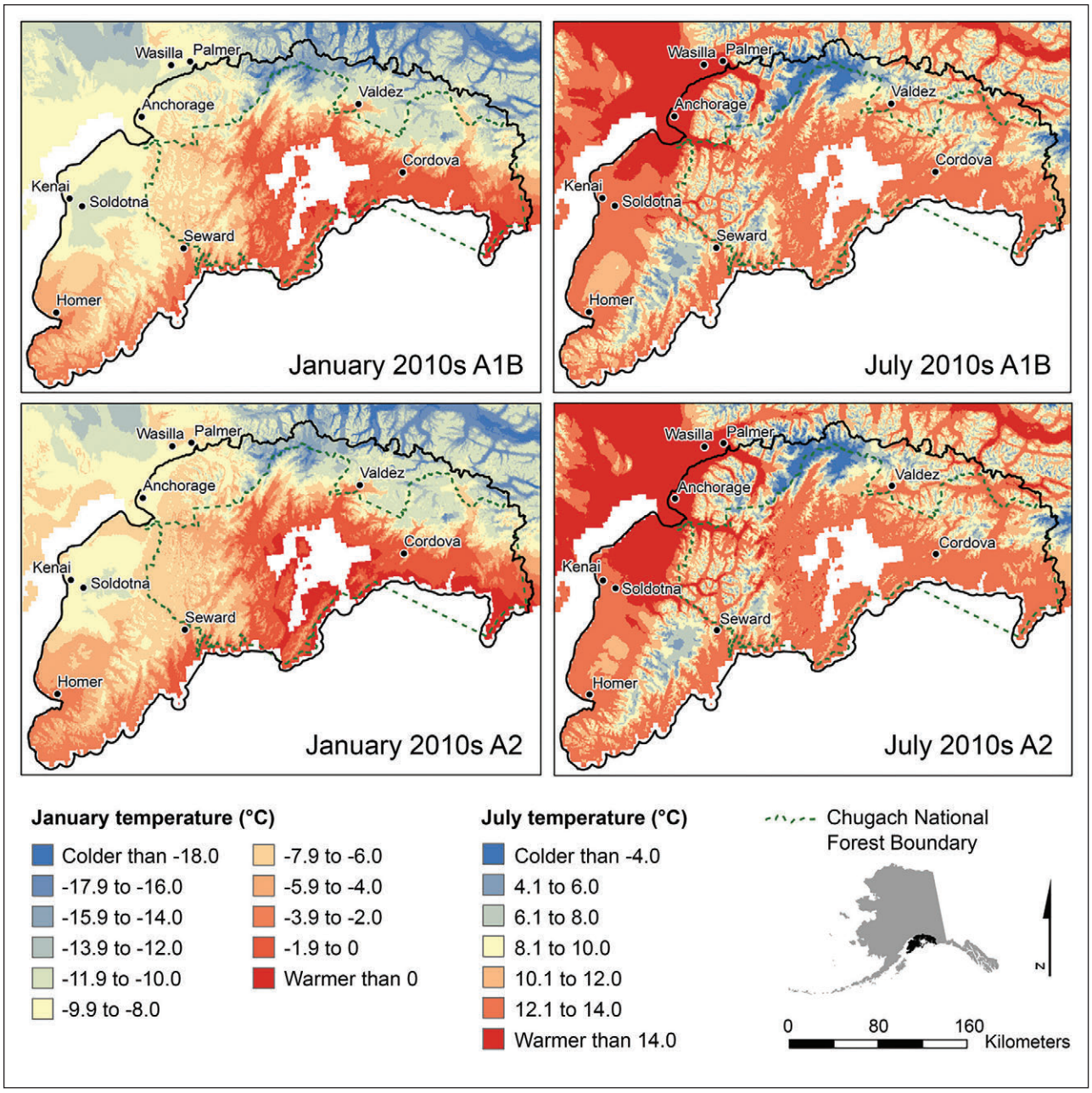


Figure A2-1—January and July temperature for the current decade for the A1B and A2 scenarios.

Areas with July temperatures below freezing are unlikely to undergo significant glacial melting, although it should be noted that daily highs may well exceed mean values, and that direct solar radiation can drive effective temperatures above recorded air temperature.

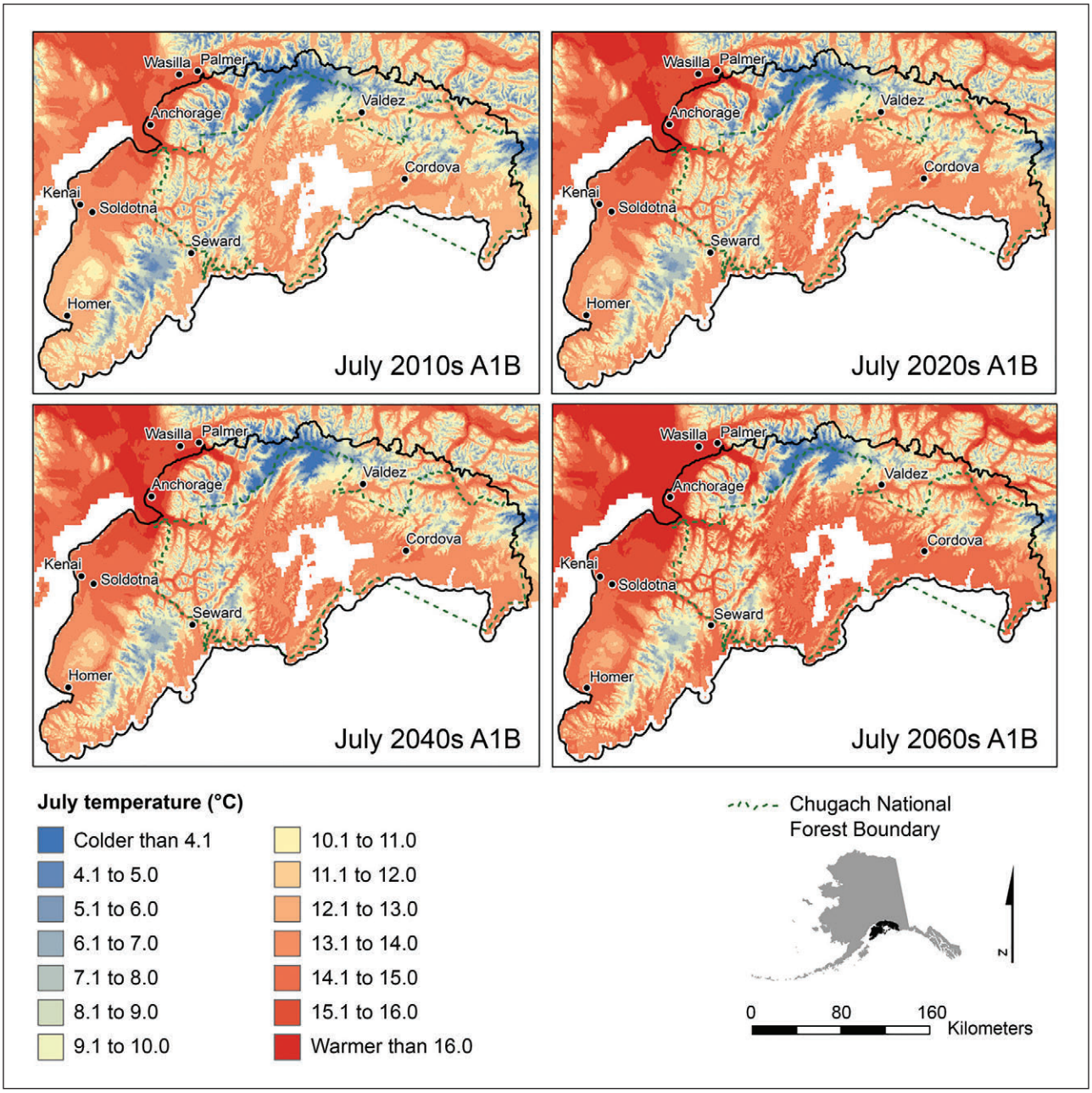


Figure A2-2—July temperature change. Maps depict the 2010s, 2020s, 2040s, and 2060s for the A1B emissions scenario.

Winter temperature change is expected to be more extreme. Figures A2-4 and A2-5 show projected change for January. As with summer conditions, winter temperatures for the two scenarios differ mainly in the rate of change, not in its geographic pattern or temporal trends.

For the A1B scenario, average temperatures in the coldest month of the year are predicted to rise from only slightly above freezing in the warmest coastal areas to well above freezing, or approximately 4.5 °C. Moreover, these warm temperatures

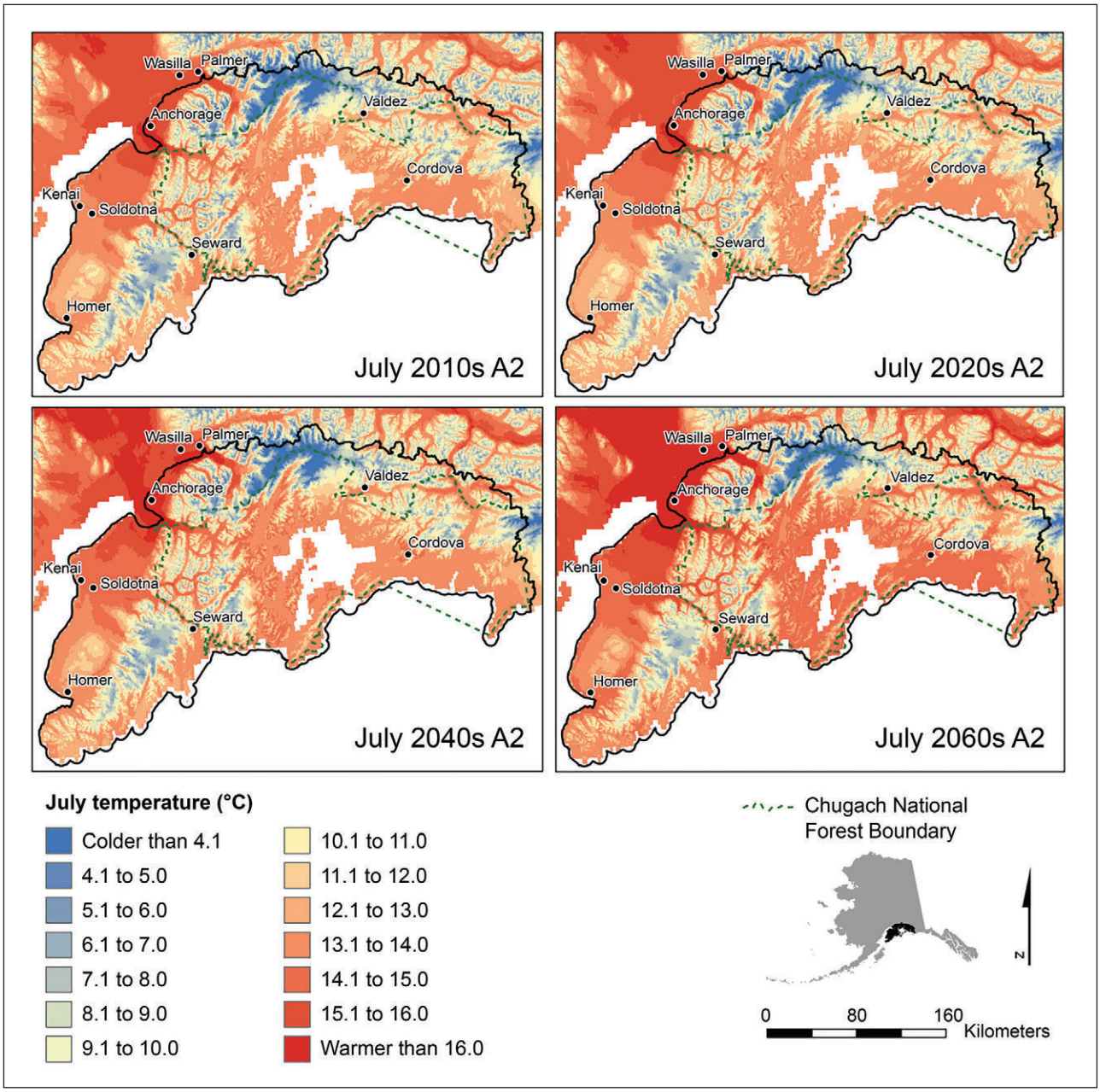


Figure A2-3—July temperature projections for the 2010s, 2020s, 2040s, and 2060s for the A2 emissions scenario.

will spread inland toward Cordova, Valdez, and Seward, with above-freezing Januaries dominating across all coastal regions of the Chugach, and some areas as much as 20 miles inland. Many rivers are seen shifting from a below freezing to above-freezing temperature regime, particularly in the A2 scenario.

Across the region, winter warming is expected to be approximately 3 to 3.5 °C for both the A1B and A2 scenario. Although the greatest impact of summer warming may be in the coldest regions of the Chugach, where snow and glaciers hang in

the balance, the greatest winter impacts may be in the warmest coastal and near-coastal regions, where a shift is underway between frozen and unfrozen winters.

Areas with mean January temperatures above freezing may still experience days or even weeks of freezing temperatures, and daily lows are likely to be significantly cooler than mean values. However, it is unlikely that significant ice formation would occur in such areas, particularly given the fact that seawater freezes at approximately -2 °C rather than at 0 °C. For brackish water, intermediate freezing temperatures are the norm.

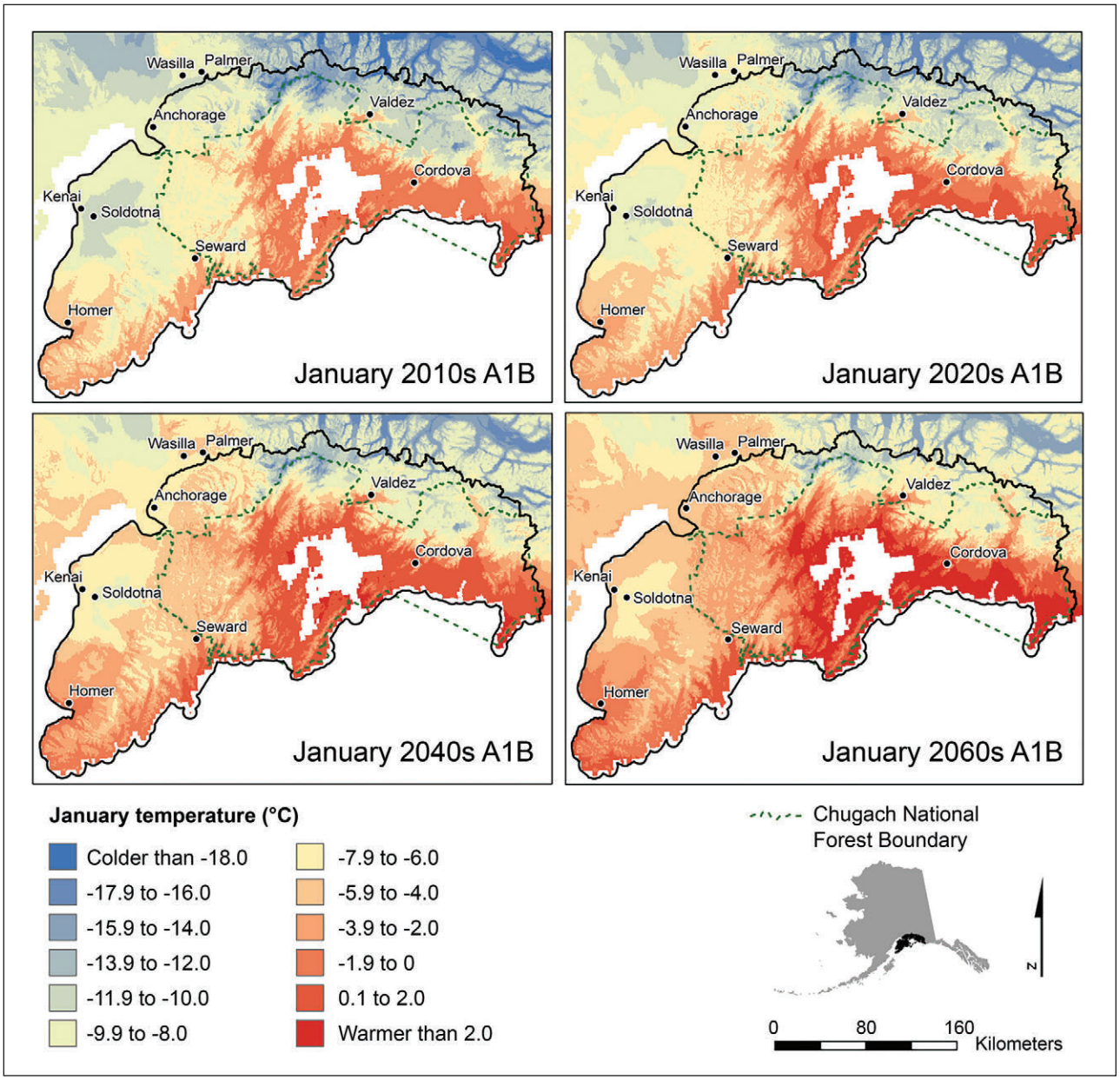


Figure A2-4—January temperature projections for the 2010s, 2020s, 2040s, and 2060s for the A1B emissions scenario.

Model predictions for precipitation (fig. A2-6) are somewhat less robust than those for temperature, in part because precipitation is intrinsically more variable across the landscape. In addition, although precipitation is predicted to increase across the landscape, the hydrologic status of soils, rivers, or wetlands is difficult to predict because of the influence of factors other than absolute precipitation. Increases in temperature may more than offset increases in precipitation, yielding a drying effect in some areas. Changes in seasonality and water storage capacity can

Increases in temperature may more than offset increases in precipitation, yielding a drying effect in some areas.

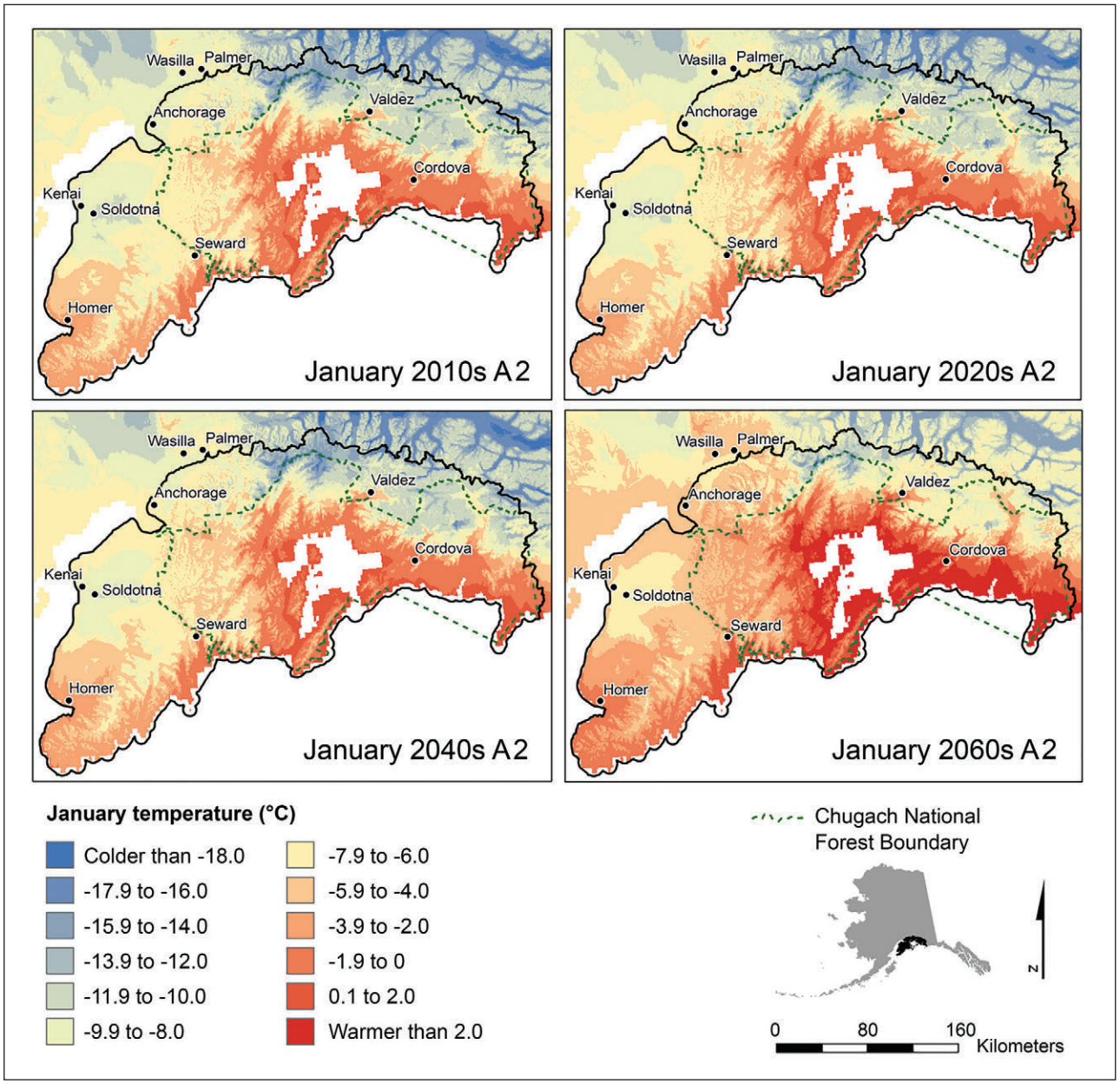


Figure A2-5—January temperature projections for the 2010s, 2020s, 2040s, and 2060s for the A2 emissions scenario.

also affect the hydrologic balance. Furthermore, a shift in the percentage of precipitation falling as snow can drastically alter the annual hydrologic profile.

Between the current decade and all future ones, the trend was toward greater precipitation in both January and July for both the A1B and A2 emissions scenarios (figs. A2-7 and A2-8). These figures depict only the starting and ending decades (2010s and 2060s) of this study. However, maps of precipitation projections for the 2020s and 2040s are also available upon request.

Model Results: Freeze Dates, Thaw Dates, and Length of Growing Season

SNAP uses monthly temperature and precipitation projections and interpolation to estimate the dates at which the freezing point will be crossed in spring and fall. The intervening period is defined as summer-season length. Note that these dates do not necessarily correspond with other commonly used measures of "thaw," "freeze-up," and "growing season." Some lag time is to be expected between mean temperatures and ice conditions on lakes or in soils. Different plant species begin their seasonal growth or leaf-out at different temperatures. Moreover, planting time for gardeners usually takes place when minimum daily temperatures, not mean daily temperatures, are above freezing. However, analyzing projected changes in these measures over time can serve as a useful proxy for other season-length metrics.

Of particular note is the shift of large areas of coastal and near-coastal land from early spring thaw to the "rarely freezes" category.

Across the Chugach, date of thaw in spring is expected to become earlier, with the A1B scenario predicting a slightly less extreme shift than the A2 scenario (fig. A2-7). Of particular note is the shift of large areas of coastal and near-coastal land from early spring thaw to the "rarely freezes" category. This is likely to correspond with lack of winter snowpack and an altered hydrologic cycle. Primarily frozen areas—ice fields and glaciers—are expected to shrink significantly under both the A1B and the A2 scenario.

In inland areas, changes are projected to occur as a shift of 3 to 10 days, on average. For example, the A2 scenario shows spring thaw occurring in Soldotna and Kenai around April 4 in the current decade, but in late March by the 2060s.

Figure A2-8 depicts similar changes for date of freeze.

Autumnal changes are, overall, slightly greater than those seen in spring, with the date at which the running mean temperature crosses the freezing point shifting noticeably later in just a single decade. For example, comparing the maps for the 2010s and the 2020s for the A1B scenario shows the Soldotna area shifting from a freeze date around October 24 to a freeze date of about October 28. During this same decade, loss of areas of ice and snow is also clearly evident.

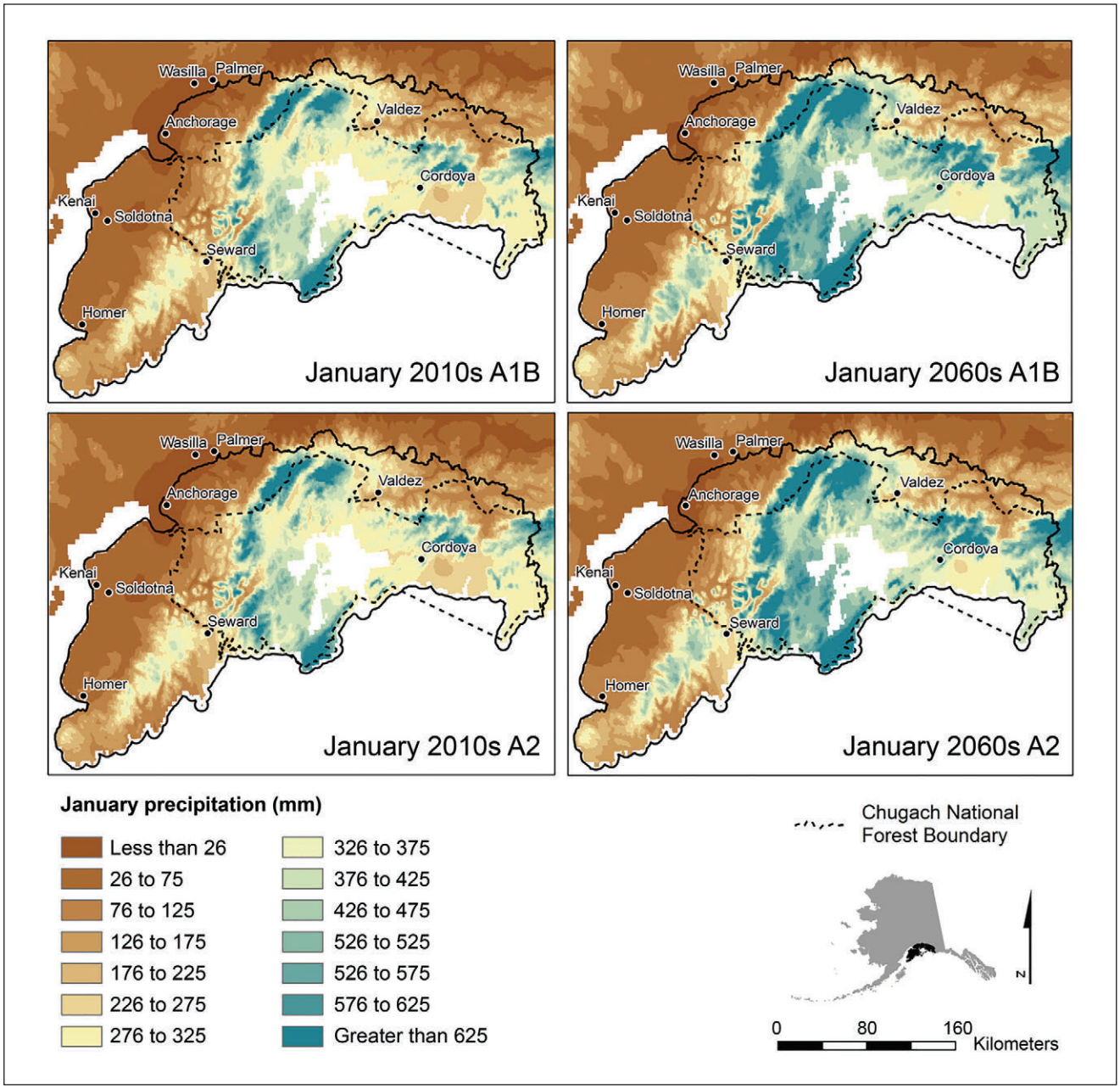


Figure A2-6—January precipitation projections for initial and ending decades of the study (2010s and 2060s) for the A1B and A2 scenarios.

Figure A2-9 combines the information in figures A2-7 and A2-8 to show the total projected length of the "warm season" (time during which mean temperatures are above freezing). Major changes in warm season length include incursion of the "rarely freezes" zone as far as 20 miles inland; an increase from about 200 days to about 230 days for Palmer, Anchorage, Wasilla, and Kenai; and an even more substantial increase for Seward, Valdez, and Cordova.

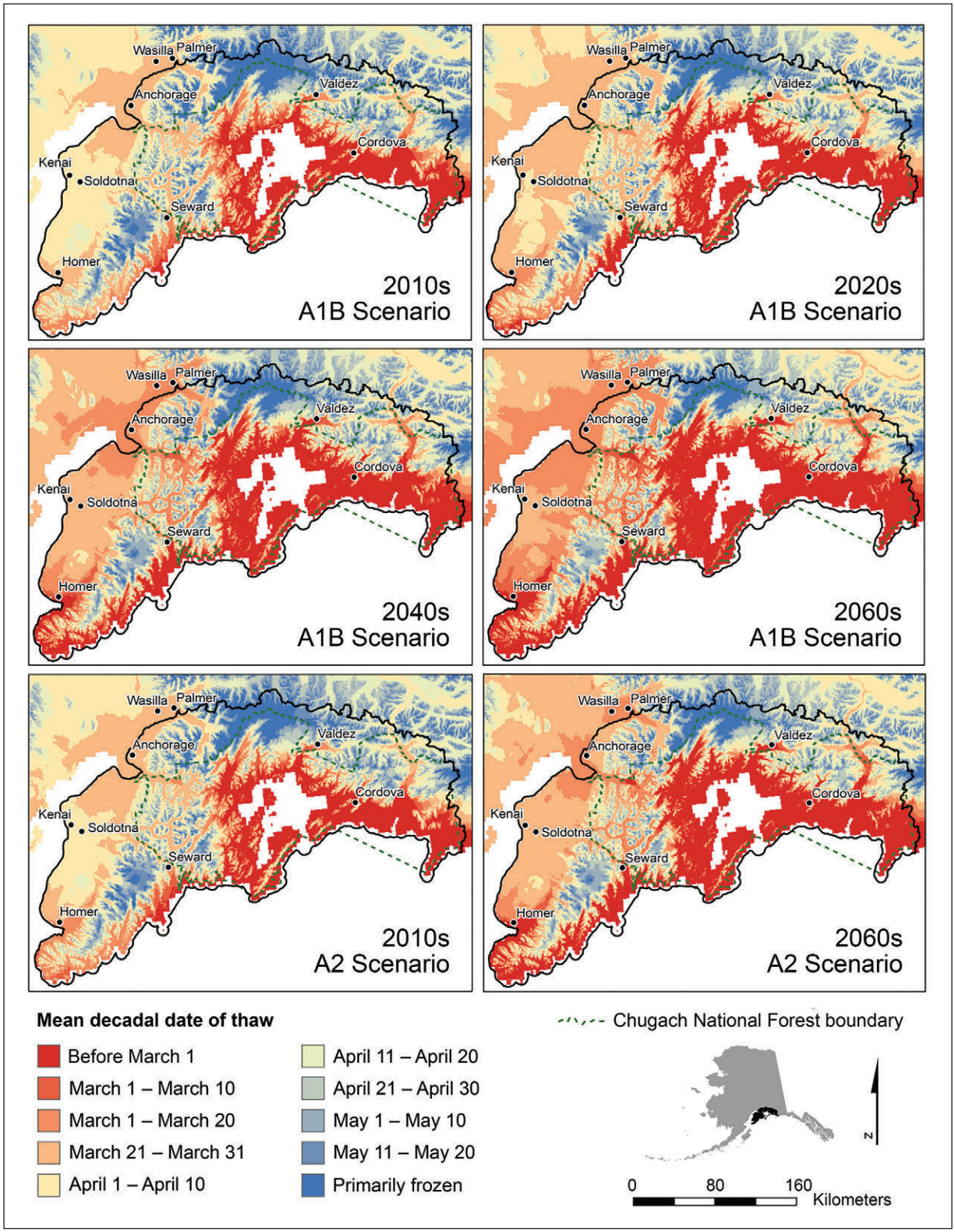


Figure A2-7—Date of thaw projection. Maps depict the date at which the running mean temperature crosses the freezing point in spring for the A1B emissions scenario for the 2010s, 2020s, 2040s, and 2060s (top four panels) and for the A2 scenario for the 2010s and 2060s (bottom two panels).

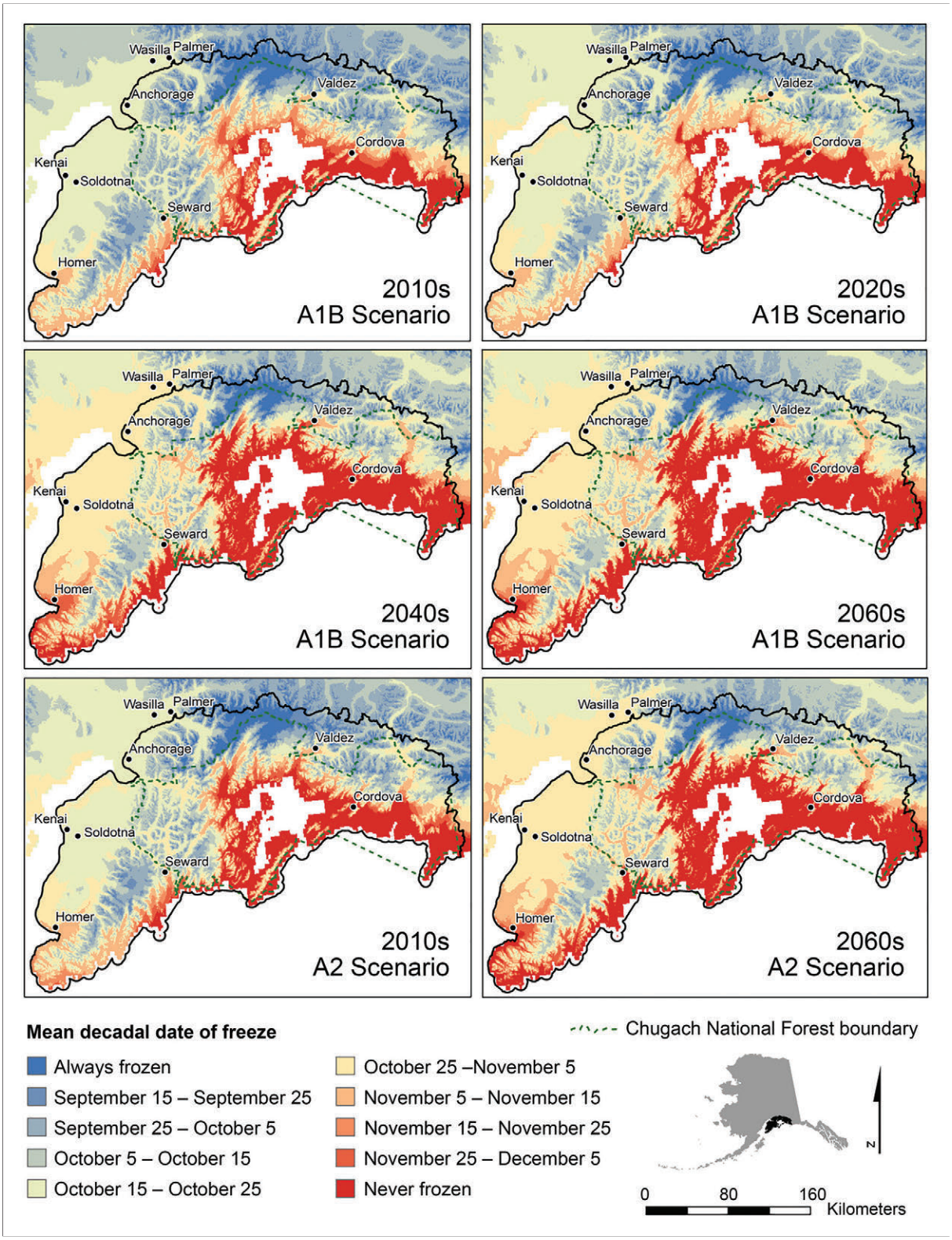


Figure A2-8—Date of freeze projections. Maps depict the date at which the running mean temperature crosses 0 °C for the A1B emissions scenario for the 2010s, 2020s, 2040s, and 2060s and for the A2 scenario for the 2010s and 2060s.

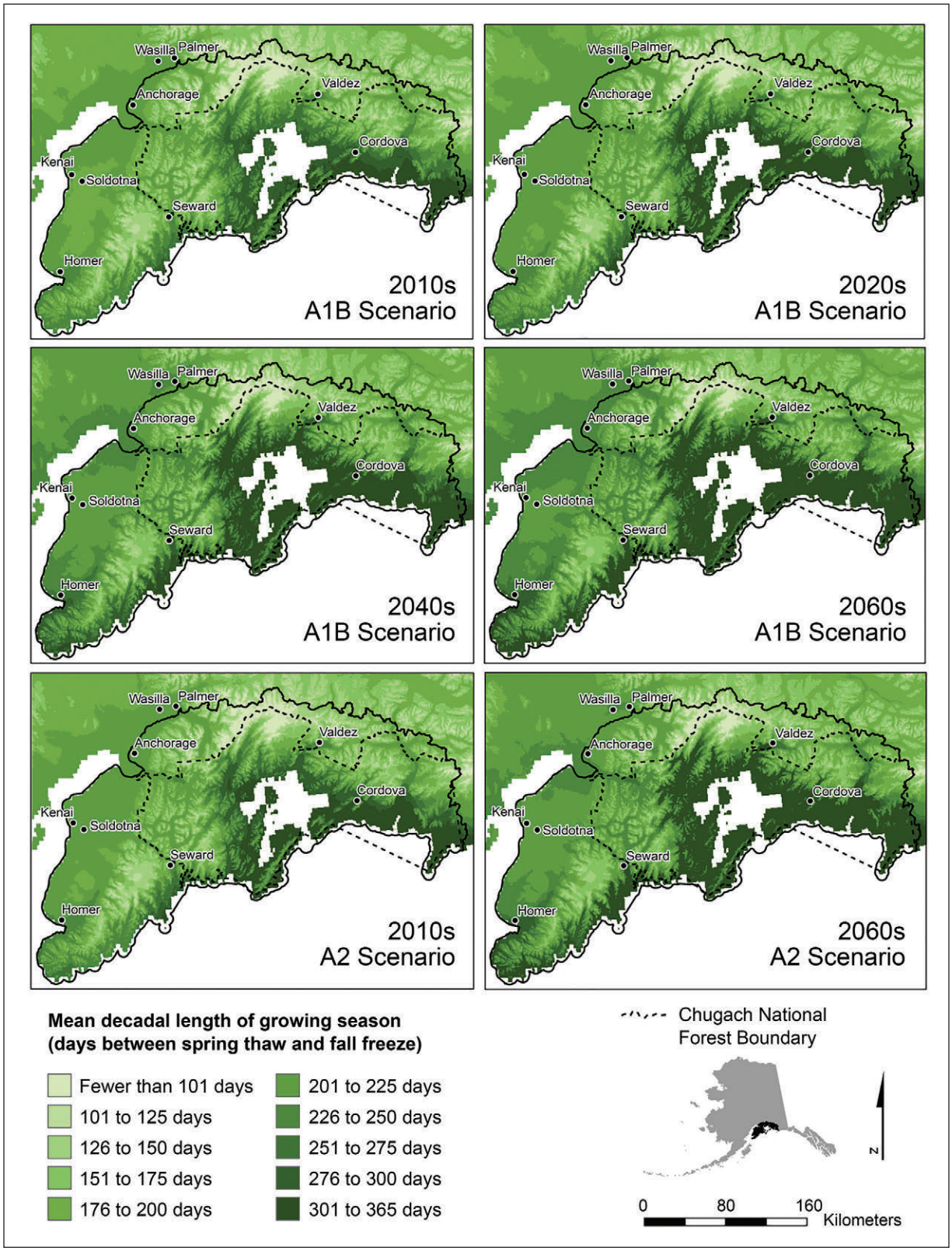


Figure A2-9—Length of growing season projections. Maps depict the number of days between the date at which the running mean temperature crosses 0 °C in spring and fall for the A1B emissions scenario for the 2010s, 2020s, 2040s, and 2060s and for the A2 scenario for the 2010s and 2060s.

Model Results: Snowline

SNAP downscaled GCM outputs do not directly model snowfall as a separate feature from overall precipitation, measured as rainfall equivalent. However, there are many possible ways to estimate snow cover. For the purposes of this project, the metric of greatest interest and clarity was snowline, as estimated by contour maps depicting the probability of snow versus rain during winter months. This work was based on algorithms derived by Legates and Bogart (2009). In other words, what proportion of precipitation can be expected to fall as snow versus rain, on a spatial basis? The 90-percent cutoff (fig. A2-10) is likely to be close to the cutoff at which snowpack occurs, although high variability is expected from year to year.

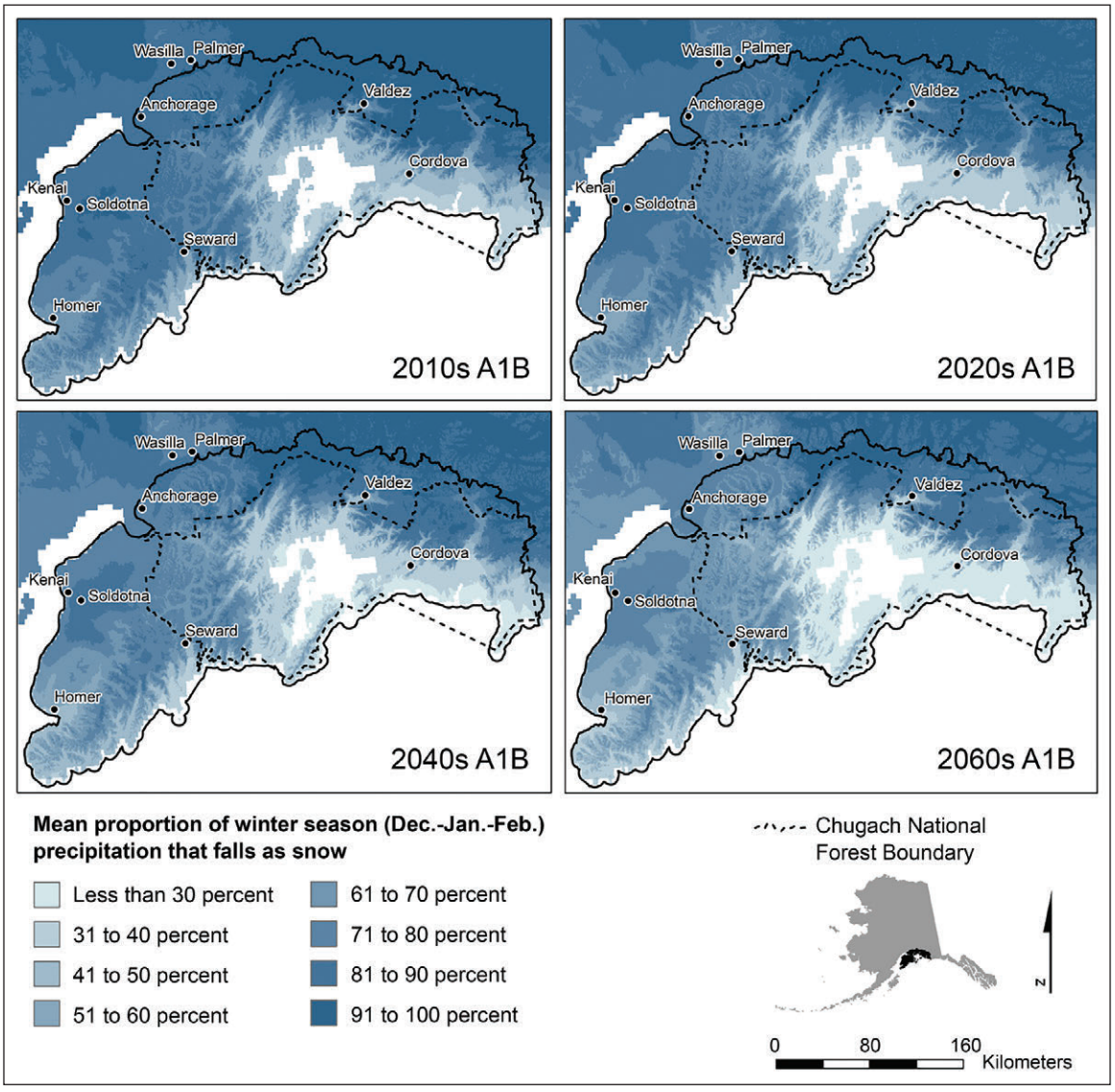


Figure A2-10—Snowline expressed as the percentage of December, January, and February precipitation that falls as snow.

Summary and Conclusions

Overall, the Chugach National Forest area is expected to become warmer in the middle of this century, with earlier springs, later falls, a longer growing season, and shorter, less severe winters. Some increases in precipitation are likely, but overall snowfall will decrease because of higher temperatures. The snowline will move higher in elevation and farther from the coast.

As can be seen, under the A1B scenario, a sharp change is expected in the snowline over each of the time steps examined. In the current decade, snowfall dominates all higher elevation areas. In the next 10 to 20 years, the modeled snowline shifts well inland from Valdez. By 2040, many areas are predicted to receive less than 30 percent of winter precipitation as snow, and, by the 2060s, snowline (as defined by the 90-percent contour) is predicted to shift back to only the highest peaks. Results for the A2 scenario (fig. A2-11) depict an even more extreme shift between the current decade and expected conditions in 50 years.

To assess the snowline during the coldest season, as opposed to the winter as a whole, we also examined the projected snowline for the month of January alone (fig. A2-12).

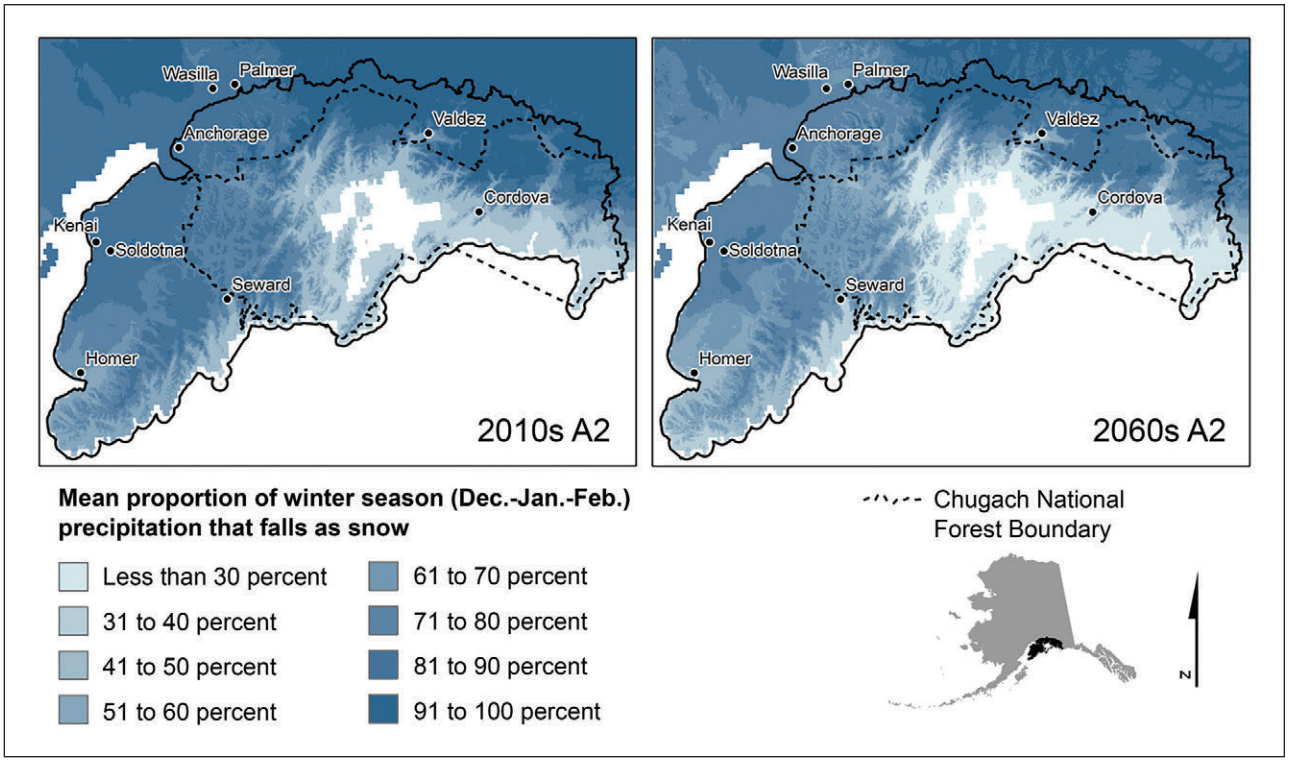


Figure A2-11—Projected snowline for the A2 emissions scenario for the current decade and a 50-year outlook.

Results show that, for many areas that typically experience almost all January precipitation as snow, this pattern may shift in coming decades. By the 2060s, Anchorage, Kenai, Soldotna, Wasilla, and Palmer may have only intermittent snow cover, even in the coldest month of the year.

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Connecting Climate with Landscape

Across the study region, modeled data point toward a significantly warmer environment, with increased precipitation but decreased snowfall. Glacial melt and loss of snowpack is likely, and as a result, annual hydrologic profiles are likely to change, with less of a spring surge, and greater runoff during winter months. The summer-season length will increase by days or even weeks, and some areas that regularly freeze now will no longer do so, or do so only rarely.

These changes are likely to have direct impacts on vegetation, including invasive species that may have previously been kept out of the area by cold winter conditions. Biome shift is likely, although trophic mismatches may occur, given discrepancies in the ability of different species to disperse and establish in new areas.

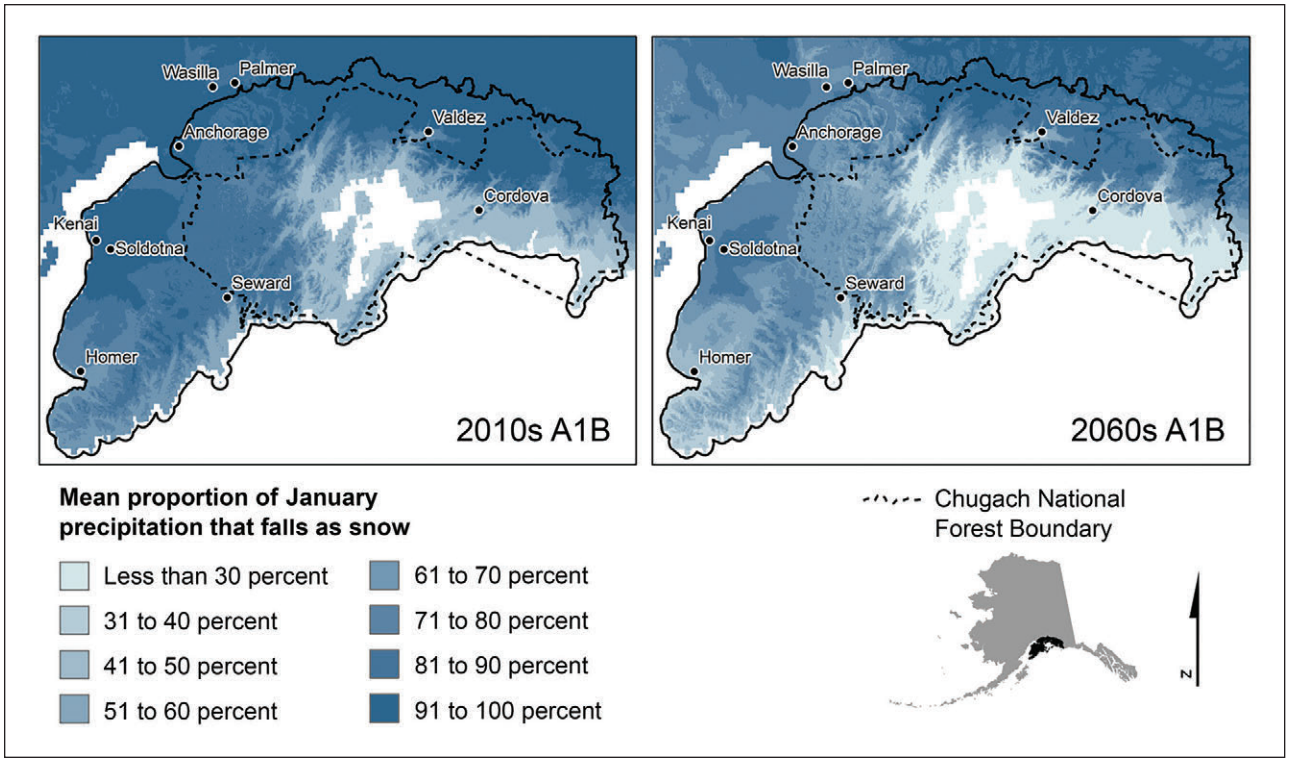


Figure A2-12—Projected proportion of January precipitation likely to occur as snow under the A1B scenario for the 2010s and 2060s.

Fire may play a larger role in the near future. Postfire, there would be a window of opportunity for succession by novel species, meaning that fire may facilitate vegetation shift, which would in turn be likely to affect wildlife. Many wildlife species are affected, either positively or negatively, by snow cover. Although it is hard to predict whether seasonal snowpack would be deeper, it is likely that the snow season would start later and end earlier.

All the above changes are pertinent to human uses of the landscape. Impacts to vegetation and wildlife directly affect hunting and gathering. Changes in season length affect hunting seasons. Subsistence hunting may be affected by species shifts and changes in species abundance. Visitor experiences are also likely to be effected, with regard to species shifts and availability of snow, ice, and glaciers. Typical wildlife viewing may also change.

Further study and ground-truthing of modeled results is necessary to further elucidate and validate these predictions. Land managers should always take into account both natural fluctuations in weather patterns and model uncertainty. However, climate trends will almost certainly play a key role in any future scenario affecting the Chugach National Forest.

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Appendix 3: Estimated Number and Economic Value of Salmon Produced from Watersheds of the South-Central Alaska Study Area

This appendix describes the method and calculations used to estimate the number and economic value of salmon that originate from the watersheds of the south-central Alaska climate vulnerability assessment area. The production estimate is also expressed as the percentage of the total salmon production for the Pacific Ocean.

The sources of data used to make production and economic values estimates were commercial, sport, and personal-use fishery information collected by the Alaska Department of Fish and Game (ADFG). Catches of salmon, by species, were obtained for Cook Inlet, Kenai Peninsula, and Prince William Sound fisheries for the 5-year period from 2009 to 2013. These data are available in ADFG (2014a) and a range of annual reports (Begich and Pawluk 2011, Botz et al. 2012, Hochhalter et al. 2011, Shields and Dupuis 2012).

Number of Salmon

Among the five species of Pacific salmon in south-central Alaska, more pink salmon were caught than any other species (table A3-1). Most of these pink salmon were produced from hatcheries operating in watersheds of Prince William Sound. From 2009 to 2013, total salmon production for this area ranged from approximately 29 million fish in 2009 to 104 million fish in 2013 (table A3-1).

Table A3-1—Millions of salmon caught, by species, in commercial, sport, and personal fisheries for the Cook Inlet, Kenai Peninsula, and Prince William Sound management areas from 2009 to 2013

Year	Chinook	Sockeye	Coho	Pink	Chum	Total
2009	0.04	4.96	0.83	20.25	3.38	29.46
2010	0.04	5.73	0.90	71.92	4.65	83.24
2011	0.05	10.07	0.92	33.78	2.07	46.89
2012	0.02	7.78	0.82	28.00	4.15	40.77
2013	0.03	5.72	1.35	93.14	4.20	104.44
5-year average	0.04	6.85	0.97	49.42	3.69	60.96

The total annual fish production for each species was estimated by dividing the number of fish that were caught by the proportion of each run that was caught. For example, if 0.40 of the salmon return was caught and the number of salmon caught was 20,000, then the total production (or run-size) would have been 20,000/0.40 = 50,000 fish.

Fishery escapement and harvest rates used in this analysis were based on fishery catch and escapement data presented by ADFG (2013), Begich and Pawluk (2011), Botz et al. (2012), and Shields and Dupuis (2012). The highest lowest harvest was the 0.40 value estimated for Chinook salmon (table A3-2). Sockeye salmon were found to have had the highest harvest (lowest escapement).

Table A3-2—Fishery harvest rates used to estimate total run-size for five species of salmon in south-central Alaska

Salmon species	Harvest rate	Comment
Chinook	0.40	Average of Kenai Peninsula and Copper River
Sockeye	0.75	Average of Kenai Peninsula and Copper River
Coho	0.57	Based on Copper River coho
Pink	0.61	Average of Prince William Sound estimates
Chum	0.50	Average of Prince William Sound estimates

Pink salmon were the dominant salmon species in the study area with a 5-year average run-size of 81 million fish.

Based on the production estimates for each species that were derived from the catch and escapement rate data, pink salmon were the dominant salmon species in the study area with a 5-year average run-size of 81 million fish (table A3-3). The pink salmon run, including a large number of hatchery-produced fish, outnumbered all other species combined by nearly 4 to 1. Across all species, the total number of salmon fluctuated considerably from 46.1 million total salmon in 2009 to 171.1 million total salmon in 2013. The combined species average production for this time period was 99.3 million salmon.

Table A3-3—Millions of salmon produced from watersheds of south-central Alaska study area, by species, expressed as total run-size from 2009 to 2013

Year	Chinook	Sockeye	Coho	Pink	Chum	Total
2009	0.10	6.61	1.46	33.19	6.76	48.13
2010	0.10	7.64	1.58	117.91	9.30	136.52
2011	0.12	13.43	1.62	55.37	4.15	74.69
2012	0.05	10.37	1.44	45.90	8.29	66.06
2013	0.06	7.63	2.37	152.68	8.41	171.15
5-year average	0.09	9.14	1.69	81.01	7.38	99.31

To put this level of production in context, the annual production of wild and hatchery-origin salmon for the entire Pacific Ocean (North America, Russia, and Japan) was estimated by Ruggerone et al. (2010) to be 634 million fish. The 99.3 million salmon production from south-central Alaska study area therefore represents about 15.6 percent of this total Pacific Ocean production (i.e., 99.3/634 = 15.6 percent).

Economic Impact of Salmon

Ex-vessel values for commercially caught salmon landed in the Cook Inlet and Prince William Sound management areas (ADFG 2014b) were used to develop an estimate of economic value of the commercial fisheries for south-central Alaska. Commercially caught sockeye and pink salmon had virtually the same total ex-vessel value of $66 million over the 5-year period from 2009 to 2013 (table A3-4). Despite the fact that the number of pink salmon caught was seven times greater, the larger size and higher price per pound for sockeye salmon resulted in the two species having nearly equal ex-vessel values. For all species combined, the 5-year average ex-vessel value was $158.6 million, with a range from $74.8 million in 2009 to $205.3 million in 2013 (table A3-4).

Table A3-4—Ex-vessel values (expressed in millions of dollars) of annual commercial catch of salmon from the Cook Inlet and Prince William Sound management areas, by species, from 2009 to 2013

Year	Chinook	Sockeye	Coho	Pink	Chum	Total
2009	1.24	39.69	4.24	15.66	13.95	74.78
2010	7.12	54.72	5.59	105.18	25.44	198.05
2011	2.84	89.52	3.37	46.57	13.51	155.81
2012	1.85	77.55	2.62	54.85	22.10	158.98
2013	1.16	70.17	7.40	108.48	18.11	205.32
5-year average	2.8	66.3	4.6	66.1	18.6	158.6

Source: ADFG (2014b).

These ex-vessel fishery values were expanded to an estimate of total economic impact using the ex-vessel value to total economic impact ratio from Northern Economics, Inc. (2009). Northern Economics, Inc. (2009) reported that an ex-vessel value of $1,550 million for Alaskan fisheries corresponded to a total economic impact of $5,800 million to the state's economy, a 3.7-fold increase over the ex-vessel value. Based on this ratio, the 5-year average ex-vessel value of all salmon caught within the south-central Alaska study area of $158.6 million was expanded by a factor of 3.7 to yield an estimated total economic impact of $587 million. Economic impact, as used here, includes direct harvesting and processing impacts, as well as indirect and induced impacts.

The economic impact of the commercial salmon fishery in the study area was estimated to have supported 7,944 seafood-industry-related jobs.

Based on information provided by Northern Economics, Inc. (2009), each $73,867 added to the economy is associated with one additional job for the industry. Using this relationship, it was estimated that the economic impact of the commercial salmon fishery for the study area helped support 7,944 seafood-industry-related jobs. This estimation is based on extrapolations from existing statewide economic impact models, i.e., IMPLAN models derived by Northern Economics, Inc. (2009).

Estimates may differ and could be higher if models or multipliers were derived specifically for salmon, the south-central region of Alaska, and data representing other years of harvest and ex-vessel prices.

Estimating the economic impact of sport fisheries for south-central Alaska is more difficult because recreational fishing visits and spending are a complex function of many factors. However, several pieces of information may help shed light on this question. The sport fishing industry, which is heavily dependent on salmon, trout, and char, contributes about $1,400 million to the economy of Alaska (Southwick Associates, Inc. 2008). Of that amount, Southwick and Associates (2008) estimated the total economic output of sport fishing by nonresidents of south-central Alaska to be $631 million. Further, they estimate that 6,365 jobs were supported by this economic impact.

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Appendix 4: From Biomes to Species: Methods for Modeling Future Vegetation Distribution

Change in Land Cover Across the Chugach National Forest/Kenai Peninsula

We used the Random Forest algorithm to link climatic conditions with biomes/land cover and applied a transition threshold representing ecological legacy to mediate land cover conversion following the methods in Magness and Morton (n.d.). We obtained downscaled climate layers from the Scenario Network for Alaska Planning (chapter 2). Our models were built using 37 climate layers: average historical decadal temperature by month (n = 12); average historical decadal precipitation by month (n = 12); average historical decadal annual temperature (n = 1); average historical decadal annual precipitation (n = 1); average decadal projected day of freeze (n = 1); average historical projected day of thaw; and average projected decadal length of growing season (n = 1). We used 1960–1990 as the temporal baseline.

We used the Multi-Resolution Land Characteristics Consortium's (MRLC) National Land Cover Database (NLCD) as the base land-cover classification (http://www.mrlc.gov/nlcd01_data.php). NLCD delineates 13 land cover classes and several anthropogenic land use types in Alaska at a 30 m resolution using LandSat Thematic Mapper imagery and several ancillary data layers (see Vogelmann et al. 1998 for methodology). We rescaled the 30 m NLCD data to 2-km pixels that correspond with the resolution of the climate layers. We classified each 2-km pixel based on the land cover with the largest maximum combined area. Anthropogenic classes (cultivated crops, high-intensity development, low-intensity development, medium development, developed open space, and pasture/hay) were not used in model development because they are driven by land use. Water pixels were also excluded from the analysis because these features are often driven more by hydrology and geomorphology than climate. Our model represents the Alaska-wide climate niche for each land cover type by a randomly selected 10 percent of the land cover pixels across the state of Alaska (n = 36,111) to use as training data for the model. The moss land cover type was excluded because only 93 pixels existed across Alaska at the 2-km scale, none of which were in the assessment area. We modeled the sedge/herbaceous cover type; however, it did not occur within the assessment area. Therefore, for this assessment, 10 land cover types were considered (see table 6-2). We applied our baseline land cover climate niche model to 2060–2069 climate conditions obtained from the Scenarios Network for Alaska and Arctic Planning (SNAP) climate projections (chapter 2).

The Random Forest™ output assigns each land cover type a proportional index of likelihood. The indices of likelihood for all land cover types sum to 1. We applied a threshold representing "ecological legacy" of 0.1 to mediate land cover conversion (Magness and Morton n.d.). When the index of likelihood for the current land cover type was >0.1, we did not allow the pixel to convert land cover. When the index of likelihood of the known land cover type was <0.1, the land cover with the highest index of likelihood was selected.

We assessed model accuracy by comparing the percentage of misclassified pixels for each land cover type that occurred when the LandSat classification was compared to the 1960–1990 modeled land cover. We assessed misclassified pixels when the conversion threshold representing ecological fidelity was used, when only the maximum index of likelihood was used, and when land cover type was selected by random chance. We also calculated the proportion of the assessment area in each land cover type using the conversion threshold representing ecological fidelity and the maximum index of likelihood in 1910–1919 and 1960–1990 to understand which land cover types were over- and underforecast.

To understand how model forecasts varied among GCMs and emission scenarios, we compared the number of acres forecast for each land cover type between the current LandSat and 2060–2069 for all GCMs and emission scenarios considered. We calculated the mean number across all eight climate projections, the standard deviation, minimum acres, and maximum acres. We mapped the number of models that forecast no land cover transition to index model uncertainty. We also mapped the number of land cover types forecast among all climate projections as indices of model agreement. We mapped the land cover forecast in 1900–1919 and 1960–1990 to represent how model outputs compare to empirical data. We also compared the LandSat map to 2060–2069 by mapping the land cover that was forecast by the largest number of models. When two or more land cover types had the highest number of models, we randomly chose from those land cover types with the largest number of models.

Finally we mapped afforestation, deforestation, stable forest, and stable nonforest. We classified each land cover type as forest (deciduous forest, evergreen forest, mixed forest) and nonforest (perennial ice/snow, barren land, dwarf shrub, shrub/scrub, grassland/herbaceous, and woody wetland). We compared current conditions to each of the eight model outputs representing GCMs and emission scenarios to classify each pixel. We mapped the most forecast output and the number of models that agreed.

Change in Spruce Distributions

To model potential spruce distribution shifts in response to climate change, we used an imputation model (detailed methods are described in Barrett et al. [2014]). The imputation method uses a mathematical model to relate presence/absence data to current climate, which is then used to predict future habitat potential based on projected future climate. We used an imputation procedure called most similar neighbors [MSN] (Moeur and Stage 1995). Presence/absence data for spruce came from a systematic grid of field plots across south-central and southeast Alaska, measured between 1995 and 2008 by the Forest Service Forest Inventory and Analysis program (Barrett and Christensen 2011). Of 2,059 forested plots sampled across this broad area, 88 percent had at least one spruce species present (table A4-1). From these inventory data, a model was developed to predict the probability of presence for the three species as a function of climate.

Table A4-1—Number of forested plots by spruce species occurrence (1 = present; 0 = absent)

Black spruce	Sitka spruce	White spruce	No spruce	Number of plots
0	0	0	1	457
0	0	1	0	165
0	1	0	0	1,286
0	1	1	0	8
1	0	0	0	51
1	0	1	0	90
1	1	0	0	1
1	1	1	0	1
Total number of forested plots				2,059

For information on climate at each plot, we used a spatial climate model called parameter-elevation regressions on independent slopes model (PRISM) (PRISM Climate Group 2002). This model predicts the minimum, mean, and maximum monthly temperature and precipitation of 30-year climate normals (1961–1990) across a GIS-based map at a 2 km resolution. We evaluated PRISM-derived climate data for each sample site and derived additional climate variables such as growing degree days, an evapotranspiration index, and length of growing season. For future climate, we used a five-model composite of the A1B scenario created by SNAP (chapter 2). Projections of potential future distributions of each spruce species were then derived from the relationship established between climate and current distribution and future climate projections.

Changes in Habitat Suitability for Three Rare Plants

Current and future ecological niches were modeled using presence data for three of the four Alaska Region sensitive plant species (Goldstein et al. 2009) known to occur within the Kenai-Chugach area (*Aphragmus eschscholtzianus* Andrz. ex DC. [APES], *Papaver alboroseum* Hultén [PAAL], and *Romanzoffia unalaschcensis* Cham. [ROUN]). Population locations were obtained from the Alaska Natural Heritage Program's rare plant database (AKNHP 2012).

The maximum entropy modeling program MaxEnt version 3.3.1 (Phillips and Dudik 2008, Phillips et al. 2006) was used to produce the species distribution models. MaxEnt calculates expected levels of species presence using presence-only data. The predictor variables used in the modeling included current and projected climate data created for Alaska by the Scenarios Network for Alaska and Arctic Planning (chapter 2). The climate projections for 2060 used intermediate (A1B) emission scenarios. Climate variables used to develop the models included mean annual temperature, mean annual precipitation, and growing-season length (number of frost-free days). Slope and elevation were also included in the models and were extracted from the National Elevation Dataset for Alaska (Gesch 2007, Gesch et al. 2002) (approximately 60 m resolution).

Model output values ≥0.7 (on a 0 to 1 scale) were considered as indicative of the highly suitable habitats. Areas covered by glaciers[1] (23.6 percent) or open water[2] (3.6 percent) were excluded from consideration as suitable habitat.

Invasive Species

Twenty-eight non-native plant species were selected that possessed modest-to-high invasiveness ranking scores (see Carlson et al. 2008, Nawrocki et al. 2011) and that represented a spectrum of current distributions in Alaska. Three species are currently not known in the state; nine species have fewer than 50 known infestations, and 16 have between 50 to more than 5,000 documented infestations in the state. Closely related species with high ecological similarity or taxonomic confusion (including cordgrasses, hawkweeds, hempnettles, sweetclovers, and knotweeds) were aggregated into species complexes.

Global occurrence data were obtained from the Global Biodiversity Information Facility (GBIF 2015). Current climate data (2.5-minute spatial resolution) were obtained from the WORLDCLIM website for 19 environmental parameters (WORLDCLIM 2008). The selected future climate dataset was obtained for 2070

[1] Source: Randolph Glacier Inventory (http://www.glims.org/RGI).

[2] Source: National Land Cover Database (http://www.mrlc.gov/ .

from the IPCC CCSM4 dataset, representative concentration pathway (RCP) 8.5, based on a relatively high greenhouse-gas concentration trajectory (IPCC 2013).

The application Maximum Entropy (MaxEnt) was used to generate current and future habitat suitability models. Model performance was evaluated using standard quantitative approaches (Phillips and Dudik 2008, Phillips et al. 2006). Final model performance was evaluated using Area Under the Curve (AUC) scores, a standard quantitative approach (Phillips and Dudik 2008, Phillips et al. 2006). Receiving Operating Characteristic (ROC) curve AUC scores plot the fraction of true positive occurrences (suitable habitat is predicted where known occurrences are located) versus the fraction of false positives (suitable habitat is predicted where model-generated pseudo-absence points indicate that no data points occurred), such that a score of 0.5 is the same as random chance (Fielding and Bell 1997). AUC scores range from 0 to 1, with a score of 0.5 meaning that predictive ability of the model is the same as random chance, and a score of 1 indicating 100-percent predictive accuracy (Gormley et al. 2011, Mukherjee et al. 2011). Final habitat suitability maps for current climate and for 2070 were generated in ArcGIS™. Scenario maps can be used to compare potential current habitat to known populations to evaluate model performance. Potential current habitat maps can also be compared to predicted future habitat maps to assess possible range changes (increases, decreases, directional shifts).

Potential current habitat maps can be compared to predicted future habitat maps to assess possible range changes (increases, decreases, and directional shifts).

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Appendix 5: Modeling and Projecting Development Status and Structure Value of Kenai Peninsula Property

To model the value of structural property on the Kenai Peninsula, we took a multi-stepped approach. The first step devised a set of equations to explain the timing and location of the first instance of a structure appearing on a parcel after 1960. The second step developed a set of equations to explain the value of the structure when it was first built and as it evolved over time. In the third step, the equations from the first two steps were projected 50 years into the future based on the assumption that the broad pattern of development will continue more or less as it has from 1960 to the present.

Step one. The basic approach for modeling the timing of development was to conduct a survival analysis for the probability that a parcel that was undeveloped in 1960 remained in an undeveloped state through a given year. Keep in mind that the objective was to model rates of development at a scale of several decades rather than at a particular point in time. If one assumes that the probability that a vacant parcel is developed is constant over time (a proportional hazard model), then the number of newly developed parcels would be bound to fall over time as the base—the set of vacant parcels—declines. Historically, this has not occurred on the Kenai Peninsula. Consequently, we assumed a proportional hazard model but allowed the hazard rate to vary over time; in fact, we hypothesized that the percentage of vacant properties developed per unit time (hazard rate) would increase over the decades.

The objective was to model rates of development at a scale of several decades rather than at a particular point in time.

A parametric proportional hazard model with variable hazard over time assumes a Weibull distribution, for which the hazard of development at time *t*, *w(t),* is given by the following function:

$$w(t) = y\rho t^{\rho - 1} \qquad (1)$$

where the baseline hazard $y = e^{x\beta}$, in which x represents a vector of explanatory factors determining variation among properties in the likelihood of development, such as proximity to roads and wetland percentage, and β is a set of coefficients to be estimated. Survival to time t in an undeveloped state, $s(t)$, is given by:

$$s(t) = exp(-yt^{\rho}) \qquad (2)$$

The parameter ρ in equation 2 is called the shape parameter. If $\rho < 1$, the hazard decreases over time, and if $\rho > 1$, the hazard increases. If $\rho = 1$, the hazard is constant over time, and the Weibull model reduces to the exponential model. Separate Weibull survival equations were estimated for development of private parcels and development of parcels in public and Alaska Native ownership over the historical period.

Step two. If a property was developed, then a panel regression model explained the value of the structure and its possible evolution over time. The panel form was used because multiple observations appeared in the data for a parcel if additions or modifications to structures on the property occurred in different years. The survival analysis used only one observation per parcel—the observation corresponding to the year a structure was first built or 2014, if it was still vacant—and included all parcels. The equations for structure value, however, included only parcels that contained structures, but included all observations in the data for those parcels. Most of the factors that could explain if or when a parcel got developed also may explain the value of what was built there. In addition, the panel regressions for structure value included the year a structure first appeared on the property and the number of years since that time. These time variables captured changes in the type of structures being built over the years as well as possible changes in the price level that were not accurately measured in the property assessments.

One could undoubtedly obtain much more accurate estimates of the value of structures by including detailed characteristics of the structure, such as square footage, number of bathrooms, etc. However, the relevant question to be addressed is not the value of the structure given its characteristics, but rather what type of structure gets built in that particular place. Modeling the improvements simply in terms of value or cost is sufficient for the objectives of this study.

The panel model assumed that the value of a structure existing on parcel i at time t, $v_i(t)$, that was first developed in year t_{1i} was given by:

$$\log v_i(t) = x_i t\beta + \gamma t_{1i} + \delta(t - t_{1i}) + u_i + \varepsilon_{it} \qquad (3)$$

where u_i represents a random error that is specific to the property i, and ε_{it} is an independently distributed random error term. Separate loglinear random-effects panel regression equations were estimated for the value of structures on developed private parcels and the value of structures on developed parcels in public and Native ownership.

Step three. The estimated equations for survival of a parcel in an undeveloped state and the value of structures on developed parcels formed the basis of long-term future projections of property at risk on the Kenai Peninsula. These projections assumed that the patterns of development that have become established on private and other lands in the region will continue over the next 50 years.

The projected probability that a parcel that was vacant today (time t_0) will still be vacant at the beginning of 2065 (time T) is based on evaluating the Weibull survival function from t_0 to T, assuming that the hazard rate continues to increase between t_0 and T at the rate it did up to t_0:

$$s^*(T) = exp(-yT^{\rho})/exp(-yt_0^{\rho}) = s(T)/s(t_0) \quad (4)$$

Spatially explicit scenarios for Kenai Peninsula property development were constructed by taking random draws for the state of development (structure built or not), with the probability that a parcel remained vacant calculated from equation 4, with T set to 2065 and t_0 set to 2015. Parcels already containing structures were assumed to contain structures in 2065 as well.

If a random draw produced a structure on a parcel in 2065 for a particular scenario, the value of structures on that parcel was established by projecting the value estimated from historical patterns for that kind of property to 2065. Additions, remodeling, and replacement of buildings on parcels already developed today were also based on established long-term trends. Specifically, if a parcel j was projected to be developed by time T (2065), the projected value of structures on that parcel was estimated as:

$$v_j^*(T) = exp[x_j\beta + \gamma t_{1j} + \delta(T - t_{1j}) + u_j] \quad (5)$$

The estimated parcel-specific error term for parcel i, u_j, was included in the projected value if parcel i had a structure by 2014, but was assumed equal to zero for parcels without structures.

Results Explaining Historical Patterns of Land Development

Table A5-1 displays the complete results of the survival analysis for development of private land parcels. The factor with by far the largest effect on the likelihood that a structure gets built on private property was the parcel's proximity to a road. The hazard rate for development for a parcel that had road frontage or lay within 400 m of a road was nearly three times that for a more remote parcel. Larger parcels were more likely to get developed, and those with a higher percentage of wetland were less likely to be developed. The baseline hazard rate for a structure being built was higher on parcels within the city limits of Kenai, Soldotna, and Homer relative to lands outside municipal boundaries. However, the baseline hazard rate was lower in Seward, perhaps because it is older than the other communities. The devastation Seward suffered from the 1964 earthquake also may have impeded development.

Areas with high fire risk were less likely to be developed, controlling for other factors.

Areas with high fire risk were less likely to be developed, controlling for other factors. Extreme fire risk was associated with an even lower hazard of development. The estimate of the coefficient ρ in the Weibull regression shown in table A5-1 is 1.63 (95-percent confidence interval 1.61 to 1.65). As hypothesized, the high estimated value for the Weibull shape parameter, ρ, means that the hazard rate for development of private lands has been strongly and significantly increasing over time (fig. A5-1). Keep in mind, however, that the parameters of the survival

Table A5-1— Survival equations for a parcel remaining in an undeveloped state on private lands

	Hazard ratio	Standard error	z	P>|z|	95-percent confidence interval	
In Kenai	1.259	0.029	10.13	0	1.204	1.316
In Seward	0.844	0.043	-3.35	0.001	0.765	0.932
In Soldotna	1.333	0.036	10.55	0	1.264	1.406
In Homer	1.233	0.029	8.92	0	1.177	1.291
Road frontage	2.903	0.081	38.01	0	2.748	3.067
Within 400 m of road	2.930	0.084	37.48	0	2.770	3.100
400 m to 2 km from road	1.024	0.035	0.70	0.483	0.958	1.095
High spring fire risk	0.961	0.017	-2.19	0.029	0.928	0.996
Extreme spring fire risk	0.800	0.017	-10.55	0	0.768	0.834
Percentage of wetland	0.799	0.025	-7.15	0	0.752	0.850
Natural log of parcel acres	1.029	0.006	4.64	0	1.017	1.042
Natural log ρ	0.488	0.005	89.09	0	0.477	0.499
ρ	1.629	0.009			1.612	1.647

Number of parcels	51,413	Number of observations	51,413
Number of failures (structure built)	27,126		
Time at risk (parcel-years)	2,127,992		
Log likelihood	-52425.1		
LR chi2(11)	4386.6	Prob > chi2	0

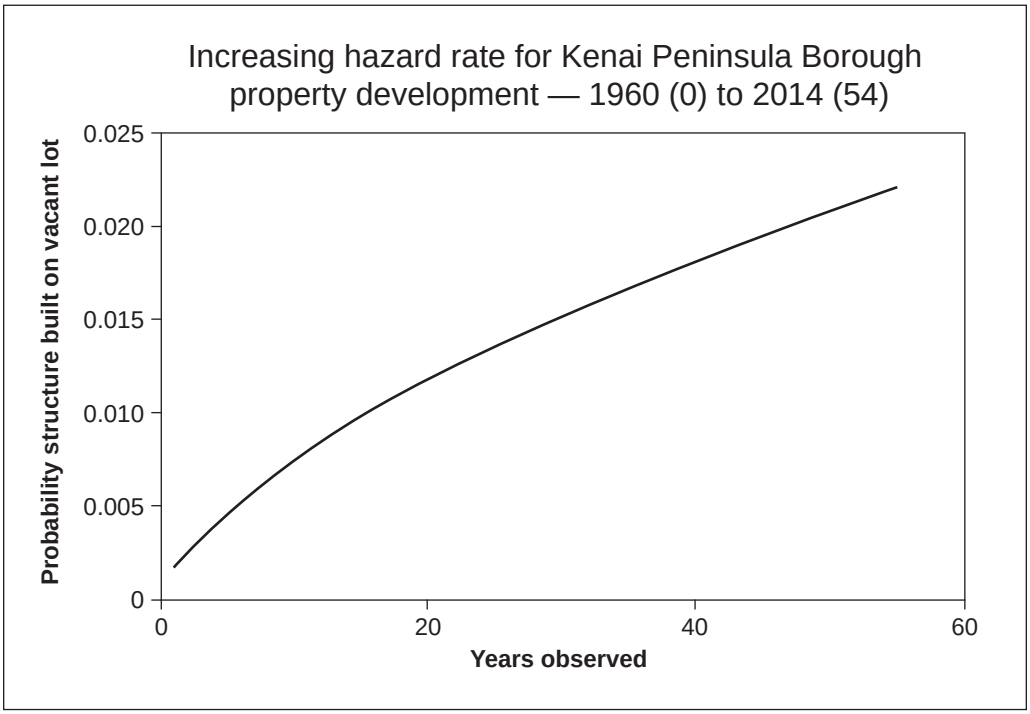


Figure A5-1—Baseline annual probability of development of a vacant private parcel estimated from the Weibull Hazard Function.

equations were estimated assuming that the set of private parcels existing in 2014 were present during the entire period since 1960, which is certainly not the case. Some of the lots were the result of subdivision of other parcels. Part of the explanation of the rapidly increasing hazard rate is that it adjusts for the ongoing subdivision of parcels, which is unobserved.

Table A5-2 displays the analogous results of the survival analysis for development of other lands. In this case, location within city limits of any of the larger towns had a large positive effect on the likelihood that a structure got built on the parcel. Road frontage still had a significant positive effect, and wetlands greatly reduced the likelihood of development, but other effects differed from those estimated for private lands. Parcels with high fire risk were much less likely to be developed, as were larger parcels. Municipal and state-owned parcels were less likely to be developed than borough, Native, and federal (the default) parcels. The estimate of the shape parameter ρ was still significantly positive—1.27 (95-percent confidence interval 1.18 to 1.37)—but the effect on increasing the hazard rate for development was much smaller than that estimated for private lands.

Table A5-2—Survival equations for a parcel remaining in an undeveloped state on other lands

	Hazard ratio	Standard error	z	P>|z|	95-percent confidence interval	
In Kenai	2.006	0.329	4.24	0	1.454	2.766
In Seward	3.236	0.575	6.61	0	2.284	4.584
In Soldotna	2.911	0.521	5.96	0	2.049	4.135
In Homer	3.228	0.541	7.00	0	2.325	4.482
Road frontage	1.548	0.214	3.15	0.002	1.180	2.031
Within 400 m of road	1.166	0.163	1.10	0.273	0.886	1.533
400 m to 2 km from road	0.962	0.145	-0.26	0.797	0.716	1.293
High spring fire risk	0.344	0.061	-5.98	0	0.243	0.488
Extreme spring fire risk	0.913	0.218	-0.38	0.702	0.572	1.456
Percentage of wetland	0.325	0.051	-7.15	0	0.239	0.442
Municipal lands	0.586	0.112	-2.79	0.005	0.402	0.853
Borough lands	0.851	0.160	-0.86	0.39	0.588	1.230
State lands	0.632	0.114	-2.55	0.011	0.444	0.899
Alaska Native lands	1.115	0.201	0.60	0.546	0.783	1.588
Natural log of parcel acres	0.865	0.017	-7.17	0	0.832	0.900
Natural log ρ	0.242	0.039	6.21	0	0.166	0.318
ρ	1.274	0.050			1.180	1.375

Number of parcels	6,336	Number of observations	6,336
Number of failures (structure built)	615		
Time at risk (parcel-years)	331,416		
Log likelihood	-2214.5		
LR chi2(11)	617.9	Prob > chi2	0

Table A5-3 displays the results of the random effects panel regression for the value of structures built on private parcels. The results show that, on average, structures in towns were much more valuable than those built outside city limits, with those built in Kenai and Soldotna worth the most. The larger towns tended to have larger commercial buildings, as well as some multifamily residences. Structures on or near roads were more valuable than those built on remote parcels, which presumably tended to be recreational cabins and associated outbuildings. The results also showed that structures on larger parcels were worth more, controlling for other factors, and the value of structures built on lands with high spring fire risk or more wetlands was lower. As expected, structures and structure additions built more recently had higher values than older structures.

Table A5-3— Random effects regression equations for value of structures on private lands with structures in 2014

	Coefficient	Standard error	z	P>|z|	95% confidence interval	
In Kenai	1.077	0.033	33.01	0	1.013	1.140
In Seward	0.830	0.062	13.39	0	0.709	0.952
In Soldotna	1.090	0.039	28.00	0	1.014	1.166
In Homer	0.764	0.032	23.86	0	0.701	0.827
Road frontage	0.682	0.039	17.58	0	0.606	0.758
Within 400 m of road	0.885	0.040	22.35	0	0.807	0.962
400 m to 2 km from road	0.279	0.049	5.64	0	0.182	0.375
High spring fire risk	-0.193	0.025	-7.63	0	-0.242	-0.143
Extreme spring fire risk	-0.046	0.029	-1.57	0.12	-0.103	0.011
Percentage of wetland	-0.207	0.044	-4.70	0	-0.294	-0.121
Natural log of parcel acres	0.129	0.009	14.36	0	0.112	0.147
Year developed—1960	0.0232	0.0006	36.45	0	0.022	0.024
Log years since developed	0.319	0.004	81.07	0	0.311	0.326
Constant	9.201	0.042	217.34	0	9.118	9.284

Between groups (parcels) standard error (u)	1.126		
Residual standard error	1.028		
ρ (between groups variance fraction)	0.545		
Lagrangian multiplier test for Var(u) = 0	9438.9	Prob > chi2	0.000

Number of observations	55,191	Observations per group:	min	1
Number of groups (parcels with structures)	28,127		max	36
R-sq: within	0.193	Between	0.100	
Overall	0.118			
Random effects Wald chi2(13)	9491.2	Prob > chi2	0	

Table A5-4 displays the results of the random effects panel regression estimated for structures built on public and Native lands. These structures are more diverse and therefore more difficult to predict, so the results show fewer significant effects. As found for private parcels, structures on lands within city limits of the larger towns were more valuable—in this case much more valuable—than those built outside city limits. Structures on or near roads were more valuable than those built on more remote parcels. Municipal structures were worth more than those on federal lands (the default), probably reflecting the fact that city-owned buildings would typically be office buildings or public utility structures, and therefore larger and more costly than residential structures. The results also showed that structures built on non-private parcels with a higher percentage of wetlands tended to have lower values, and structures with more recent additions were worth more than older structures.

Table A5-4—Random effects regression equations for value of structures on other lands with structures in 2014

	Coefficient	Standard error	z	P>|z|	95% confidence interval	
In Kenai	2.010	0.324	6.20	0	1.375	2.646
In Seward	2.635	0.365	7.23	0	1.921	3.350
In Soldotna	2.166	0.352	6.15	0	1.475	2.856
In Homer	1.886	0.336	5.62	0	1.229	2.544
Road frontage	-0.332	0.290	-1.14	0.252	-0.899	0.236
Within 400 m of road	0.068	0.323	0.21	0.833	-0.566	0.702
400 m to 2 km from road	-0.963	0.363	-2.65	0.008	-1.675	-0.250
High spring fire risk	0.334	0.391	0.85	0.393	-0.433	1.101
Extreme spring fire risk	0.193	0.494	0.39	0.696	-0.776	1.162
Percentage of wetland	-0.768	0.361	-2.12	0.034	-1.476	-0.059
Natural log of parcel acres	0.064	0.046	1.41	0.158	-0.025	0.154
Year developed—1960	0.0082	0.0065	1.27	0.205	-0.004	0.021
Log years since developed	0.466	0.030	15.75	0	0.408	0.524
Municipal lands	0.745	0.378	1.97	0.049	0.003	1.486
Borough lands	-0.557	0.356	-1.57	0.118	-1.254	0.140
State lands	-0.568	0.386	-1.47	0.141	-1.324	0.188
Alaska Native lands	0.024	0.409	0.06	0.953	-0.777	0.826
Constant	9.980	0.430	23.20	0	9.137	10.824

Between groups (parcels) standard error (u)	1.854		
Residual standard error	0.978		
ρ (between groups variance fraction)	0.782		
Lagrangian multiplier test for Var(u) = 0	279.35	Prob > chi2	0

Number of observations	1,103	Observations per group:	min	1
Number of groups (parcels with structures)	630		max	17
R-sq: within	0.332	Between	0.247	
Overall	0.236			
Random effects Wald chi2(17)	433.6	Prob > chi2	0	

Projected Kenai Peninsula Property Development in 2065

The equations provided the basis for projecting future property vulnerability to wildfire. As discussed above, spatially explicit scenarios for Kenai Peninsula property development were constructed from the equations shown in tables A5-1 through A5-4. For a parcel that was vacant through 2014, whether the parcel was still vacant or had a structure at the start of 2065 was determined by a random draw. The probability that the structure was still vacant in the random draw was a calculated by evaluating survival equations (4) at 2065 for parcels that were currently vacant. The shape parameter, ρ, was projected to increase the hazard from the 2014 base at the historical rate, implying that the historical pattern of subdivision of private property continues. The development status of currently vacant private and other parcels was projected separately using the respective results displayed in tables A5-1 and A5-2. Parcels with structures present in 2014 were assumed to have structures in 2065.

A number of scenarios were constructed using different random draws from the projected survival functions for private property and other lands. As it turned out, the sample of properties is so large, and the estimated standard errors so small, that taking different sets of random draws made almost no difference in the results. The spatial distribution of developed and undeveloped properties was also similar, because what is predictable spatially—roads and wetlands—was also included in the survival likelihood. Because different property development scenarios produced essentially identical results, the results are reported below for a single representative scenario. The only real difference among scenarios amounted to the projected random location of a few relatively low-value structures on large tracts of public lands with low probability of development.

The equations projected that the total value of structures on private lands would increase by 66 percent over the next 50 years, and somewhat less, by about 60 percent, on other lands.

Projected Values at Risk to Wildfire in 2065

Evaluating the survival equations to 2065 projects a 53-percent increase in the number of private parcels with structures. The value of structures on these parcels was estimated by evaluating the panel regression equations displayed in tables A5-3 for structures on private lands, and in table A5-4 for structures on other lands. The equations projected that the total value of structures on private lands would increase by 66 percent over the next 50 years, and somewhat less, by about 60 percent, on other lands. The projected increase in value of structures is nearly identical for each wildfire risk category, yielding a symmetrical distribution of the enhanced value across categories.

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