Chapter 4. Impacts of Climate Change on Ecosystem Services

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Key Findings

- By 2050, climate change will triple the fraction of counties in the U.S. that are at high or extremely high risk of outstripping their water supplies (from 10 percent to 32 percent). The most at risk areas in the U.S. are the West, Southwest and Great Plains regions.
- Regulation of drinking water quality will be strained as high rainfall and river discharge conditions may lead to higher levels of nitrogen in rivers and greater risk of waterborne disease outbreaks.
- Climate change will have uneven effects on timber production across the U.S. Recent increases in tree mortality due to disease and pests, and the intensity of fires and area burned will continue to destroy productive forests. On the other hand, in some regions climate change is expected to boost overall forest productivity due to longer growing seasons.
- There is a better than 50 percent chance that climate change will overwhelm the ability of natural systems to mitigate the harm to people resulting from extreme weather events (such as heat waves, heavy rains, and drought).
- Vulnerability of people and property in coastal areas is highly likely to increase dramatically – due to the effects of sea-level rise, storm surge, and the loss of habitats that provide protection from flooding and erosion. The areas at greatest risk to coastal hazards in the U.S. are the Atlantic and Gulf coasts.
- The human communities most vulnerable to climate-related increases in coastal hazards are the elderly and the poor who are less able to respond quickly before and during hazards and to respond over the long term through relocation.
- Changes in abundance and ranges of commercially important marine fish are highly likely to result in loss of some local fisheries, and increases in value for others if fishing communities and management practices can adapt.
- In recreation and tourism, the greatest negative climate impacts will continue to be felt in winter sports and beach recreation (due to coastal erosion). Other forms of recreation are highly likely to increase due to better weather, leading to a redistribution of the industry and its economic impacts, with visitors and tourism dollars shifting away from some communities in favor of others.
- Supporting, regulating, and provisioning ecosystem services all contribute to food security in the United States, and the fate of the nation's food production are very likely to depend on the interplay of these services and how the agriculture and fishery sectors respond to climate stresses.

4.1. INTRODUCTION: WHAT ARE ECOSYSTEM SERVICES AND WHY DO THEY MATTER?

Climate change will likely put at risk many of nature's benefits, or ecosystem services, that humans derive from our lands and waters. Climate-mediated loss or disruption of ecosystem functions are very likely to have repercussions for society's dependence on ecosystems for wild-caught and farmed food, recreation, nutrient cycling, waste processing, protection from natural hazards, climate regulation, and other services. One of the many advantages of nature-based services is that not only can they provide jobs and economic opportunities, but they are not subject to "economic bubbles" – in other words they can be reliably counted on as long as ecosystems are well-managed. In addition, ecosystem structures and functions typically provide multiple services; for example, the same habitats that can buffer devastating impacts of floods or storms also provide other benefits, including critical habitat for commercial and recreationally valued species, filtration of sediment and pollutants, and carbon storage and sequestration.

The social values of ecosystem services are broad and include those reflected in markets, avoided damage costs, maintenance of human health and livelihoods, and cultural and aesthetic values. Understanding how human activities and a changing climate are likely to interact to affect the delivery of these ecosystem services is of the utmost importance as we make decisions now that affect the health of terrestrial, coastal, and marine systems and their ability to sustain future generations.

There are a number of ways of accounting for the value of ecosystem services (NRC, 2005), and the literature cited in this Chapter reflects this diversity of methods. The most reliable methodology for estimating how *changes* in human or natural drivers lead to *changes* in ecosystem-derived value is production function analysis (NRC, 2005; Daily and others, 2009; Kareiva and others, 2011). Information about demand for ecosystem services (for example, the distribution of people who use the services supplied) and their social value can be combined with biophysical supply estimates to generate predictive maps of service use and value (Daily and others, 2009; Nelson and others, 2009; Tallis and others, 2011). Economic valuation methods take changes in the supply of ecosystem services as input and translate these into changes in human welfare in monetary terms (Daily and others, 2000; Arrow and others, 2004). There is a common misconception that valuing ecosystem services requires converting everything to a dollar value, when in fact this is not the case (Reyers and others, 2012). The value of ecosystem services can be effectively captured in terms of reduced risk, jobs, and human well-being, without having to convert everything to a dollar bottom line.

The state of our understanding of climate impacts on ecosystem services across the U.S. is relatively undeveloped, primarily because there is no national system for tracking the status or trends in ecosystem services for the USA (PCAST, 2011). However, there are numerous studies from which one can identify selected, albeit not comprehensive, impacts of climate change on ecosystem services.

4.2. WHAT ARE OBSERVED IMPACTS OF RECENT CLIMATE CHANGE ON ECOSYSTEM SERVICES AND THEIR VALUE?

Because there is no national assessment of ecosystem services for the USA, it is impossible to report on the overall status of all of the nation's natural assets. However, specific studies and analyses allow us to survey a range of documented impacts of recent climate changes on ecosystem services and their values. These are summarized in **Table 4.1** (table is located at the end of *Chapter 4*). There is strong evidence of negative effects on human wellbeing having already occurred due to climate change through such impacts as: increased forest wildfires, reduced carbon storage in coastal marine systems, reduced storm protection, shifting marine fish ranges and localized reduction in fish harvest, decreased trout and salmonid recreational fisheries, shortened season for winter recreation, loss of subsistence hunting for Inupiat communities, and closed campgrounds as a result of drought and wildfire risk. These highly focused studies likely reflect only a small fraction of the impacts of climate change that have already occurred, when one considers the total value of ecosystem services in the United States. By looking at specific ecosystem services it is possible to make a start on assessing the economic and employment losses due to recent climate trends.

4.2.1. Marine fishery yields

The economic value of fishery-related services from the ocean is substantial. In 2009, marine living resource industries had $116 billion in sales and contributed $48 billion in value added to the U.S. economy (NMFS, 2010). In 2010, 8.2 billion pounds of fish and other marine species were landed at U.S. ports, worth $4.5 billion in ex-vessel values (Van Voorhees and Lowther, 2011)

Although fisheries are a small fraction of the total U.S. Gross National Product, marine fishing is central to the economies and identities of hundreds of local and regional economies. For example, coral reef fisheries provided $54.7 million to American Samoa and Northern Marianas from 1982-2002 (Zeller and others, 2007); and tuna canneries provide 90 percent of total exports for American Samoa (BEA, 2010). U.S. consumers in all States like to eat seafood: we ate 15.8 pounds of fish per person in 2010, and that quantity has been slowly growing for decades (Van Voorhees and Lowther, 2011). Almost all communities within the Pacific Islands derive over 25 percent of their animal protein from fish, with some deriving up to 69 percent (NCA, 2009).

Fisheries provide a culturally important source of employment in coastal communities that often have few other economic opportunities. In 2009, 1 million people were employed in full- and part-time jobs by commercial fishing, seafood processors and dealers, seafood wholesalers and distributors, importers, and seafood retailers (NMFS, 2010). Where vibrant fishing industries exist, supporting industries are also sustained, including boat building and maintenance, shipping, processing, and service industries.

Climate change already is affecting where and how much fish biomass is available for harvest, and thus the value of fisheries for local fishers. The distributions of many fished species are shifting poleward as sea surface temperatures warm (Nye and others, 2009; Murawski, 1993; Mueter and Litzow, 2008); resulting in concomitant poleward shifts in jobs, catch and value (**Box 4.1**) (McCay and others, 2011; Pinsky and Fogarty, written communication 2012). In Alaska, salmon production increased when ocean temperatures warmed as part of the Pacific

Box 4.1. Climate Impacts on New England Groundfish Fisheries
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Fishing in New England has been associated with bottom-dwelling species of fish, collectively called groundfishes, for more than 400 years and is a central part of the region's cultural identity and social fabric. Atlantic halibut (*Hippoglossus hippoglossus*), cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) were among the earliest species caught, but this fishery has now expanded to include over fifteen species, including winter flounder (*Pseudopleuronectes americanus*), white hake (*Urophycis tenuis*), pollock (*Pollachius virens*), American plaice (*Hippoglossoides platessoides*), and yellowtail flounder (*Limanda ferruginea*). The fishery is pursued by both small boats (less than 50 ft) that are typically at sea for less than a day to large boats (greater than 50 ft) that fish for a day to a week at a time. These vessels use home ports spread across more than 100 coastal communities from Maine to New Jersey, and they land fish worth about $60 million at the dock each year (New England Fishery Management Council, 2011). Captains and crew are often second- or third-generation fishermen who have learned the trade from their families and who hope to pass the tradition on to their children (New England Fishery Management Council, 2011).

The documented impacts of warming temperatures on this fishery over the last few decades suggests indications of further changes ahead. From 1982-2006, sea surface temperature in the coastal waters of the northeastern U.S. warmed by 0.23°C, close to twice the global rate of warming over this period (0.13°C) (Belkin, 2009). The velocity of climate change from 1960-2009 was 20-100 km/decade in the Northeastern U.S., with spring temperatures advancing by 2-10 days/decade (Burrows and others, 2011). Long-term monitoring of bottom-dwelling fish communities in New England revealed that the abundance of warm-water species increased, while cool-water species decreased (Collie and others, 2008; Lucey and Nye, 2010). A recent study suggests that many species in this community have shifted their geographic distributions northwards by up to 200 miles since 1968, though substantial variability among species also exists (Nye and others, 2009). The northward shifts of these species are reflected in the fishery as well: landings and landed value of these species have shifted towards northern States such as Massachusetts and Maine, while southern States have declined (Pinsky and Fogarty, written communication 2012). A number of the commercially important groundfish species in the region such as cod, haddock, winter flounder and yellowtail flounder are at the southern extent of their range in the Northeast and are particularly vulnerable to temperature increase.

Climate projections for this region suggest similar trends in the future. A coarse global projection of future fisheries potential under IPCC scenario A1B (720 ppm CO_2 in 2100) suggests a 15-50 percent loss of fisheries in this region (Cheung and others, 2010). Specific projections for pollock and haddock also suggest substantial declines in this region by 2090 based on changes in temperature and salinity (Lenoir and others, 2010). Under the A1fi emissions scenario (970 ppm CO_2 in 2100), increasing temperatures suggest a substantial loss of cod in the Mid-Atlantic Bight and a decline on Georges Bank (Fogarty and others, 2007). These losses appear substantially less likely to occur under low emissions scenarios (B1, 550 ppm CO_2 by 2100). In contrast, subtropical species such as croaker (*Micropogonia undulatus*) appear likely to increase in the northeast (Hare and others, 2010). To both avoid overfishing of these declining populations and to take advantage of expanding populations, fisheries management will need to adjust exploitation levels, including benchmark measures such as maximum sustainable yield, to account for the impacts of climate change on changing species distributions (Hare and others, 2010).

Box 4.1, continued.

The economic and social impacts of these biophysical changes depend in large part on the response of the human communities in the region (McCay and others, 2011). Fishing communities have a range of strategies for coping with the inherent uncertainty and variability of fishing, including diversification among species and livelihoods, but climate change imposes both increased variability and sustained change that may push these fishermen beyond their ability to cope (Coulthard, 2009). Technology plays a role in this transition. Larger fishing boats can follow the fish to a certain extent as they shift northward, while smaller inshore boats will be more likely to leave fishing or switch to new species (Coulthard, 2009). The past decade in New England has seen dramatic changes to the groundfish industry that has already pushed boats towards larger sizes (New England Fishery Management Council, 2011). However, long-term viability of fisheries in the region is likely to ultimately depend on a transition to new species that have shifted from regions further south (Sumaila and others, 2011).

In light of these transitions, actions that enhance the flexibility of the industry in the region will be important (Coulthard, 2009). Co-management, or the sharing of regulatory decision-making between the government and fishing stakeholders, has been suggested as one mechanism for enhancing the ability of fishing communities to cope with change (McCay and others, 2011). Secure and exclusive fishing rights also promote future-oriented action that can help with difficult transitions (McCay and others, 2011). New England fisheries management includes some of these mechanisms, including fishing industry representation on the management council and a newly implemented sector management program that provides fishermen with more flexibility and responsibility for managing their resources. These measures, however, were primarily focused on ending overfishing in the region. Climate change presents a new challenge that will likely require additional effort to align individual and industry incentives with a sustainable transition to new fishing opportunities before traditional fisheries decline further under the combined impacts of climate and intensive fishing.

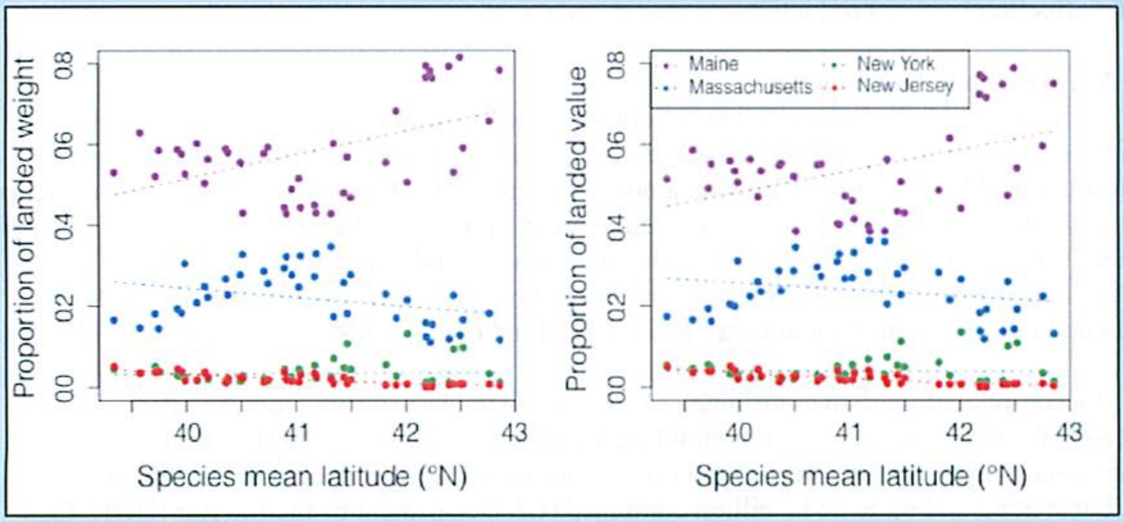

Figure 4.1. Winners and losers as a result of lobster range shifts: Northern ports (for example, Maine) land relatively more lobster by weight and by value as lobster stocks shift north (towards the right side of graph), while southern ports do worse (for example, Massachusetts). Data are from Van Vorhees and Lowther, 2011, and Nye and others, 2009.

Decadal Oscillation, while salmon production decreased in the Pacific Northwest; additional heterogeneity in stock abundance in response to climate also occurs at smaller geographic scales (Hare and others, 1999, Schindler and others, 2008). In Monterey Bay, CA, albacore tuna abundance and catch per unit effort increased during past warm periods, while Chinook salmon declined (Dalton, 2001). The overall economic impact on fishermen of recent warming temperatures was positive for tuna and negative for salmon (Dalton, 2001).

Geographic shifts in fish species in response to climate change could be due to a number of interacting factors, including physiological tolerance thresholds, phenology mismatches of competitor, predator and prey species (for example, Beaugrand and others, 2003), and through effects of climate on habitats that in turn affect fish population dynamics (Jennings and Brander, 2008). Together, these shifts are creating transitions from cold-water fish communities to a different set of warm-water species available for harvest in specific regions (Collie and others, 2008; Lucey and Nye, 2010). In some cases, new industries have developed in response to novel warm-water fish species (Pinnegar and others, 2010; McCay and others, 2011). Furthermore, warm surface water temperatures are driving some fish species deeper (Nye and others, 2009; Dulvy and others, 2008; Perry and others, 2005), which will affect harvest strategies and potentially, costs of exploitation, as fish move to deeper waters (Caputi and others, 2010).

Research is ongoing to explicitly link climate and the condition of natural habitats to fisheries production; yet numerous examples demonstrate that the relationship is often close. On the east coast of the U.S., approximately two out of every three species of economically important fish species rely on estuaries for shelter and resources when young (nursery habitat) (Able and Fahay, 1998). Gulf of Mexico shrimp support the largest crustacean fishery in the U.S., and up to 66 percent of their production may rely on salt marshes (Zimmerman and others, 2000). Similarly, about a quarter of the Gulf's blue crab fishery may be dependent on salt marshes (Zimmerman and others, 2000). The supporting value of marshes for the blue crab fishery in the Gulf is $0.19 to $1.89/acre (Freeman, 1991). Climate impacts on marsh and other habitats affecting fishery production are well documented.

4.2.2. Nature-dependent tourism

Climate change is known to impact opportunities for outdoor recreation by increasing beach erosion, reducing winter snows, increasing wildfire risk, threatening coral reefs, and decreasing valuable cold-water fisheries, among other impacts (**Table 4.1**). To date, the evidence for current climate change impacts on recreation are mostly anecdotal or indirect; for instance, in summer 2008, as a result of tree die-offs related to drought and beetle infestations in the West, Colorado and Wyoming closed 38 campgrounds (Robbins 2008). However, the size of the tourism and outdoor recreation industry gives a good indication of the assets may be at risk in the future.

Ocean-related tourism contributed $82 billion to the U.S. Gross Domestic Product in 2009 (NOEP, 2005); skiing and snowmobiling together contribute another $88 billion (International Snowmobile Manufacturers Association); while recreational fishing, hunting, and wildlife watching add up to $113 billion combined (US Department of the Interior (DOI), Fish and Wildlife Service (FWS), Department of Commerce (DOC), 2006). Some of these activities have profound local impacts. For instance, Hawaiian reefs allowed about 100 dive operators to make $50-60 million/year in total (van Beukering and Cesar, 2004), while Florida's east coast marshes are worth $6471/acre for their support of recreational fishing alone (Bell, 1997).

California has the nation's largest ocean economy, valued at approximately $43 billion annually, with about 80 percent of this coming from tourism and recreation (NOEP, 2005).

Demand for recreation is sensitive to improvements and declines in the health of the ecosystem. For instance, implementation of a beach replenishment policy in North Carolina to increase beach width by 100ft was expected to increase the average number of trips by visitors from 11 to 14, with beach goers willing to pay $166/trip or $1574 per visiting household per year (Landry and Liu, 2009). Another study of North Carolina beaches found that widening beach width increases the consumer surplus of visitors by $7/trip (Whitehead and others, 2009). Conversely, economists have estimated that a single catastrophic fire in New Mexico would reduce forest visits by 7 percent, resulting in a loss of 1,900 jobs and $81,000,000 (Starbuck and others, 2006).

4.2.3. Hazard Reduction: Coastal protection services

Nationwide, more than one-third of the U.S. population currently lives in the coastal zone; and 14 of the 20 largest U.S. urban centers are located along the coast. As population and development along our coasts continue to increase (Crossett and others, 2004), so will their vulnerability to coastal hazards such as storms and sea-level rise. A 17ft storm surge from Hurricane Andrew cost $26.5 billion worth of damage to Miami residents in 1992. In 2005, Hurricane Katrina caused $85.6B worth of damage, with New Orleans taking the brunt of the economic and social damage (First American, 2010). Following Hurricane Katrina and international disasters such as the Indian Ocean Tsunami of 2004, attention has been focused on the ability of coastal ecosystems, such as wetlands and mangroves, to provide protection from ocean-related hazards (Danielsen and others, 2005; Kathiresan and Rajendran, 2005; Das and Vincent, 2009; Koch and others, 2009; Wamsley and others, 2010). A variety of these coastal habitats border the edges of the U.S. shoreline, reducing the vulnerability of people and property to coastal hazards. But marine and coastal ecosystems that provide protection are at risk from coastal development, pollution, destructive fishing practices, aquaculture, marine transportation and other ocean uses. Loss of these ecosystems and the protection they provide could prove devastating for U.S. coastal communities. For example, reduced coastal protection due to salt marsh loss and degradation is thought to have contributed to the extent of the disaster caused by Hurricanes Katrina and Rita in the Gulf of Mexico, which caused over 1,500 deaths (Day and others, 2007). Here we focus on risks of coastal communities to climate impacts and the documented role of protective habitats in ameliorating impacts of sea level rise and storms to people.

Some regions of the U.S. are experiencing more dramatic climate-related coastal hazards. The two primary biophysical processes affecting risk to coastlines and people from climate change are (1) erosion from sea-level rise and storm-induced waves and (2) flooding from sea-level rise and storm surges (**Table 4.1**). Long-term data (greater than 30 yrs) from tide stations indicate that the greatest increases in sea level are occurring along the Atlantic coast from New York south to Virginia (3-6 mm/yr) and in the Gulf of Mexico from Louisiana to Texas (3-12 mm/yr). The majority of the U.S. coast is experiencing a rise of 1-3mm/yr (NOAA, 2011). Furthermore, wave heights from hurricanes (greater than 3m, during the summer months) have increased by 0.7-1.8 m during the last 30 years, increasing erosion processes. The observed increases in wave heights have been greater in higher latitudes (Allan and Komar, 2006; Komar and Allan, 2008); but whether such increases are due to climate change or background environmental variability remains unclear (Komar and others, 2009).

Some of the observed geographic variation in coastal climate impacts in the U.S. is caused by heterogeneity in the distribution of habitats such as wetlands, marshes, mangroves, seagrasses, coral reefs, and dunes that can offer protection from flooding by attenuating storm surges and protection from erosion by dampening wave heights (Barbier and others, 2008). For example, estimates suggest that 0.4 million ha of salt marsh has been lost in North America over the last 200 yrs (Sifleet and others, 2011). It is not known how much of this loss has been due to climate change. Some studies have found that salt marshes in the U.S. are keeping pace with the current long term rate of relative sea-level rise (for example, in North Carolina (Morris and others, 2002); yet other studies show the opposite (Craft and others, 2009; Gedan and others, 2011). In the Chesapeake Bay, satellite imagery suggests that more than half of the tidal marsh area has been degraded by erosion since 1000 AD; and erosion rates have increased from 0.5mm per year to more than 3.2 mm per year during the 20th century (Stevenson and others, 2002). This erosion has caused marsh loss—for example, from 1849 to 1992, the land area of one of the large saltmarsh islands in the Bay decreased by 579 acres or 26 percent of the area (Downs and others, 1994). The documented loss of protective habitats to climate change, human activities, and natural disasters is putting more people and property at risk from coastal hazards. For example, salt marshes along the central Louisiana coast are estimated to reduce storm surges by 3 inches (0.25 feet) per mile of marsh (USACE, 2006). Many years of coastal erosion coupled with Hurricane Katrina's damages to the estuaries surrounding New Orleans have reduced the natural storm defenses around the city by more than 500 square miles (USACE, 2006).

Vulnerability to erosion hazards depends both on physical and social characteristics of coastlines. A social vulnerability index accounting for such attributes as poverty status, race, gender, development density and infrastructure reliance calculated for the U.S. found that social and physical vulnerabilities to erosion hazards from storms are not uniformly distributed (Boruff and others, 2005). For example, the vulnerability of the Gulf coast to erosion is more a product of social than physical characteristics because of the relatively high prevalence of low-income communities along the coast. The reverse is true for the Pacific and Atlantic counties, where physical characteristics are more influential in determining erosion-hazard vulnerability (Boruff and others, 2005).

The value to people of the protection offered by coastal habitats is impressive. For example, marshes are worth an estimated \$8235/yr/ha in reduced hurricane damages to the U.S. (Costanza and others, 2008). An analysis of the economic damages associated with 34 major hurricanes striking the United States coast since 1980 found that the additional storm protection value per unit area of coastal wetlands from a specific hurricane ranged from a minimum of U.S. \$23 per hectare for Hurricane Bill to a maximum of U.S. \$463,730 per hectare for Hurricane Opal, with a median value of just under U.S. \$5,000 per hectare (Costanza and others, 2008).

4.2.4. Fire Regulation

The risk of severe wildfires is a function of climate, forest composition and management practices in that forest or grassland. Wildfires in the U.S. damage hundreds of homes in the U.S. each year and annual fire-fighting expenditures alone regularly exceed \$1billion dollars per year (Whitlock, 2004). The incidence of large forest fires in the western U.S. increased nearly four-fold in the 1980s onward, and the total area burned by fires six-fold (Westerling and others, 2006). Most of this increase can be explained by increased spring and summer temperatures (Westerling and others, 2006). However, management of forests, grazing regimes, and thinning can dramatically impact the spread and risk of wildfires. For example the Arizona Wallow fire of

2011, which was Arizona's largest fire on record, did not burn ridges where there had been previous thinning of the forests. The thinning effort in portions of Arizona was a forest stewardship project aimed to reduce fire risk and to create jobs. It did both (BIA, 2011). Thus, well-managed forests provide the auxiliary service of fire risk reduction—a service whose importance increases as warming trends can exacerbate background propensity for severe fires. The nexus of climate and forest fires is a flashpoint for several other pathways towards degraded ecosystems services such as water supply and quality (**Box 4.2**).

Box 4.2. Climate Impacting Fire Risk, Water Supply, Recreation, and Flood Risk in Western U.S. Forests

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The 2009 National Climate Change Assessment (CCSP, 2009) documented the broad-scale forest dieback as a threshold response to climate change in the Southwestern United States (Fagre and others, 2009) and noted this can be a precursor to high severity wildfires. Since that assessment, in the summer of 2011 the largest recorded wildfires in Arizona (Wallow - greater than 538,000 acres with 15,400 acres in New Mexico; greater than$100 million in suppression costs) and New Mexico (Las Conchas - ~156,600 acres) occurred. Both fires had significant impacts on a range of ecosystem processes, individual species, and a number of ecosystem services provided by these systems.

The Las Conchas fire in northern New Mexico burned over 63 residences, 1100 archeological sites, more than sixty percent of Bandelier National Monument (BNM), and over 80 percent of the forested lands of the Santa Clara Native American Pueblo (16,600 acres), and was severe enough to cause forest stand replacement scale damage over broad areas. Following the fire, heavy rain storms led to major flooding and erosion throughout the fire area. Scientific modeling found that this type of storm (25-year event) would lead to river runoff approximately 2.5 times greater and sediment yield three times greater due to this fire in the main canyon of Bandelier National Monument (Semmens and others, 2008; **Table 4.1**).

Climate change a likely contributing factor: There is good evidence for warmer temperatures, reduced snowpack, and earlier onset of springtime leading to already observed increased wildfires in the western U.S (Westerling, 2006). The National Research Council (2011) projected 2 to 6 times increase in areas in the West burned by wildfires given a 1°C increase. Recent research employing paleodata and an ensemble of climate models projects that the frequency of droughts, which cause broad-scale forest die-back may occur approximately 50 times per century by 2100, far beyond the range of variability of the driest centuries in the past millennium (Williams and others, 2012).

Other Stressors Exacerbating Fire: Forest management practices and invasive insect pests contributed to catastrophic wildfire occurring in these systems. Even-aged second growth forests much denser than natural occur in the West, remove more water out of the soil and increase the likelihood of catastrophic crown fires. In addition, naturally occurring bark beetles breed more frequently and successfully under conditions that are projected to become more frequent with climate change (Jonsson and others, 2009; Schoennagel and others, 2011). Outbreaks of bark beetles and associated tree mortality have increased in severity in recent years, suggesting a

Box 4.2, continued

possible connection between large fires and the changing fuel conditions caused by beetle outbreaks. In turn, the dead trees left behind by bark beetles can make crown fires more likely (Hoffman and others, 2010; Schoennagel and others, 2011).

Impacts to species and biodiversity: The catastrophic crown fire conditions during the Las Conchas fire undoubtedly had a devastating impact on above-ground wildlife (McCarthy, 2012). Relatively few animals living above ground likely survived. In addition, the mid-elevation areas of all the major canyon systems of Bandelier National Monument experienced extensive to near complete mortality of all tree and shrub cover while leaving dead trees standing. Mexican Spotted Owls (*Strix occidentalis lucida)* nesting and roosting habitat has been altered, potentially affecting its suitability for this species (Jenness and others, 2004). The Jamez salamander is an endangered species whose population was put in further danger due to this fire (McCarthy, 2012).

Impacts to recreation: Post-fire localized thunderstorms on a single day resulted in at least ten debris flows originating from the north slopes of a single canyon in Bandelier National Monument. Popular recreation areas in the Monument were evacuated for four weeks and flash floods damaged the newly-renovated multi-million dollar National Park Service visitor center. In addition, other recreation areas managed by the U.S. Forest Service, U.S. Army Corps of Engineers, and the Bureau of Land Management closed down recreation areas due to the fire, and associated flooding and erosion.

Impacts to Urban water supply: The increased sediment and ash eroded by the floods in the wake of the fire were transported to downstream streams and rivers, including the Rio Grande, a major source of drinking water for New Mexico and 50 percent of the drinking water supply for Albuquerque. The sediment and ash led to Albuquerque's water agency to turn off all water supplies from the Rio Grande for a week, and reducing water withdrawals in the subsequent months due to increased cost of treatment (Albuquerque Journal, September 2, 2011 http://www.abqjournal.com/main/2011/09/02/news/2-agencies-curtail-rio-grande-draws.html)

An adaptation effort is needed: Safeguarding against fire related impacts and adaptation to change will require innovative solutions, large-scale action and engagement among a variety of different stakeholders. The Southwest Climate Change Initiative (SWCCI), led by The Nature Conservancy, is an example of this type of adaptation planning effort. SWCCI is a public-private partnership developed in 2009 with the University of Arizona Climate Assessment for the Southwest, Wildlife Conservation Society, National Center for Atmospheric Research, and Western Water Assessment along with government agency partners with the goal of providing information and tools to build resilience in ecosystems and communities of the southwestern U.S. The SWCCI is currently leading efforts across the Southwest, including adjacent to the Las Conchas fire area, to identify and implement adaptation solutions that help prevent these types of catastrophic events. Some of the solutions being considered include forest restoration activities such as non-commercial mechanical thinning of small-diameter trees, controlled burns to reintroduce the low-severity ground fires that historically maintained forest health, and comprehensive ecological monitoring to determine effects of these treatments on forest and stream habitats, plants, animals, habitats and soils.

4.2.5 Carbon storage and sequestration

Carbon accumulates in soil and biomass (for example, vegetation), and represents a greater pool of carbon than is present in the atmospheric pool (Lal, 2004a). When carbon is released from the earth during cultivation, deforestation, fire, and other land use practices, it binds with other chemicals to form greenhouse gases (GHG) in the atmosphere and accelerates global climate change (Lal, 2004b). The conservation of carbon sinks or pools is therefore important to mitigate GHG levels. Property owners and land managers can influence the pace of global climate change and related impacts through climate-smart land use decisions that maintain, rather than perturb or destroy carbon sources (Post and Kwon, 2008). Carbon sequestration and other actions that reduce emissions have become valued goods and services that benefit and potentially reduce global economic damage from climate change (Conte and others, 2011). Estimates of the global economic value created by each ton of carbon that is sequestered or reduced through lowering emissions ranges from $25 to $675 (Tol, 2009). This large range in values is in part explained by uncertainties in climate change projections, mitigation actions, climate change adaptation, and the resilience of ecological systems to future changes (Aldy and others, 2010).

Because carbon sequestration and reduced emissions can create an economic value, society is willing to pay to encourage it. Carbon markets are a manifestation of this willingness to pay. Several mandated and voluntary markets that pay landowners to sequester carbon have been created in the last decade (Canadell and Raupach, 2008; Arriagada and Perrings, 2011). The carbon market price and the policy infrastructure that supports the carbon market is likely to be an important determinant for U.S. landowners to remove or prevent emissions to the atmosphere (Lubowski and others, 2006). A well-functioning market can approximately equate the carbon price with the global value created by a ton of sequestered. If climate changes reduce the capacity of ecosystems to sequester carbon, the ability to mitigate global economic damages caused by climate change is likely to decrease.

Forest carbon

Climate change-induced perturbations in forest distribution, growth rates, and risk of wildfire, invasive species, and disease are impacting the rates of carbon sequestration and expectations for length of storage. Dry, warm conditions over the last 10 years across 20 million hectares in western North America have led to extensive insect outbreaks and mortality of diverse tree species, including oaks in the Midwest and southeastern U.S. (Allen and others, 2010). Although these tree mortality rates are higher than any observed in 50 years, greater than 99 percent of forest species inventory available for harvest remains unaffected (Oswalt and others, 2009). Governments at all levels and private landowners are investing significant sums to protect forests from further damage. For example, the cost to Federal agencies for fire suppression now exceeds $1 billion annually (U.S. Government Accountability Office, 2006).

An extrapolation of current economic dynamics in the conterminous U.S. suggests that forested areas could increase by 10 to 14 million hectares from 2001 to 2051 (Radeloff and others, 2012), resulting in about 220 million hectares of forest across the conterminous U.S. by 2051. This same study suggests that a combination of payments for landowners converting to forest lands and taxes on those who cut their trees could increase the area of forest in 2051 by an additional 30 million hectares, resulting in forest carbon storage levels that are orders of magnitude larger than storage levels under the current baseline. Payments for landowners who decide not to deforest are beginning (for example, through the United Nations Collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) policies), and the potential for management incentives to change forest area is great (Canadell and Raupach, 2008; Arriagada and Perrings, 2011).

Marine Carbon

Research on carbon storage and sequestration has focused predominantly on terrestrial forest and deep ocean ecosystems. Vegetated coastal ecosystems are not part of either ecosystem type, creating a gap in estimates of global carbon storage and sequestration capacity estimates (Mcleod and others, 2011). Coastal ecosystems dominated by plants such as mangroves, salt marshes and seagrasses, sequester and store carbon in the short term in biomass and over the long term in sediments (Duarte and others, 2005; Mcleod and others, 2011). The annual burial of carbon in mangroves, salt marshes, and seagrass beds across the world is estimated to be 31–34 teragrams (Tg), 5–87 Tg, and 48–112 Tg C per year, respectively (Mcleod and others, 2011). The carbon storage and sequestration potential of these marine habitats is impressive. In just the first meter of coastal and nearshore sediments, soil organic carbon averages 500 - 4966 t carbon dioxide equivalent (CO_2e)/ha for sea grasses, 917 t CO_2e/ha for salt marshes, 1060 t CO_2e/ha for estuarine mangroves, and nearly 1800 t CO_2e/ha for marine mangroves (Murray and others, 2011).

Approximately 0.4 million hectares of salt marsh has been lost in North America over the last 200 yrs (Sifleet and others, 2011). Currently, 1.9 million hectares of salt marsh in the U.S. store and sequester carbon. Most annual estimates of salt marsh carbon sequestration fall below 2.2 Mg per hectare (Sifleet and others, 2011). Most U.S. studies on carbon storage and sequestration in salt marshes are from the northeastern States.

Estimates of carbon sequestration rates in Floridian mangroves range from 0.03-3.8 Mg of C per hectare (Sifleet and others, 2011 and citations therein). Annual carbon sequestration rates have been calculated for 39 mangrove sites worldwide. Values range from 0.03 to 6.54 Mg of carbon per hectare. However, most estimates fall below 1.9 Mg per hectare per year (Sifleet and others, 2011 and citations therein). Annual carbon sequestration data are available for 377 seagrass sites worldwide. Values range from -21 to 23.2 Mg of C per hectare. A large number of estimates show annual net losses of carbon (Sifleet and others, 2011). Most estimates of annual seagrass bed sequestration show 1.9 Mg of C per hectare.

Soil carbon

Climate change induced perturbations in nutrient cycling and precipitation is very likely to impact the ability of soil to sequester and store carbon. Currently, soil carbon levels are most influenced by rates of land use change. In general, switching from cropland to grassland and forest increases carbon levels in the soil (Post and Kwon, 2000; Powlson and others, 2011). How much additional soil is conserved in such transitions is open to debate (Dlugofl and others, 2010; Syswerda and others, 2011; Rumpel and Kogel-Knabner, 2010; Powlson and others, 2011). Further, the soil carbon sequestration benefits created by various less intense land use management practices are in doubt; for example, benefits from reduced tillage are relatively small, and increased N_2O emissions observed in some cases could offset increases in stored carbon (Powlson and others, 2011).

4.3. HOW WILL CLIMATE CHANGE AFFECT ECOSYSTEM SERVICES AND HUMAN WELL BEING OVER THE NEXT 50 TO 100 YEARS?

The status of ecosystem services summarized above point to regional, species- and habitat-based differences in the current distribution of services and their impacts on human well-being. Below we summarize information on the vulnerability of ecosystem services under future climate conditions (**Table 4.1**). In some cases, ecosystem service delivery and value will increase; and in others, there is a high likelihood that the benefits from ecosystem processes to humans will be severely reduced under projected future climate. Vulnerability in ecosystem services and the impacts on human communities are likely to vary in the future due to where people are located, or because of particular susceptibility of habitats or species upon which the service values depend. Here we briefly highlight ecosystem services that are particularly vulnerable to climate change or that have not been previously summarized (**Table 4.2;** table is located at the end of *Chapter 4*)).

4.3.1 Marine fishery yields

The range and abundance of economically important marine fish already are shifting due to climate change and they are highly likely to continue to change; some local fisheries are very likely to cease to be viable, whereas other fisheries may increase in value if the fishing community can adapt to the changes. Globally, fish species are projected to shift 45-49 km/decade poleward under the A1B future climate scenario (Cheung and others, 2009), and thus the abundance and availability of fish are projected to decline (Cheung and others 2011). Fisheries potential is projected to decline under future climate in coastal lower 48 States, but increase in parts of Alaska (Cheung and others, 2010). In the northeastern U.S., Atlantic croaker are likely to increase, while pollock, haddock, and cod decrease (Hare and others 2010; Fogarty and others, 2007; Lenoir and others, 2010) (**Box 4.1**). In the NE Atlantic, fish distributions are projected to shift 5.1 m/decade deeper under future climate (A1B) (Cheung and others, 2011). Salmon ocean habitat is projected to disappear from the Gulf of Alaska (Abdul-Aziz and others, 2011). Not all marine species can move quickly in response to climate. Some fishes and invertebrates spend little time dispersing as larvae and move little as adults (Kinlan and Gaines, 2003; Shanks, 2009). Whether these and other species will keep up with climate change remains an important question. Similarly, fishery-based industries are likely to bear increased costs due to transitioning to new species, relocation of processing plants and fishing jobs poleward (NCA, 2009; Sumaila and others, 2011), but these socio-economic impacts have not been well studied.

4.3.2 Nature-based recreation and tourism

Climate change impacts on outdoor recreation are projected to be most profound in winter sports and in beach recreation (**Tables 4.1 and 4.2**). There is a high probability of abbreviated ski seasons in many parts of North America. The California ski season is expected to shorten by 49-103 days, potentially missing the Christmas-New Year's week (Hayhoe and others, 2004). Snow seasons are very likely to shorten by 5-60 percent in various parts of the Northeast (Scott and others, 2006; Dawson and Scott, 2007; Scott and others, 2008). In the Pacific Northwest, 12.5 percent of ski areas in the Cascades and 60 percent of ski areas in the Olympic range are at risk due to increasingly frequent warm winters (Nolin and Daly, 2006), and Arizona resorts may be unable to forestall losses to the ski season after 2050, due to insufficiently cold temperatures for snowmaking (Bark and others, 2010). If drier conditions lead to a greater frequency of dust storms, windblown dust on snow will also increase rates of snowmelt, shortening the ski season and increasing evapo-transpiration, resulting in reduced water flows to the Colorado River (Painter and others, 2010). Snowmobile areas will be particularly vulnerable to economic losses because snowmaking is not practical on the terrain exploited by snowmobile enthusiasts (Scott and others, 2008). In addition to economic losses from lower visitation and increased costs of snowmaking at ski areas, homeowners in winter sports resort areas are expected to suffer declines in home value (Butsic and others, 2011).

Beach recreation losses will result from loss of beach width due to the combined effects of sea level rise and erosion. Narrower beaches make it harder to access fishing sites for anglers, and are less attractive to sunbathers. An analysis of projected losses due to beach erosion from 2006 to 2080 in North Carolina estimates losses of over $1 billion due to reduced recreation (Whitehead and others, 2009); a similar analysis for Southern California projects negative impacts of climate change on beaches, amounting to $63 million annually (Pendleton and others, 2011). However, beach user days may increase with warmer, drier weather, possibly resulting in economic gains in some areas (Loomis and Crespi, 1999).

The potential for longer stretches of more pleasant weather for enjoying the outdoors may actually increase some recreation opportunities, or simply shift others to new areas. For these activities, it is unclear what the net effect in human well-being will be; for instance, one study found that visitation to Rocky Mountain National Park would increase with higher temperatures (Richardson and Loomis, 2005), while other parks are projected to lose visitors if catastrophic fires result from drier conditions (Starbuck and others, 2006). "Winter sun" and "summer cool" destinations for retirees will redistribute around North American cities (Scott and others, 2004), whale-watching outfitters will have to shift locations to improve the reliability of their sightings (Lambert and others, 2010), and some recreational anglers will have to switch from cold-water species like salmon and trout to warm-water fish like bass and perch (Pendleton and Mendelsohn 1998). Golfing and boating are projected to increase with good weather (Loomis and Crespi, 1999; Shaw and Loomis, 2008); diving and snorkeling may experience losses due to declines in coral reef habitat.

Recreation is considered an ecosystem service not only because it has economic value, but also because it contributes to cultural well-being. Another cultural service at risk from future climate change is traditional subsistence hunting by indigenous people of the Arctic. Among coastal Inupiat people, hunting is a substantial contributor to dietary protein, a source of cash income, and a cultural touchstone (Gearheard and others, 2006). Climate change is decreasing the extent of sea ice and breaking up the sea ice earlier (Gearheard and others, 2006), changing the abundance and migratory patterns of wildlife (Kruse and others, 2004), decreasing the predictability of weather conditions (Ford and others 2006), increasing storminess and windiness (Ford and others, 2006; Hinzman and others, 2005), and generally increasing hazards to traditional hunters (Ford and others, 2006; Ford and others, 2008). Indigenous hunters in Alaska are projected to spend less time hunting (Berman and Kofinas, 2004), suffer decreased wildlife harvests (Hinzman and others, 2005; Kruse and others 2004) and the obsolescence of the traditional ecological knowledge that has guided weather prediction and risk assessment for centuries (Ford and others, 2006).

4.3.3 Hazard reduction by coastal habitats

Climate change has a very high likelihood of increasing property loss and vulnerability of people to coastal hazards (**Table 4.1**). With the projected accelerated rise in sea level and increased storm intensity in some areas, the conflicts between development along the coast and the protective value of natural processes will likely increase, causing negative economic and societal impacts (Titus and others, 2009). Modeling of future storm surges suggests that the number of people affected by flooding worldwide will increase five-fold by 2080 (Nicholls and others, 1999). Rising sea level is making populations in low-lying coastal areas increasingly vulnerable to catastrophic floods and coastal erosion from storms (McGranahan and others, 2007; Fitzgerald and others, 2008). In summary, over the next 50 to 100 years the vulnerability of people and property in coastal areas is highly likely to increase dramatically – due to the effects of sea-level rise, storm surge, and the loss of habitats that provide protection from flooding and erosion.

Some regions of the U.S. are particularly at risk from climate-related coastal hazards (**Table 4.2; Box 4.3**). The Atlantic and Gulf of Mexico coasts are most vulnerable to the loss of coastal protection services provided by wetlands and coral reefs. A prime example is the Gulf of Mexico coast, where a combination of sea level rise (SLR), exposure to large storms, coastal development, large river systems, and engineered coastlines puts thousands of people and acres of property at risk from flooding and erosion from storm surge flooding (**Box 4.3**). Along the California coast, a 1.4 m sea level rise would put an anticipated 480,000 people at risk of a 100-yr coastal flooding event, and cause nearly $100 Billion in damages (Heberger and others, 2009). In addition, large sections of the Pacific Coast are vulnerable to erosion – which would accelerate with sea level rise. Such erosion is projected to result in a loss of 41 sq. miles from the California coast by 2100, affecting more than 14,000 people who currently live in the area (Heberger and others, 2009). In the northeast, a Long Island example indicates that even modest sea level rise (0.5 m by 2080) would dramatically increase the number of people (47 percent increase in persons affected) and property loss (73 percent increase) impacted by storm surge (Shepard, 2011). Similarly, approximately 1 percent to 3 percent of the land area of New Jersey would be permanently inundated over the next century under modest sea-level rise scenarios (0.61m-1.22m) (Cooper and others, 2008). As a result, coastal storms coming ashore in New Jersey could temporarily flood low-lying areas up to 20 times more frequently as marsh and other protective habitats are inundated (Cooper and others, 2008).

In addition to direct increases in inundation and erosion through sea-level rise, loss of protective coastal habitats places certain regions at particular risk of greater damages in the future. Effects of climate change on coastal hazards will depend both on changes in wave and storm events, and on effects of sea level rise and other climate-related variables on coastal habitats (for example, coastal forests, wetlands, dunes, and corals). Climate impacts on these habitats will likely include increases in the intensity and frequency of storms, sea level rise, salt water intrusion, warming temperature, and ocean acidification, and human modification of the shoreline in response to rising seas. The ability of coastal ecosystems to provide protection from future climate-related hazards depends upon their ability to adapt to changing conditions (Alongi, 2008). Wetlands are extremely vulnerable to sea-level rise and can maintain their elevation and viability only if sediment accumulation (both mineral and organic matter) keeps pace with sea-level rise and tidal range is not too extreme (Morris and others, 2002; Temmerman and others, 2004; Stevenson and Kearney, 2009). Controversy exists about whether wetlands,

Box 4.3: Climate Impacts on Coastal Hazards in the Gulf of Mexico
Author: Katie Arkema

The Gulf coast region is especially vulnerable to a changing climate because of its relatively flat topography, rapid rates of coastal lands subsidence, land and waterway engineering, coastal development and exposure to large storms. Sea level rise is likely to increase the vulnerability of Gulf coast communities by increasing flooding during storm events. For example, Katrina and Rita were the fourth and fifth most powerful storms to strike the Mississippi Delta since 1893 with respect to maximum wind speed at landfall, but they both were more devastating for the hundreds of kilometers of the coast affected by a storm surge exceeding 3 m. Climate models project that sea level will rise by 0.3 to 1.0 m along the Gulf Coast in the next century (Twilley, 2007). Because of high rates of land subsidence in the Mississippi Delta, relative sea-level rise – the combination of absolute sea level rise and subsidence – is about 1 cm/yr in contrast to eustatic sea level rise of 1.5 mm/yr (Day and others, 2007).

In addition to the direct effects of sea level rise and storms, vulnerability of the Gulf coast to climate change also accrues through indirect processes, through the loss of protective salt marshes and coastal forests caused by a combination of rising ocean temperatures, ocean acidification, flooding and salt-water intrusion (Craft and others, 2009). Simulations from numerical models (Wamsley and others, 2010) and empirical observations (USACE, 2006) have highlighted the importance of coastal wetlands for providing the Gulf coast with protection from flooding and storms. Yet, some regions of the Gulf coast, such as the Mississippi River delta and Florida Everglades are experiencing some of the highest wetland loss rates of the country (Twilley, 2007). Nearly 5,000 km^2 of wetlands have been lost from coastal Louisiana at rates as high as 100 km^2/year (Gagliano and others, 1981; Britsch and Dunbar, 1993). Coastal development and engineering can increase the vulnerability of these wetlands to climate change and diminish their ability to provide protection for surrounding areas in the future. Large restoration efforts are underway to restore the functioning of the system (Day and others, 2007), but climate change will likely also affect watersheds that feed coastal ecosystems. Hydrology will depend on effects on precipitation, evaporation and management of water resources, which could lead to periods of drought as well as flooding. For example, a 25-month drought, interacting with other environmental stresses, is considered the main cause of a severe dieback of 100,000 acres of salt marsh in coastal Louisiana in 2000 (Twilley, 2007).

The Gulf Coast is vulnerable to climate related coastal hazards for social as well as physical reasons (Boruff and others, 2005). Relatively high vulnerability of the Gulf Coast to erosion hazards is due primarily to the percent of the population over 65 years old, followed by birth rate, sea-level rise, mean wave height, and median age of the population. More generally, the effects of hurricanes may be indicative of the potential consequences of rising sea levels and changes in wave height under future climate scenarios. Communities unprotected by levees or where levees failed were inundated during hurricanes Rita and Katrina. More than 1500 people died as a direct or indirect result of Hurricane Katrina, almost 1100 of them in Louisiana (Day and others, 2007). Sea level rise would increase costs incurred due to storm surge flooding. For example, the economic damages resulting from Hurricanes Carla (1961), Beulah (1967), and Bret (1999) in Corpus Christi, Texas would increase by $30-$1,100 million under a 2080 climate scenario (Frey and others, 2010). Furthermore, the area of land flooded and the number of people affected in the projected storms would increase with respect to those impacts in the original storm (Frey and others, 2010).

Box 4.3, continued.

Climate adaptation planning is underway at the State, county, and local government levels along the Gulf coast (NOAA, 2011). These efforts are varied, ranging from assessments of the effects of rising sea levels on infrastructure, transportation systems, and property rights and using ecosystem protection as a means of reducing hazard risks in Louisiana.

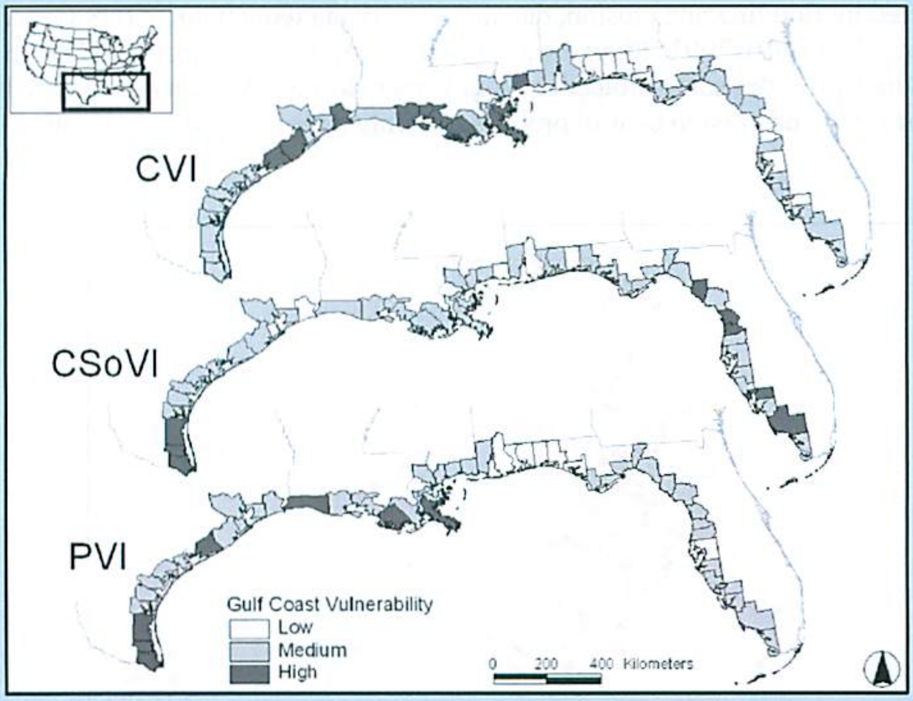

***Figure 4.2.** Vulnerability of Gulf coastal counties based on physical (CVI) and social (CSoVI) indicators and their integration into place vulnerability (PVI) (From: Boruff and others, 2005).*

and in particular U.S. marshes, can accrete and keep up with sea level rise or be lost to open water (Craft and others, 2009; Morris and others, 2002; Gedan and others, 2011). For example, the Atlantic coast of North America may experience one of the world's largest losses in wetlands due to projected sea-level rise (Nicholls and others, 1999). On the other hand, simulations of mangrove forest dynamics along the southwest coast of Florida suggest that forests will change in structure and composition; although diminished in height, future mangrove forests will likely be able to adapt to sea level rise and migrate inshore (Doyle and others, 2003, 2010).

There is a high likelihood that coral reefs will suffer much damage from climate impacts. Roughly one third of all reef-building corals are estimated to be at elevated risk of extinction due to projected climate change (Carpenter and others, 2008). Coral cover in Hawaii, Florida and the Gulf is likely to decrease, as warming and acidifying seas are very likely to compromise coral reef carbonate accretion worldwide (Hoegh-Guldberg and others, 2007). Degradation of other protective habitats, such as barrier islands along the Texas coast, combined with sea level rise may lead to increased flooding from even intermediate hurricane events (Irish and others, 2010; Frey and others, 2010).

Vulnerability and loss of protective habitats will be greater for those populations lacking the social and economic means to cope with the short and long-term consequences of coastal hazards. One study that projected storm surge inundation showed that for Hampton, Virginia, the most vulnerable regions to storm surge are those areas where the most socially vulnerable populations live (Kleinosky and others, 2007). In Alaska, 86 percent of Alaskan Native villages are already affected by flooding and erosion, due in part to rising temperatures (US General Accounting Office (USGAO), 2003; **Figure 4.3**). Further warming is projected to lead to greater loss of sea ice, which provides some protection from winter storms. As many of these villages do not qualify for flood and erosion control projects, the only option would be relocation (USGAO, 2003).

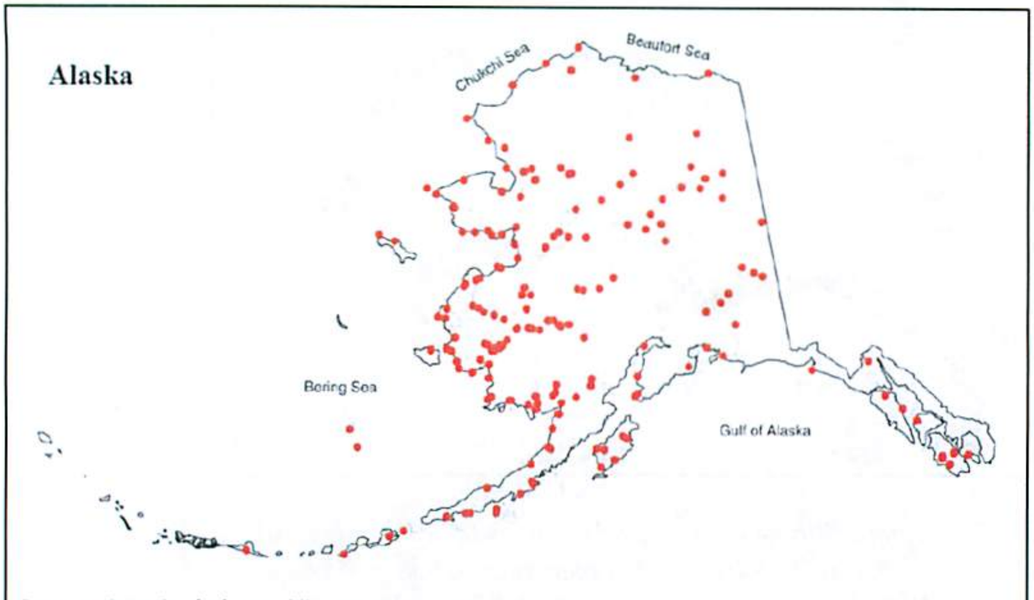

Figure 4.3. *Location of the 184 out of 213 Alaska Native villages already affected by flooding and erosion, due in part to rising temperatures (USGAO, 2003).*

4.3.4. Water supply and water quality under future climate

It is widely appreciated that water scarcity and water quality could become a significant problem for the United States. Some of this is driven simply by human population growth and human activities. However, climate is modifying the hydrological cycle in a way that makes water supply in some places increasingly subject to flash floods, and enhances evaporation and (or) evapo-transpiration (**Table 4.1**).

Much of the Western U.S. is projected to experience decreasing water yield under a number of future climate scenarios, especially the Southwestern U.S., Great Basin, and California (Walker and others, 2011). Snow pack driven systems are especially susceptible to changes in hydrology, with these river systems experiencing earlier peak flows and a reduction in dry season base flows throughout the western U.S. (Hamlet and others, 2005). Snowpack water storage has already been reduced in much of the U.S., with a greater percentage of precipitation falling as rain, and future projections for 2040 springtime (March-April) snow water equivalent indicate a reduction in all of the conterminous U.S (**Figure 4.4**) (Mote and others, 2005; Adam and others, 2009). To compound the problem, decreases in runoff—particularly during the dry season—may be coupled with increased flooding in some parts of country (Bukovsky and Karoly, 2011).

An increase in the number of U.S. counties with water sustainability risk by 2050 is projected as a consequence of climate change (**Figure 4.4**; Roy, 2012). Using a county-level water supply sustainability index based on attributes of susceptibility to drought, increase in water withdrawal, increased need for storage, and groundwater use, this research found that by 2050 climate change is projected to double the percent of counties with moderate or higher water sustainability risk (35 percent to 70 percent). Even more striking, the number of counties with high or extreme water sustainability risk (10 percent to 32 percent) would triple, and the number of counties with extreme risk is projected to increase 14-fold. The most at risk areas in the U.S. are the West, Southwest and Great Plains regions.

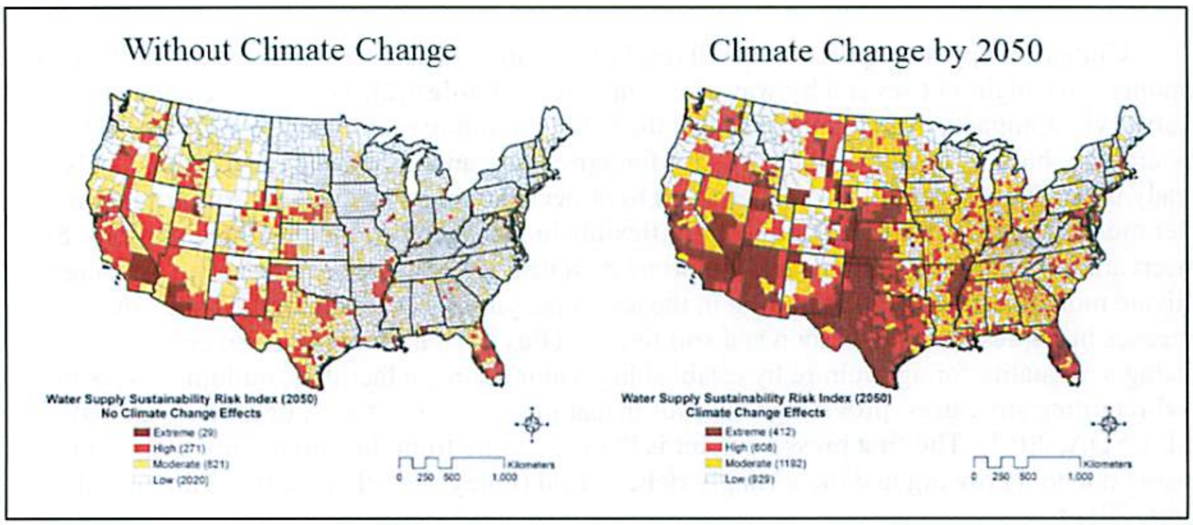

Figure 4.4*. The number of U.S. counties with water sustainability risk by 2050 with and without climate change (Roy and others, 2012).*

As the climate continues to warm and soil moisture deficits accumulate beyond historical levels, a consensus among climate model simulations suggests that sustaining water supplies in parts of the Southwest will be a challenge (Cayan and others, 2010). If this happens, an array of impacts could affect the American Southwest, including more dust storms that affect human health and traffic safety, and reduced soil fertility that affects agricultural yields and food security.

Some of these changes in climate and hydrology are expected to cause changes in water quality. The links between precipitation, temperature and nitrogen retention are well described (Vitousek and others, 1997). The flux of nitrogen from watersheds and exported to coastal waters is correlated with high rainfall and river discharge conditions (Howarth and others, 2012). Similarly, extreme precipitation and river discharge events are positively correlated with waterborne disease outbreaks (Curriero and others, 2001). Higher water temperatures can be associated with increases in nitrogen retention, but the relationship is weaker than the relationship of nitrogen with precipitation and discharge (Howarth and others, 2012).

Although these links with water quality have been observed under current climate conditions, few studies have projected the impacts of climate change on water quality. Several studies state that waterborne illness is likely to increase because extreme precipitation events increase the loading of contaminants to waterways (Rose and others, 2001; Curriero and others, 2001; Ebi and others, 2006). One regional study estimates the impacts of climate change on nutrient retention and the downstream impacts on the coastal ocean. Climate change projections for the Mississippi Basin (under doubled CO_2) indicate a 20 percent increase in river discharge that will lead to higher nitrogen loads and a 50 percent increase in primary production in the Gulf of Mexico, a 30-60 percent decrease in deep water dissolved oxygen concentration and an expansion of the dead zone (Justic and others, 1996).

4.4. WHAT RESPONSE STRATEGIES COULD ADDRESS THE MOST HARMFUL IMPACTS OF CLIMATE CHANGE ON ECOSYSTEM SERVICES?

Climate adaptation approaches will need to be implemented across all sectors of the U.S. economy—we highlight several by way of example here (**Table 4.2**). To combat expected negative yield impacts from climate change, the U.S. agriculture sector can improve the soils they crop on, both by reserving the best soils for agriculture and improving the marginal soils already used. Farmers could also better adapt to projected climate change by using irrigation water more strategically and becoming more flexible in management and planting decisions. Soil conservation will become particularly important as several global forces increase the pressure to cultivate more marginal lands, resulting in the accompanying risk of increased erosion and decreases in sequestered soil carbon and soil fertility (**Box 4.4**). Farmers can also enhance existing soil quality for agriculture by establishing major drainage facilities, building levees or flood-retarding structures, providing water for irrigation, removing stones, or grading gullied land (USDA, 2012). The first pressure point is likely to come from the strong growth in food demand due to a growing and increasingly richer world (Foley and others, 2011; Tilman and others, 2011).

Box 4.4. Adapting to Climate Change By Maximizing a Supporting Service: Soil Quality
Author: Erik Nelson

Projected climate change is very likely to require adaptation in crop production processes in the U.S. within the next 100 years. Farmers are likely to use technology and adaptive management (for example, different crop and variety choices, different input use, changing planting and harvesting dates) to maintain profits in the face of climate change. One significant pathway to adaptation could be shifting crops to the most productive soils, or improving the quality of existing soils.

The benefits of adaptation through improved soils can be estimated with a statistical model that describes variation in corn yield in Illinois, Indiana, Iowa, Minnesota, Michigan, and Ohio counties as a function of time, county growing season weather, and distribution of soil capabilities (USDA-NASS, 2011; CRU, 2010; Radeloff and others, 2012). The model uses annual 1950 to 2008 data as well as data on percent of county land used for corn, soybeans, wheat, and all other land use types. Counties are grouped according to their soil quality profile; counties with the most capable soil profiles are in the soil class 5 group, counties with slightly less productive soils are in the soil class 4 group, and so on. Soil class 1 includes the counties with the least capable soils (**Figure 4.5**). **Table 4.3** presents the expected average annual yield on a typical acre in each soil class using 2000 to 2008 data on average crop type distribution and growing season weather. The estimated yields from **Table 4.3** are plotted in **Figure 4.6**.

Table 4.3. *Predicted annual corn yield from 2000 to 2008*[3]

Soil Class	Estimated yield (bu / acre)	Avg. annual growing degree days (GDD)	Avg. annual growing season precipitation (mm)	Average annual share of class corn production across 6 States
5	156	2,301	521	34 percent
4	147	2,292	503	26 percent
3	141	2,391	512	22 percent
2	134	2,427	517	15 percent
1	121	2,178	499	3 percent

Table 4.3 Notes: Temperature only adds to GDD if it is 5 degrees Celsius or greater for corn growing seasons defined in Sacks and others (2010). Only precipitation that occurs during the growing season is counted. Counties with significant missing data on soil capabilities are dropped from the dataset used to estimate the model.

As expected, after controlling for growing season weather from 2000 to 2008 and distribution of land uses across counties, a typical acre in soil class $c + 1$ is predicted to generate higher yield than a typical acre in class c. The results in **Table 4.3** indicate how much U.S. corn production could increase under current weather conditions if corn production was shifted from lesser soils to better soils (and the associated change in management practices associated with farming on better soils). There is significant capacity to do this right now without negatively affecting the production of other crops. The number of acres available for cropland use in the

[3] Data and statistical model code can be found at (http://www.bowdoin.edu/faculty/e/enelson/index.shtml); data used for predictions are from 2000-2008

Box 4.4, continued.

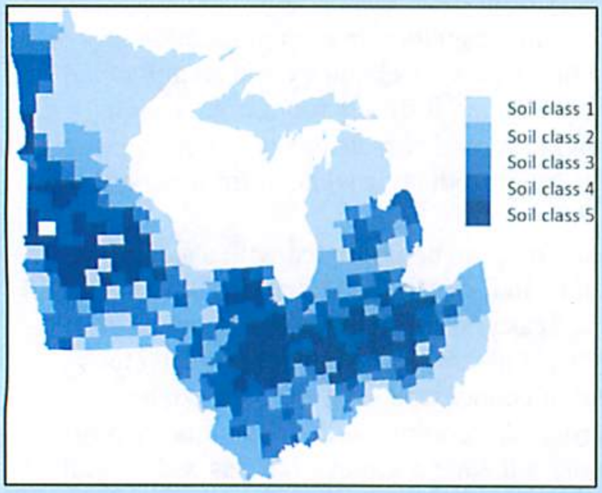

***Figure 4.5**. A map of soil classes.*

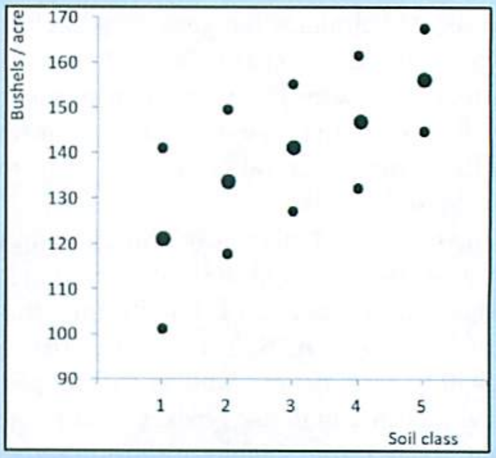

***Figure 4.6**. Estimated average corn yield from 2000-2008 by soil class. The smaller dots indicate estimated yield plus and minus 1 standard deviation.*

most capable soils (the type of soils found in the typical acre in soil class 5) in each soil class as of 2001 is given in **Table 4.4**.

The use of these better soils would come at an ecosystem service cost, however, as much of this soil is under forest and other natural land covers (for example, restored prairie) and conversion to cropland would result in a reduction in stored carbon, habitat for some species, water regulation capacity, and recreational lands.

Another management strategy for increasing current corn production with little to no ecosystem service loss would be to increase the soil capability on a typical acre in soil class $c - 1$ such that it mimicked the soil capability of a typical acre in soil class c (and adopted the higher class' typical management practices as well). **Table 4.5** reports expected contemporaneous yield gains given recent weather trends (2000 through 2008) for an acre in soil class $c - 1$ that mimics the soil capacity of an acre in class c.

***Table 4.4.** Acres available for cropping on the best soils as of 2001*

Soil Class	Acres of undeveloped acres in the most capable soils as of 2001	Average number of acres used for corn harvest from 2000 to 2008
5	2,088,003	12,843,674
4	3,362,076	10,089,931
3	4,240,432	8,295,655
2	5,414,875	5,575,536
1	19,183,846	1,314,666

Table 4.4 Notes: Data in the "Acres of undeveloped acres in the most capable soils as of 2001" column comes from Radeloff and others (2012). Undeveloped acres available in the most capable soils for cropping include protected cropland and protected and unprotected pasture, forest, and range in the land capability classes 1 and 2 (USDA-NRCS, 2012).

Box 4.4, continued.

Table 4.5. *Contemporaneous yield impact of marginal soil improvement*

Soil Class Improvement	Increase in expected yield due to soil improvement (bu /acre)	Average number of acres harvested for corn from 2000 to 2008 in the original soil class (acres)	Gain in corn production all else equal (bu)
4 → 5	4.2	10,089,931	42,377,710
3 → 4	-1.1	8,295,655	-9,125,221
2 → 3	2.0	5,575,536	11,151,072
1 → 2	15.1	1,314,666	19,851,457
Total			64,255,018

Table 4.5 Notes: These results use the observed weather from class $c - 1$. For example, the predicted increase in expected yield due to improving the corn soil typically found in counties in class 1 to corn soil typically found in counties in class 2 uses the observed weather from soil class 1.

By multiplying the typical number of corn acres in a class "Average number of acres harvested for corn from 2000 to 2008 in the original soil class (acres)" by the expected gain in yield due to soil improvement, the productive value of a uniform one-soil-class improvement across the 6 States is determined "Gain in corn production all else equal (bushels)". Using this number as a baseline, this uniform improvement in soil capabilities across all classes would increase bushel production across the six State area by 1 percent, all else being equal.

Climate change

Measured climate change, especially change in GDD, over corn acres in the six States was relatively minor from 1950 to 2008. **Table 4.6** reports the percentage change in average annual GDD and growing season precipitation by soil class between the periods of 1950–1958 and 2000–2008.

Most climate models predict much more rapid climate change over these six States in the next 50 years. **Table 4.7** presents predicted average corn yield in the period 2050–2058 by soil class assuming that average annual GDD and growing season precipitation increase 10 percent between the periods of 2000–2008 and 2050–2058 across the entire study area.

Table 4.6. *Change in average annual corn GDD and growing season precipitation between the periods of 1950–1958 and 2000 –2008*

Soil Class	Change in average annual GDD	Change in average annual growing season precipitation
5	0.9 percent	13.2 percent
4	0.9 percent	13.2 percent
3	0.2 percent	14.0 percent
2	1.0 percent	11.5 percent
1	4.5 percent	10.7 percent

Even with accelerated climate change, average corn yields are predicted to be much higher in 50 years than they are today over all soil classes (see **Table 4.3** for comparison).

Box 4.4, continued.
Much of the expected gain in yield corn as reported in **Table 4.7** is due to the extrapolation of past technological rates of change into the future. In **Table 4.8**, we predict average yields between 2050–2058 with uniform 10 percent climate change, but now assume that technological improvements in corn farming occur at half the rate that they did in the past.

Table 4.7. *Predicted average corn yield in the period 2050–2058 assuming that average annual GDD and growing season precipitation increase 10 percent between the periods of 2000-2008 and 2050 – 2058 across the entire study area.*

Predicted 2050 – 2058				
Soil Class	**Average annual GDD**	**Average annual growing season precipitation**	**Predicted yield (bu /acre)**	**Percentage increase in yield between 2000-2008 and 2050 – 2058**
5	2,531	573	235	50.6 percent
4	2,521	553	222	51.0 percent
3	2,630	564	209	48.2 percent
2	2,670	569	204	52.2 percent
1	2,395	549	184	52.1 percent

Table 4.8. *Predicted average corn yield in the period 2050–2058 assuming that average annual GDD and growing season precipitation increase 10 percent between the periods of 2000-2008 and 2050–2058 across the entire study area but technological improvements in corn farming occur at half the rate that they did in the past.*

Predicted 2050–2058				
Soil Class	**Average annual GDD**	**Average annual growing season precipitation**	**Predicted yield (bu. /acre)**	**Percentage increase in yield between 2000-2008 and 2050–2058**
5	2,531	573	191	22.4 percent
4	2,521	553	181	23.1 percent
3	2,630	564	171	21.3 percent
2	2,670	569	164	22.4 percent
1	2,395	549	151	24.8 percent

A more pessimistic scenario would include more rapid climate change. **Table 4.9** shows the results from such a scenario—specifically an across the board GDD and growing season precipitation increase of 20 percent from 2000–2008 to 2050–2058 and technological progress slowing to half its historic rate.

Under this last scenario of accelerated climate change and slowing technological progress, there is great opportunity for adaptation by improving the most marginal corn soils (**Table 4.10**). Specifically, an extra 23 bushels could be obtained per acre by improving the soil quality of the most marginal corn land (and adopting the management practices typical on slightly better soils).

Box 4.4, continued.

These analyses of soil supporting services in conjunction with climate change show that better selection of high quality soils, and improving lower quality soils will likely provide a strong capacity for adaptation. Examples of management changes to improve soil quality include establishing major drainage facilities, building levees or flood-retarding structures, providing water for irrigation, removing stones, or large-scale grading of gullied land (USDA 2012). Previous analyses of ecosystem services have focused on the direct impacts of climate change on provisioning and regulating services. One hypothesis suggested by analyses of soil supporting services is that better management of supporting services in general could provide substantial adaptive capacity for the negative impacts of climate change on other services.

Table 4.9: *Predicted average corn yield in the period 2050–2058 assuming that average annual GDD and growing season precipitation increase 20 percent between the periods of 2000-2008 and 2050–2058 across the entire study area but technological improvements in corn farming occur at half the rate that they did in the past.*

Predicted 2050–2058				
Soil Class	**Average annual GDD**	**Average annual growing season precipitation**	**Predicted yield (bu. /acre)**	**Percentage increase in yield between 2000-2008 and 2050–2058**
5	2,761	625	172	10.3 percent
4	2,750	603	166	12.9 percent
3	2,869	615	156	10.6 percent
2	2,912	621	151	12.7 percent
1	2,613	599	143	18.2 percent

Table 4.10. *Potential improvements by improving marginal corn soils.*

Soil Class Improvement	**Marginal gain in expected yield due to investment in soil (bu. /acre)**
4 → 5	2.1
3 → 4	-4.5
2 → 3	-3.0
1 → 2	23.3

Other agriculture management approaches could help address climate impacts on nitrogen retention. The main driver of nitrogen pollution in U.S. waterways is anthropogenic input (Howarth and others, 2012). Reducing fertilizer application rates could reduce pollution directly. Many current practices, such as tile drains and leaving fields fallow without cover crops, circumvent the ability of natural capital to retain nitrogen before it reaches riverways (Raymond and others, 2012). Reducing the use of tile drains and increasing the use of cover crops could increase nitrogen retention on the landscape.

For timber production, private forest managers have the financial incentive and the flexibility to protect against extensive loss from climate-related impacts. They can use several existing management techniques: short rotations to reduce the length of time that a tree is influenced by unfavorable climate conditions; planting improved varieties developed through selection, breeding, or genetic engineering to reduce vulnerability; and thinning, weeding, managing pests, irrigating, improving drainage, and fertilizing to improve general vigor. Such actions are likely to reduce the probability of moisture stress and secondary risks from fire, insects, and disease.

Strategies to secure food and secondary feed supplies from fisheries can use existing management approaches. Stock assessments that form the basis of regulated catch limits increasingly incorporate modeled climate-driven shifts in fish spatial distributions (Barange and others, 2011; Ianelli and others, 2011); and protection and restoration of habitats for nursery and other life stages can bolster stock resilience to environmental change (Hughes, 2007; Perry and others, 2010; McGilliard and others, 2011). However, the more rapid the rate of climate change, the more it may strain the ability of ecosystems to support the supply of crops, timber, or fish (Oswalt and others, 2009; Lobell and others, 2011; Perry and others, 2010). A faster rate of warming also may limit species constrained by slow dispersal rates and/or habitat fragmentation, or those that are already stressed by other factors, such as pollution.

Developing alternative livelihood options as part of climate adaptation strategies for food and timber producing sectors can help avoid surprises under future climate (Marschke and Berkes, 2006; Coulthard and others, 2011). These strategies can help identify conditions under which fishing- or timber-based communities should be encouraged to undergo livelihood diversification, shift the location of their fishing and timber harvest, or change livelihoods.

Assessments show that where ecological resilience is high (for example, habitat heterogeneity and connectivity among habitats is maintained), marine and terrestrial systems will be better equipped to respond to climate-related changes in storms, freshwater runoff, harvest pressures, and other potential stressors (Adger and others, 2005; Gaines and others, 2010; Howes and others, 2010). There is promise in using restoration of key habitats to provide a broad suite of benefits ameliorating climate impacts with relatively little ongoing maintenance costs. For example, if an oyster reef or mangrove restoration strategy included consideration of not only sea level rise, but also fish habitat benefits for commercial and recreational uses and coastal protection services, the benefits to surrounding communities could multiply quickly (Aburto-Oropeza and others, 2008; Das and Vincent, 2009). Although restoration strategies are less certain—and often more expensive—than protection of intact ecosystems, in many parts of the world protection alone will be insufficient to ensure the provision of benefits. More work is needed to move beyond general principles and understand the cost effectiveness of alternative 'gray' versus 'green' approaches to climate adaptation and to identify conditions under which ecosystem versus technological approaches are most likely to sustain benefits.

Payments for ecosystem services are occurring through standard approaches such as wetland banking, land acquisitions for conservation (Madsen, 2011), and payments for watershed services, which totaled $1.35 billion in the U.S. in 2008, primarily through the Farm Bill (Stanton, 2010). The only ecosystem market explicitly developed to address climate concerns is for carbon. Forest carbon sequestration projects already exist and payment plans for landowners who decide not to cut their trees are beginning to come on-line (Canadell and Raupach, 2008; Arriagada and Perrings, 2011). In 2010, global prices paid for qualified sequestered forest carbon ranged from $4.30 to $47.50 per ton (Diaz and others, 2011).

Further, innovative approaches to adjusting user-fees to account for maintenance and protection costs of valuable, natural habitats are growing in popularity. For example, destructive fishing in coral reefs has high initial economic value, but the combined sustainable fishing, tourism and coastal protection benefits of more protected reefs have higher value for climate adaptation over time (WB, 2010).

Ecosystem services do not vary independently of one another, and as a result, one general strategy for responding to harmful reductions in one ecosystem service is to boost another ecosystem service, or to reduce interacting stressors. One hypothesis suggested by analyses of soil-supporting services is that better management of supporting services in general could provide substantial adaptive capacity for the negative impacts of climate change on other services. A second general principle is that policies and incentives aimed at getting people to behave differently, or change the location and type of livelihoods they engage in, may be necessary. For example, paying farmers to increase soil carbon and retain nitrogen could compensate for the negative impacts of climate change on water quality and on carbon sequestration.

4.5. CRITICAL GAPS IN KNOWLEDGE, RESEARCH, AND DATA NEEDS FOR CLIMATE IMPACTS ON ECOSYSTEM SERVICES

Among the numerous gaps in our scientific understanding of how ecosystem services will respond to climate change, a few stand out as critical to answer in the next 5-10 years if society is to be able to reduce the human and economic costs of the climate disruption we are already observing:

- What are the likely effects of climate change on rates of carbon storage and sequestration in soils and vegetation? Are there farming practices that can be implemented to substantially enhance soil carbon in a predictable manner?
- What are likely effects of climate change on water quality regulation in freshwater streams and rivers?
- How can fishery management best respond to climate impacts in a way that maintains harvest and jobs without putting the resource base at risk?
- "Green" energy use in the U.S. is increasing in part as a response to climate change. What impact will an increasing reliance on "green" energy have on ecosystem services? For example, how do windmills, solar panel arrays, and land area and water used to create biofuel feedstocks affect service delivery and value?
- What specific incentives, regulations, management strategies, or investments can be implemented to allow fishing, farming, timber, agricultural and aquaculture communities to adapt to changing and more variable climate conditions?
- What is the relative cost-effectiveness of engineered versus ecosystem-based approaches to reducing vulnerability of communities to coastal hazards?
- What is the current distribution and abundance of coastal habitats that provide protection from coastal hazards? Where could restoration of these habitats deliver the greatest value to coastal communities?
- How can vulnerable communities get specific information about projected climate change impacts at local and regional scales that would be useful in planning for hazards and promoting resilience?

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***Table 4.1.** Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Coastal flood protection	Over the past 200 years, 0.4 million ha of salt marsh has been lost in North America (Sifleet and others, 2011). Globally, seagrasses have been disappearing at a rate of 110 km^2/yr since 1980 (Waycott and others, 2009); and mangrove systems worldwide have declined at 1.4 percent/yr (Valiela and others, 2001). Coastal protection services have been lost (Barbier and others, 2011). Decrease in sea ice extent and earlier breakup of sea ice (Gearhead and others, 2006; Jones and others, 2009), are contributing to erosion and flooding of coastal areas.	Coastal marshes provide \$8236/ha/yr in reduced hurricane damages (Costanza and others, 2008). Some Native Alaskan communities have had to relocate their villages due to loss of protective sea ice (U.S. General Accounting Office 2003).	Total impacts of sea-level rise are expected to put as many as 480,000 people at risk from a 100-yr flood event, causing ~\$100 Billion in damages (Heberger and others, 2009). Modest and probable sea level rise in Long Island (0.5 m by 2080) increases the number of people (by 47 percent) and property loss (by 73 percent) impacted by storm surge (Shepard and others, 2011). Climate change contribution to losses in extent of coastal marsh, mangrove and seagrass habitats is uncertain.	Sea-level rise and warming temperatures may promote expansion of coastal habitats to higher latitudes or further inland, provided that space to migrate upslope is available. Climate change may also alter rainfall patterns, which would in turn change local salinity regimes and competitive interactions of coastal plant communities with other wetland species (USGS 2004). Ability of mangroves and coastal marshes to keep up with sea level rise is uncertain. There is greater certainty that coral reefs will suffer severe damage. As much as one-third of reef building corals worldwide are at risk of extinction from climate change (Carpenter and others, 2008) Sea ice will continue to decline in spatial extent (Doney and others, 2012).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Coastal erosion protection	Coastal erosion and Hurricane Katrina's damages to the areas surrounding New Orleans have reduced the natural storm defenses around the city by more than 500 square miles (U.S. ACE 2006). (see Coastal flood protection)	Preventing beach erosion along an 8 km beach in Maine and New Hampshire was worth $4.45/household (Huang and others, 2007). Oceanfront property increases in value by $233 per meter of beach width in Tybee Island, Georgia (Landry and others, 2003). If erosion remains at current levels, the cost of allowing Delaware beaches to retreat inland is about $291 million (Parsons and Powell 2001).	Over the past 2-3 decades, wave heights have increased all along the coast of the U.S., causing higher rates of erosion (Komar and Allan, 2006, 2008). It is unclear whether this is due to climate change or environmental variability. Governments are incurring high costs to maintain their beaches. For example, from 1990-2000 Delaware paid $15-$20 million to replenish its 25 miles of beaches (Parsons and Powell 2001). (see Coastal flood protection)	(see *Coastal flood protection*)

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Fire regulation	Average of 6.5M acres/yr burned in U.S. (NOAA 2011).	U.S. FS spent more than $1B/yr on fire suppression alone in 5 of the 7 years during 2003-2009 (Venn and Calkin 2011).	Increased evapotranspiration, earlier spring, and higher temperatures have lead to 4x increased incidence of wildfire and 6x increased area burned since mid 1980s.	Area burned in western U.S. forests would increase 3-6.5x with each 1°C increase. Plant communities expected to change w/ changing fire regimes (Westerling and others, 2011).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Carbon storage and sequestration in forest biomass	Increased biomass sequestration and storage slows down rates of climate change. Forests in the lower 48 are sequestering approximately 191 Tg of C/year (Woodbury and others, 2007; EPA 2008); equivalent to 10 percent of the U.S.'s annual CO_2 emissions. Currently, forest biomass carbon stocks are highest in the Pacific Northwest (Washington, Oregon, northern California; Woodbury and others, 2007); moderate stocks occur along the Appalachian Mountains (Oswalt and others, 2009). Sequestration rates in managed forests are highest in the Northeast (E. Nelson analysis).	Increased biomass sequestration and storage slows down economic damages associated with climate change. Estimates of the value of every additional ton of C sequestered range from $25 to $675 (Tol 2009).	Climate change has induced perturbations in forest distribution, forest growth rates, and risk of degradation via fire, invasive species, and disease. These perturbations are reducing rates of sequestration and expectations for C storage periods (Allen and others, 2010).	Climate change is predicted to affect the rate of tree growth in managed forests, both positively and negatively (Latta and others, 2010). The types of trees and/or management practices in an area also may change. Further, the risks to forests from fire and disease will increase (Allen and others, 2010; Lata and others, 2010; Liu and others, 2010; Haim and others, 2011). Payment for C storage and sequestration services would generate private value and alter the distribution of wealth in the U.S. Biomass carbon payment programs could affect the 11.3 million private forest owners who own 171 million ha in the U.S. (Oswalt and others, 2009).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Carbon storage and sequestration in soils	Transition from cropland to grassland and forest increases soil carbon (Post and Kwon 2000). However, how much additional soil is conserved in such transitions is open to debate (Dlugofl and others, 2010; Syswerda and others, 2011; Rumpel and Kögel-Knabner 2010; Powlson and others, 2011).	Increased sequestration and storage of carbon in the soil slows down rates of climate change and associated economic damages. Estimates of the value of every additional ton of C sequestered range from $25 to $675 (Tol 2009).	No known attribution of recent climate to changes in C storage and sequestration in soils.	Climate change is predicted to reduce the amount of carbon stored in soils world-wide (Parton and others, 1995). Payment for C storage and other ecosystem services would generate private value and alter the distribution of wealth in the U.S. The 2.2 million farms and 373 million hectares of farmland in the U.S. (40 percent of all U.S. land) could be impacted by such a payment program (U.S.DA-ERS 2012).
Carbon storage and sequestration in marine habitats	Coastal ecosystems sequester and store carbon in biomass in the short term and in sediments in the long term (Duarte and others, 2005; McLeod and others, 2011). Carbon sequestered by salt marshes, mangroves, and seagrass beds varies widely, from 0.003 to 17.13, 0.03 to 3.81, and -21 to 23.2 Mg of C per hectare, respectively (Sifleet and others, 2011).	Increased carbon sequestration and storage slows down rates of climate change and associated economic damages. Estimates of the value of every additional ton of C sequestered or not emitted range from $25 to $675 (Tol 2009).	The relationship between coastal habitat losses and climate change is unknown.	Changes in productivity of coastal habitats due to increasing temperature and changes in salinity are predicted to affect C storage and sequestration to an unknown degree. (see *Coastal flooding protection*)

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Water quality regulation	Sediments and turbidity currently impair 25 percent of lakes and 17 percent of rivers. Phosphorus impairs 18 percent of lakes and 14 percent of rivers. Nitrogen impair10 percent of lakes and 4 percent of rivers (EPA 2011).	Studies estimating the costs of nitrogen pollution are rudimentary and range from less than $1.00/kg N exported to $56/kg N exported (Compton and others, 2011).	Precipitation and river discharge are negatively correlated with nitrogen retention (Howarth and others, 2012). Temperature is positively correlated with nitrogen retention (Howarth and others, 2012). Areas with expected increases in precipitation could lose this service, and areas with expected increases in temperature could gain it. Extreme precipitation and discharge events are positively correlated with waterborne disease outbreaks (Curriero and others, 2001).	Waterborne illness is predicted to increase with climate change because extreme precipitation events increase the loading of contaminants to waterways (Rose and others, 2001; Curriero and others, 2001; Ebi and others, 2006). Climate change predictions for the Mississippi Basin (under doubled CO_2) indicate a 20 percent increase in river discharge that can lead to higher nitrogen loads and a 50 percent increase in primary production in the Gulf, a 30-60 percent decrease in deep water dissolved oxygen concentration and an expansion of the dead zone (Justic and others, 1996).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Timber yield	Since the 1950s, overall land devoted to timber production in the U.S. has stayed relatively constant, and the amount of reserved forests has increased 200 percent (Oswalt and others, 2009). Net growth of forest stock has consistently exceeded removals by approximately 3 percent. Timber mortality rates have remained well below 1 percent of inventory during the same time period; but mortality rates relative to inventory are currently at the highest level in 50 years (Oswalt and others, 2009).	Since the late 1980s the volume of the U.S. timber harvest has fallen slightly (approximately 450 million cubic meters of wood was produced in the U.S. in 2006 (Oswalt and others, 2009)), and imports are forming an increasingly larger portion of U.S. timber consumption (Oswalt and others, 2009).	Drought and warm temperatures across western North America in the last decade have led to extensive insect outbreaks and mortality throughout the region, affecting 20 million ha from Alaska to Mexico (Allen and others, 2010). It is uncertain whether current mortality rates are beyond the range of normal variability (USFS 2011). Wildland fire intensity and area burned have increased in recent decades (Running 2006; Westerling and others, 2006; Miller and others, 2008), and Federal agencies now spend more than $1 billion annually on fire suppression efforts (U.S. GAO 2006).	Overall increase in forest productivity is predicted to increase long-term timber inventory (Alig and others, 2002). "Timber harvests in most scenarios rise over the next 100 years, lowering timber prices, and reducing costs of wood and paper products to consumers and returns to owners. of timberland." (Alig and others, 2002, p. 9). How the increased risk to forests stands from fire and disease will affect these trends is unclear (Westerling and others, 2006, Oswalt and others, 2009; Allen and others, 2010; Liu and others, 2010). (see Carbon storage and sequestration in forest biomass)

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	**Human Well-being**	**ES and Human Well-being**	**ES and Human Well-being**
Agricultural yield	Currently, cropland accounts for 18 percent of land in the U.S. Pasture and rangeland account for another 27 percent of land in the U.S. (USDA ERS Datasets, "Major Land Uses"). In 2009, U.S. agriculture produced 31 percent of the world's coarse grains and 11 percent of the world's oilcrops (FAO STAT 2012).	The U.S. produced 10 percent of the globe's net production value in food in 2009 (FAOSTAT 2012).	Compared to the rest of the world, growing season weather has changed relatively little in the U.S. over the past 30 years (Lobell and others, 2011). This suggests yield trends in the U.S. over the past 30 years have been primarily driven by farm management, managed input use, technology, and cropland soil quality (Lobell and others, 2011).	Accelerated climate change may lead to greater yield impacts over the next 50 years. Temperature changes have had a more dramatic impact on corn, wheat, soybean, and rice yields around the world than changes in precipitation (Lobell and others, 2011). We estimate that in the Midwest U.S., climate change could reduce mid century maize yields by 2 to 14 percent compared to expected yields given no climate change; wheat yield could be reduced by 1 to 7 percent; and soybean yield could be reduced by 0.6 to 10 percent; (data and statistical model code can be found at http://www.bowdoin.edu/faculty/e/enelson/index.shtml).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Water provision (all)	Water largely allocated, with some conflicts (Christian-Smith and others, 2012).	36 percent of U.S. counties have moderate or higher water-supply sustainability risk (Roy and others, 2012).	Observed changes in precipitation, increasing ET (Dai and others, 2011; Hamlet and others, 2007), increasing extremes (U.S. GCRP 2009), snow to rain events (Hamlet and others, 2005). Effects of climate-induced changes in water provision on human well being are not well documented.	Predictions indicate changes in precipitation patterns (esp. decreases in Southwest, increases in North), increasing ET (Hamlet and others, 2007; Diaz and others, 2011), increasing extremes (IPCC SREX, 2011), snow to rain (Adam and others, 2009).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	**Current Status**		**Climate Change Impacts**	**Expected Future Climate Change Impacts**
	Ecosystem Service (ES)	**Human Well-being**	**ES and Human Well-being**	**ES and Human Well-being**
Marine fishery yields	In 2009, 7.9 billion pounds of fish and shellfish were landed in U.S. ports (NMFS 2010).	Fisheries added $48.3 billion and 1 million jobs to the U.S. economy in 2009 (NMFS 2010). Almost all communities within the Pacific Islands derive over 25 percent of their animal protein from fish, with some deriving up to 69 percent (NCA 2009).	Fish populations are shifting poleward and deeper (Nye and others, 2009; Murawski 1993; Mueter and Litzow 2008; Dulvy and others, 2008; Perry and others, 2005) and communities are transitioning from cold-water to warm-water species as local temperatures warm (Collie and others, 2008; Lucey and Nye 2010). Jobs, catch, and value for individual species are moving poleward as temperatures warm and as species shift poleward (McCay and others, 2011; Pinsky and Fogarty, written communication 2012.).	Globally, fish populations are predicted to shift 45-49 km/decade poleward (Cheung and others, 2009). Species like Atlantic croaker are predicted to increase in the northeastern U.S., while pollock, haddock and cod are predicted to decrease (Hare and others, 2010; Fogarty and others, 2007; Lenoir and others, 2010). Oceanic habitat for salmon is predicted to disappear from the Gulf of Alaska (Abdul-Aziz and others, 2011).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Marine aquaculture yields	In 2009, 720 million pounds of marine aquaculture were produced in the U.S. (Van Voorhees and Lowther 2010).	Shellfish produced in the U.S. was worth $280 million in 2009 (Van Voorhees and Lowther 2010).	Ocean acidification impedes growth and reproduction, particularly in calcifying organisms such as shellfish (Kurihara 2008; Miller and others, 2009; Kroeker and others, 2010). New diseases have moved poleward as temperatures warmed (Hofmann and others, 2001).	Warm temperatures are predicted to increase aquaculture potential in poleward regions, but decrease it in the tropics (De Silva and Soto 2009). Acidification, will reduce growth and survival (Cooley and Doney 2009).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	**Current Status**		**Climate Change Impacts**	**Expected Future Climate Change Impacts**
	Ecosystem Service (ES)	**Human Well-being**	**ES and Human Well-being**	**ES and Human Well-being**
Recreation-winter sports		26 percent of U.S. population participates in winter sports activities (NSRE 2000). The ski/snowboard/ snowshoe industry in U.S. is worth $66 billion and supports 556,000 jobs (Southwick Associates 2006). Snowmobiling adds $22 billion annually and 90,000 jobs (International Snowmobile Manufacturers Association).		Ski seasons are predicted to be shorter: the California season would be shorter by 49-103 days (Hayhoe and others, 2004); Michigan and Vermont shorter by 5-60 percent (Scott and others, 2006; Dawson and Scott 2007); 6-48 percent shorter ski season in Northeast (Scott and others, 2008). It is projected that the ski season will disappear in Arizona after 2050 (Bark and others, 2010). 12.5 percent of Cascades ski areas and 60 percent of Olympic ski areas at risk due to predicted warm winters (Nolin and Daly 2006). Severe losses of snowmobiling season (>50 percent) predicted in Northeast (Scott and others, 2008).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Recreation - coral reefs	See Culver and others, 2012	Net benefits of $360 million annually to Hawaiian economy from 1660 square kilometers of reef area (Cesar and others, 2004); $50-60 million annual revenues from Hawaiian dive operations (Van Beukering and Cesar 2004).	See Culver and others, 2012	
Recreation-coastal	See Culver and others, 2012; Griffis and others, 2012.	Ocean-related tourism contributes $82 billion to GDP and supports 5 million jobs in leisure and hospitality in coastal states (NOEP 2011).	(see *Coastal erosion protection*)	Beach erosion projected to cost more than $1 billion annually in coastal state tourism losses; $63 million annually in southern California (Bin and others, 2007; Whitehead and others, 2009; Pendleton and others, 2011). Some economic gains may result from an increase in user days with better weather (Loomis and Crespi 1999).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	**Current Status**		**Climate Change Impacts**	**Expected Future Climate Change Impacts**
	Ecosystem Service (ES)	**Human Well-being**	**ES and Human Well-being**	**ES and Human Well-being**
Recreation - angling	(see *Marine fishery yields*)	U.S. anglers take 74 million saltwater fishing trips annually, with combined saltwater and freshwater economic impact of more than $45 billion/year on trips and equipment (U.S. DOI, FWS, DOC, and U.S. CB 2006). 327,000 full- and part-time jobs are related to saltwater and freshwater recreational fisheries (NMFS 2010).	(see *Marine fishery yields*)	Predictions indicate a decrease in cold-water fishing (trout, salmon); may be offset by increase in warm-water fish catch, such as bass and perch (Pendleton and Mendelsohn 1998).

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Recreation-other	Campground closures are projected due to hazard trees and fire risk (Robbins 2008; Starbuck and others, 2006); decreases in visitation to parks suffering catastrophic fires (Starbuck and others, 2006); decreased reliability of whale-watching opportunities (Lambert and others, 2010); increase in visitation to Rocky Mountain NP with increased temperatures (Richardson and Loomis 2005); redistribution of "winter sun" and "summer cool" destinations in North America (Scott and others, 2004); increase in golfing, boating, and other activities promoted by warmer, drier weather (Loomis and Crepsi 1999; Shaw and Loomis 2008). The net effect is predicted to be a redistribution of the industry and its economic impact, with visitors and tourism dollars shifting away from some communities in favor of others.			

Table 4.1. *Current status, and projected future impacts of climate on ecosystem services.*

Specific Service	Current Status		Climate Change Impacts	Expected Future Climate Change Impacts
	Ecosystem Service (ES)	Human Well-being	ES and Human Well-being	ES and Human Well-being
Subsistence hunting and foraging		For indigenous Alaskans, wildlife hunting provides a large component of the diet, contributes to cash income, and serves as an important cultural touchstone. Subsistence hunting of wildlife (whales, seals, walrus, caribou, fish, and birds) is greater than 100kg per capita among coastal Inupiat (Gearhead and others, 2006); hunters also earn cash income from seal, narwhal, and polar bear hunts.	Wildlife migratory patterns and abundance are changing, and weather conditions becoming more hazardous and unpredictable, leading to decreased reliability of traditional ecological knowledge and fewer days spent hunting. Predictions are for decreases in sea ice extent and earlier breakup of sea ice (Gearhead and others, 2006); changes to abundance and migratory patterns of wildlife, including bowhead whales and geese; decline in Porcupine caribou herd of up to 85 percent over 40 years (Kruse and others, 2004); less predictable weather (Ford and others, 2006); increased windiness/ storminess leading to fewer boatable days (Ford and others, 2006; Hinzman and others, 2005).	

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Coastal flood protection	Sea-level rise would increase risk of storm related coastal hazards for many coastal communities. Currently, no published studies quantify the marginal change in human well-being due to impacts on hazard reduction due to storm surge dampening.	Coastal development, sediment and nutrient runoff, nearshore management.	Southeast; the Atlantic coast of North America may experience one of the world's largest losses in wetlands (Nichollas and others, 1999). Losses in extent of coastal marshes have already impaired human well-being. This is especially evident in the Gulf coast with respect to hurricane damage.	Recreation, residential, insurance	Sea walls, restoration and protection of habitats, relocation of people or infrastructure.

***Table 4.2.** Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Coastal erosion protection	14,000 people currently live in the 41 sq. miles of coastline that is predicted to be lost to sea-level rise and coastal hazards by 2100 (Heberger and others, 2009).	Wave heights (which lead to higher erosion) have increased all along the coast of the US with greater increases occurring in higher latitudes (Komar and Allan, 2006, 2008), but it is unclear whether due to climate change or variability.	Pacific coast (Boruff and others, 2005); especially Alaska in places where protective sea ice is disappearing (Jones and others, 2009).	see *Coastal flood protection*	see *Coastal flood protection*
Fire regulation	Where warmer, drier temperatures occur and where fuel build-up due to fire suppression has taken place, fires will be more frequent and/or more intense.	Fuel loads, invasive species, disease, forest management.	Western U.S.	Forest products, rural residential, carbon emissions	Forest/fuels management

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Carbon storage and sequestration in forest biomass	Climate change is projected to continue perturbations in forest distribution, forest growth rates, and risk of degradation via fire, invasive species, and disease. These perturbations will continue to reduce rates of sequestration and expectations for C storage periods (Allen and others, 2010).	Economic drivers of land use change (for example, 220 million hectares of forest are expected in the U.S. by 2051, due in part to cropland and pasture abandonment Radeloff and others, 2012), forest management, invasive species, disease.	Western U.S.	Global impact; local recipients of C sequestration projects	Markets for forest carbon sequestration projects exist and are expanding (Canadell and Raupach 2008; Rodrigo and Perrings 2011); forest management.
Carbon storage and sequestration in soils	Land-use change will have a large impact on carbon soil sequestration and storage, with transitions from cropland to forest and urban areas having a positive impact on soil carbon storage (E. Nelson analysis).	Economic drivers of land-use change; agricultural and timber management practices affecting erosion.	Soils in Minnesota, Iowa, Vermont, New York, and Maine have the potential to store the most carbon (E. Nelson analysis).	Global impact; local recipients of C sequestration projects.	Programs that pay landowners to increase their soil carbon (IBRD/WB 2011; Glenk and Colombo 2011); agricultural and timber management practices affecting erosion.

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Carbon storage and sequestration in marine habitats	If climate change reduces the extent of marine features that have positive sequestration rates, or reduces their capacity to sequester and store carbon, all else equal, global economic damages could increase (Westerling and others, 2006).	Coastal development, sediment and nutrient runoff, nearshore management.	Atlantic coast of North America may experience one of the world's largest losses in wetlands (Nichollas and others, 1999, 2004); SE U.S. where mangroves occur.	Global impact; local recipients of C sequestration projects.	Programs that pay landowners to increase their marine habitat-based carbon; restoration and protection of habitats.
Water quality regulation	Not aware of estimates of current climate impacts on water quality regulation.	Nitrogen and phosphorus application rates will strongly interact with climate change (NCA 2009).	See *Water Resources Chapter,* NCA 2012	Households, industries reliant on natural water supplies.	Increased water treatment; increased health care to counteract health impacts; altered land use practices (fertilizer application, tillage practices, buffers, feed and livestock management, manure management). (NCA 2009, 2012).

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Timber yield	The effects of climate change on forestry remains somewhat uncertain. Changes in weather patterns could lead to more rapid tree growth and greater harvest volumes and profits, or to less rapid tree growth and smaller harvest volumes and profits. It is thought that both dynamics will occur in the Pacific Northwest (Latta and others, 2010). Greater risk of forest destruction due to fire and/or disease could lower the profits of timber firms, resulting in job losses.	Economic drivers of land-use change (for example, Radeloff and others, 2012), forest management, invasive species, disease.	Pacific Northwest, Southeast	Logging and mill workers, construction industry	Forest management

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Agricultural yield	Yields impacts expected over the next 50 years. Temperature changes have had a more dramatic impact on corn, wheat, soybean, and rice yields around the world than changes in precipitation (Lobell and others, 2011).	Drivers of agricultural land conversion (Radeloff and others, 2012).	Agriculture in the areas of the U.S. that will experience the most dramatic climate change will have the greatest transition costs.	Agriculture and fertilizer, pesticide, food processing.	Agricultural management, subsidies.
Water provision (all)	U.S. counties with water-supply sustainability risk would double to 70 percent (Roy and others, In Press).	Changing demands from households, industry, agriculture.	Southwest, Great Plains, Southeast U.S.	Agriculture, municipal, and wetland/aquatic ecosystems.	Increase water-use efficiency, price adjustments, recycling.

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Marine fisheries	Fisheries are predicted to decline in the lower 48 states, but increase in parts of Alaska (Cheung and others, 2010). Costs of fishing are predicted to increase as fisheries transition to new species and as processing plants and fishing jobs shift poleward (NCA 2009; Sumaila and others, 2011).	Fishing (Hare and others, 2010), habitat destruction (Beck and others, 2001), eutrophication and coastal water quality, and invasive species (NCA 2009).	The continental U.S. and Hawaii (Cheung and others, 2010).	Coastal states and communities (Coulthard 2009; McCay and others, 2011).	Switch to warm-water species (Sumaila and others, 2011); adjust fisheries quotas or subsidies (Hare and others, 2010); conduct international negotiations over transboundary species.
Marine aquaculture	U.S. mollusk fisheries may have economic losses of $0.3-5.1 billion in Net Present Value by 2060 (Cooley and Doney, 2009); aquaculture operations face increased costs and less predictability (De Silva and Soto 2009).	Coastal water quality; eutrophication.	West Coast U.S. in areas of upwelling (Feely and others, 2008); areas of land runoff, hypoxia, sulfur dioxide precipitation, and eutrophication (Kelly and others, 2011).	Aquaculture industry, coastal states and communities (Da Silva and Soto 2009).	Switch to less sensitive species (Da Silva and Soto 2009); mitigate sources of local acidification (Kelly and others, 2011).

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Recreation-winter sports	Doubling of cost of snowmaking (+5 percent total operating costs to ski areas) under high emissions scenario (Scott and others, 2008; Dawson and Scott 2007); lower home prices in ski areas where snow reliability is low (Bustic and others, 2011).		Ski areas located at lower elevation or lower latitude (Bark and others, 2010); snowmobiling operations where snowmaking is not an option (Scott and others, 2008).	Winter sport industry and tourism.	Snowmaking (Scott and others, 2006; Scott and others, 2008; Bark and others, 2010).
Recreation - coral reefs	Loss of coral cover due to lowering of ocean pH, warm temps (Culver and others, 2012; Griffis and others, 2012).	UV stress, coastal development, recreational impacts, invasive species.	Areas with coral	Tourism, recreational and commercial fishing on coral-dependent species.	Protection and restoration, reduction of pollution and habitat-destroying activities.

Table 4.2. *Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Recreation-coastal	Losses due to beach erosion (Bin and others, 2007; Whitehead and others, 2009; Pendleton and others, 2011); potential increase in user days with better weather, resulting in economic gains (Loomis and Crespi 1999).	coastal development, sediment impoverishment from upstream changes to hydrology.	Gulf and Pacific coasts (Culver and others, 2012)		Sand replenishment on beaches
Recreation - angling	Decrease in cold-water fishing (trout, salmon); may be offset by increase in warm-water fish catch, such as bass and perch (Pendleton and Mendelsohn 1998).	Overfishing, pollution	Atlantic coast	Recreation & tourism	Stocking with warm-water species; fishery management

***Table 4.2.** Factors affecting adaptation responses to climate change impacts*

Specific Service	Ecosystem Effects on Human well-being	Interacting Stressors	Most vulnerable geographic region	Most vulnerable sector or part of society	Human Response (list of actions that may be taken)
Subsistence hunting & foraging	Increased hazards to hunters and travelers (Ford and others, 2008; Ford and others, 2006); less time spent hunting (Ford and others, 2006; Berman and Kofinas 2004); obsolescence of traditional ecological knowledge about weather prediction and risk assessment (Ford and others, 2008; Ford and others, 2006); decreased harvest of wildlife or switch to lower-value wildlife species (Ford and others, 2006; Hinzman and others, 2005; Kruse and others, 2004).		Alaska	Indigenous people	Hunters may get improved access to weather prediction and safety technology (Ford and others, 2006). Hunters may switch to different prey with less associated risk (Ford and others, 2006).