Climate change's impact on key ecosystem services and the human well-being they support in the US

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Climate change alters the functions of ecological systems. As a result, the provision of ecosystem services and the well-being of people that rely on these services are being modified. Climate models portend continued warming and more frequent extreme weather events across the US. Such weather-related disturbances will place a premium on the ecosystem services that people rely on. We discuss some of the observed and anticipated impacts of climate change on ecosystem service provision and livelihoods in the US. We also highlight promising adaptive measures. The challenge will be choosing which adaptive strategies to implement, given limited resources and time. We suggest using dynamic balance sheets or accounts of natural capital and natural assets to prioritize and evaluate national and regional adaptation strategies that involve ecosystem services.

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Climate change has altered and will continue to alter the provision, timing, and location of ecosystem functions across landscapes. Ecosystem *functions*, such as nutrient recycling in soil and the timing and volume of water flows, become ecosystem *services* when humans translate them into valuable processes, materials, and commodities. For example, crop production, which takes advantage of the former ecosystem function, and flood protection, which manages the latter ecosystem function, are ecosystem services. Climate change is expected to increasingly impact, both positively and negatively, the provision and value of welfare-enhancing services in the US and around the world (Staudinger *et al*. 2012). Scientists' understanding of the effects of climate change on ecosystem service provision and value is improving rapidly. Although no comprehensive national system for tracking the status or trends in US ecosystem service provision and value exists, numerous studies and databases are available from which researchers can begin to identify the ecosystem services that are sensitive to climate change (PCAST 2011). Here we use a selection of these studies and databases to identify some ecosystem services that have been and will continue to be affected by climate change and the potential impact of these service transformations on human well-being in the US.

In a nutshell:

- Climate change will modify crop and seafood production in the US; identifying and implementing cost-effective adaptive responses to maintain productivity in these sectors will be challenging
- Increasingly stormy weather and rising sea levels are enhancing the value of the country's undeveloped coastal habitats as "protectors" of populations and property; in some areas, the value of these protective services may exceed the value from development
- Drought and more variable hydrological cycles will change US water-supply patterns and threaten water availability; more reservoirs and water markets could lead to more efficient use of water
- Government agencies, private companies, and nongovernmental organizations can assess and prioritize possible ecosystem service-based adaptations to change through a natural capital and assets "balance sheet" framework

This paper complements a broader technical review of the impact of climate change on US ecosystem service provision and value (Staudinger *et al*. 2012). That technical review is an input into the Third National Climate Assessment Report, the final version of which is planned for completion in 2014 (see www.globalchange.gov/what-we-do/assessment for details). Unlike the technical review, the aim of this paper is not to provide an encyclopedic treatment of the documented and expected impacts of climate change on ecosystem service provision and value in the US, but to extract highlights regarding selected ecosystem services. In particular, we focus on services that (1) are important to a broad swath of US society and to the nation's economy, (2) if altered could substantially impact the well-being of many people living in the US, and (3) are sufficiently represented in the literature so that conclusions about their sensitivity to climate change can be drawn. To put it more simply, we highlight many of the ways that

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Americans will experience and notice climate change.

Given the high values of these vulnerable ecosystem services, we expect Americans will become increasingly interested in their conservation. Therefore, we also highlight some potential policies and strategies to conserve service flows under a changing climate. We conclude with a discussion on how the US Federal Government and other entities can prioritize ecosystem-service-based climate-change adaptations, given limited resources and time. We argue that the establishment of a national-level natural capital and natural asset "balance sheet" will guide the nation and its citizens and businesses toward more efficient investment in ecosystem-service-based climate-change adaptations. It is our hope that the ideas presented in this paper will promote the foundation and application of such a balance sheet.

Crop production

Humans combine soil, nutrient, and water cycling processes with sunlight, machinery, and labor to produce crops. A changing climate will alter the ability to translate the various ecosystem functions that support crop growth into food, feed, and fiber. Although US farms currently only contribute 1% to US annual gross domestic product (GDP) and support just 0.5% of all US jobs (www.bea.gov/iTable/index_industry.cfm), any substantial climate-change-induced disruption in US crop and livestock production would likely increase global food prices and worsen the standards of living worldwide (Parry *et al.* 2007). In fact, given that every American household routinely purchases food for sustenance, climate-change-caused variation in US agricultural production and food prices could be the most pervasive and consistent impact of climate change in the US. For example, Nelson *et al.* (2009) predicted that climate change will disrupt agricultural productivity both domestically and internationally to such an extent that global prices for wheat, maize, and beef, to name just three commodities, will be 90%, 50%, and 20% higher, respectively, by 2050 than they would be without climate change. Such price increases would markedly affect the welfare of many American households on a daily basis.

Climate change could disrupt American agriculture and drive global food prices higher in several ways. First, growing season temperatures that are hotter than historical averages will reduce the yields of most US-grown crops (eg Schlenker and Roberts 2009). Second, attempts to cope with changes in temperature and precipitation patterns will be hampered by the spatial inflexibility of most irrigation water sources and the recent lack of public investment in US agricultural research and development (eg Alston *et al.* 2010). Third, under climate change, certain crops may no longer be produced in the US, potentially making these crops more expensive for Americans due to the additional costs associated with international trade. Many fruit and nut trees, for instance, produce an economically viable yield only if there is a sufficient winter chill prior to a warm growing season (Luedeling *et al.* 2011). If such crop belts disappear or migrate from the US, domestic production of these fruits and nuts will cease and their prices in the US will likely increase. Of course, the migration of distinctive crop belts can also create new American economic opportunities if they stay within US borders, although the impacts of the transition could be financially demanding for some stakeholders. An example of this migration dynamic is seen in the improving climatic conditions for wine grape production in the Willamette Valley of Oregon and the emerging evidence that wine grape quality may be decreasing in California due to climatic change (eg WebPanel 1; Dello and Mote 2010; Lobell and Field 2011; Hannah *et al.* 2013).

Ultimately, the impact of climate change on American agriculture and its customers' pocketbooks will largely depend on the scope and cost of adaptive measures that the sector adopts in its attempt to remain highly productive. If the chosen adaptive measures are relatively straightforward to implement and effective, then disruptions to US food production could be relatively rare and food prices are more likely to remain stable. Therefore, an important task for scientists is to identify the most cost-effective adaptations for US agriculture. For example, improving cropland soil quality will help counteract the negative effects of climate change on crop production (eg Panel 1; WebPanel 2; Cong *et al.* in review). Farming on improved soils could also reduce some of the negative impacts that modern agricultural techniques have on water quality (Bossio *et al.* 2010). Or consider the expectation that the US Midwest will experience more frequent growing season droughts but will also receive excessive precipitation during the remainder of the year. This growing temporal mismatch between periods of high water demand and high water supply could hamper yield growth and force greater use of irrigation water in the region. Baker *et al.* (2012) proposed an elegant solution to this problem: store the excessive precipitation created over the non-growing season in a refurbished network of midwestern ponds and wetlands and then use the water as supplemental irrigation during the summer. Such a system could also reduce flood risk after the winter thaw and improve wetland habitat for wildlife in the spring. There are many opportunities for ecosystem-service-based adaptation in US agriculture; determining which strategies are feasible and most cost-effective is an important next step for researchers, economists, and policy makers.

Wildfire regulation

Most forests systems have evolved under natural fire regimes. However, many of the valuable services that forests provide, including timber and space for recreation and aesthetic views, are degraded by wildfire. The US therefore devotes substantial resources every year to fighting and suppressing forest wildfires; annual expenditures

Panel 1. Predicting the effect of climate stress on midwestern US agricultural systems and targeted soil reclamation as an adaptation strategy

Widespread drought in the US Midwest reduced 2012 maize and soybean yields in the region to levels not seen since the early 1980s. Many climatologists believe such severe weather, and warmer temperatures in general, will become much more common in the region. Here we explore whether marginal improvements in cropland soil capability – a key adaptation strategy for US agriculture – can maintain midwestern yield trajectories in the face of climate change. Reclamation projects that can improve soil capabilities 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–NRCS 2012).

Using a statistical model that explains crop yield as a function of each crop's growing degree days (GDD; a measure of heat accumulation over a crop's growing season) and growing season precipitation, as well as soil capability, we predict the distribution of county-level maize and soybean yields from 2050–2058 for five soil capability classes under several plausible mid-century Midwest climate scenarios (Figure 1). Our predictive model also considers alternative time trends of productivity gains (ie manifested technological and managerial innovations) in maize and soybean production. Depending on soil type and modeled future, we project an 8–28% decline in average county-level Midwest maize yields and a 7–23% decline in average county-level Midwest soybean yields by mid-century as compared with a 2050–2058 baseline of no climate change and no slowdown in maize and soybean productivity gains. As expected, cropping on soils that require less management and present fewer cropping limitations (more capable soils according to USDA–NRCS 2012) consistently leads to greater expected yields.

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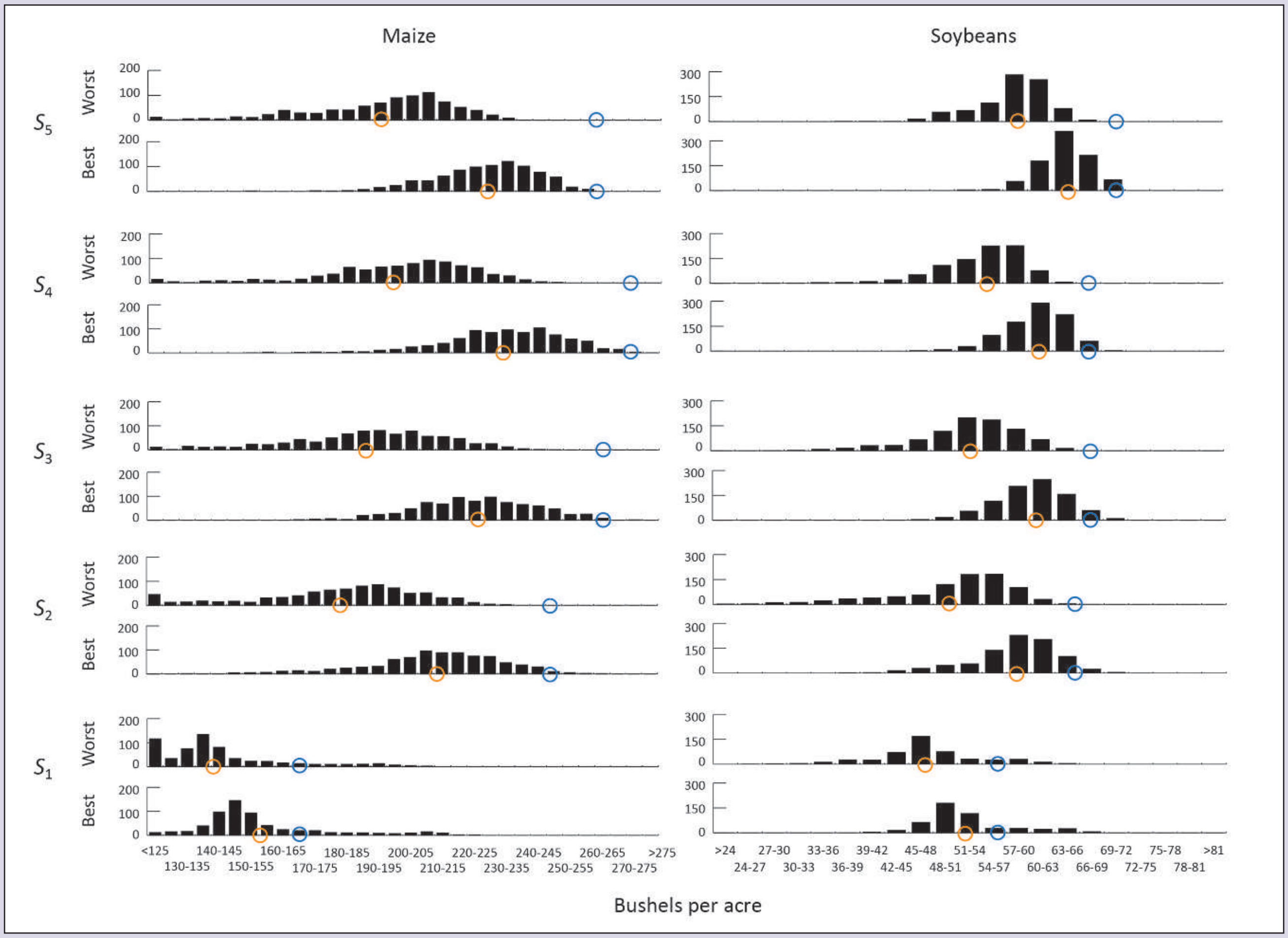

Figure 1. *Distribution of predicted average annual yields for maize and soybeans from 2050–2058 across five cropland soil capability classes in the US Midwest under two different future climate possibilities.* S_q *for* $q = 1,\ldots,5$ *indicates the soil capability class where lower index values denote less capable soils. The y axes measure the frequency of annual average county-level 2050–2058 per acre yields. The "Best" climate possibility considered assumes a 10% increase in each crop's growing degree days (GDD) from 2000–2008 levels across the study area, no change in each crop's growing season precipitation (PRECIP) from 2000–2008 levels across the study area, and an 11-year slowdown in each crop's yield trend growth. The "Worst" climate possibility considered assumes a 20% increase in each crop's GDD from 2000–2008 levels across the study area, a 10% decrease in each crop's PRECIP from 2000–2008 levels across the study area, and an 18-year slowdown in each crop's yield growth trend. Orange circles indicate the mean value of each distribution, whereas blue circles indicate the mean value of the baseline 2050–2058 yield distribution (no climate change between 2000–2008 and 2050–2058 and no slowdown in yield growth trend).*

Panel 1. – *continued*

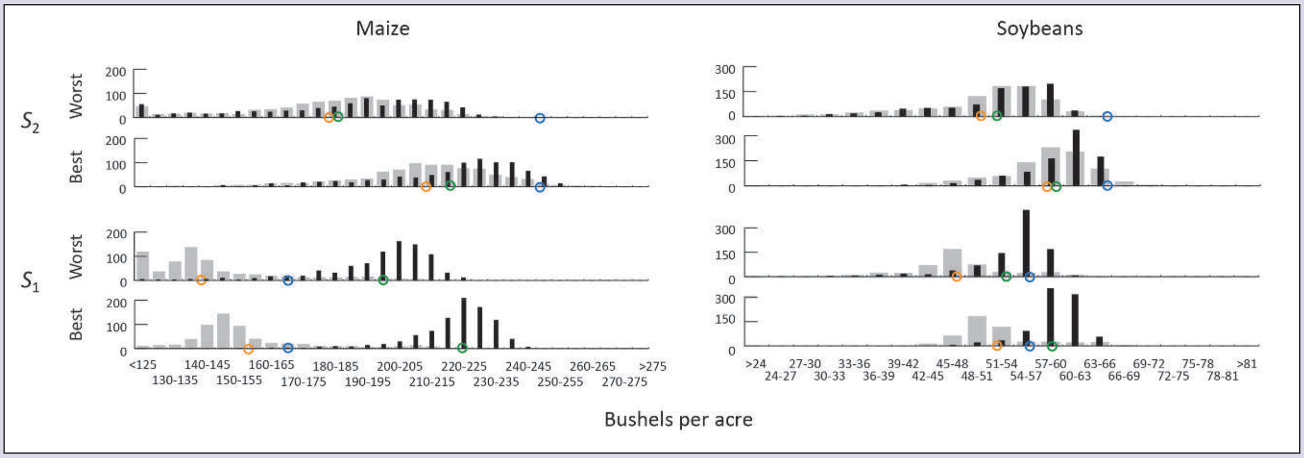

***Figure 2.** Impact of marginal soil capability improvements on the distribution of predicted average annual crop yields for maize and soybeans from 2050–2058 in the Midwest's most marginal cropland soils under two different future climate possibilities. S_1 and S_2 indicate soil capability class. See Figure 1 legend text for details on the "Best" and "Worst" climate possibilities considered. The gray (black) histograms represent the predicted distribution of county-level averages in the soil capability classes without (with) marginal soil reclamation. Green (orange) circles represent distribution means with (without) marginal soil reclamation, and blue circles represent the mean values of the baseline distribution (no climate change between 2000–2008 and 2050–2058 and no slowdown in yield growth trend).*

Next, we predict average 2050–2058 per acre yields assuming the cropped soil in each soil capability class was improved enough to mimic the soil capability on the typical acre in the next highest soil capability class. Figure 2 shows predicted yield distributions by 2050 to 2058 with and without marginal capability improvements in cropped areas currently in soil capability classes 1 and 2 assuming moderate and more severe climate change. We find that marginal improvements in the least capable cropped soil can appreciably increase predicted maize and soybean yields under several potential future climates in the Midwest. For example, annual production of maize on a typical acre of the least productive cropland soils in the Midwest is predicted to be 39.4–41.8% higher by the middle of the 21st century with marginal reclamation than without, all else being equal. Assuming 2000–2008 average net returns to a bushel of midwestern maize holds in 2050–2058, this entails an extra $41.67 or $48.84 (adjusted to 2000 dollars) of net returns from maize per year on a reclaimed acre of the least capable soil (not including soil reclamation costs). Given that the net return on the average midwestern maize acre was $94.88 (adjusted to 2000 dollars) from 2000–2008, the gains from marginal soil reclamation can be substantial. See Nelson (2013) for technical details.

For policy makers to cost-effectively act upon the promising adaptation of crop soil reclamation, several important questions still need to be answered. What variety and extent of soil reclamation is required to generate a "marginal" improvement in soil capability? Where in the Midwest, and for what crops, is the predicted stream of additional annual revenues and value of water-quality and soil-erosion improvements due to marginal soil reclamation expected to be greater than the cost of reclamation? Will individual farmers have the ability to undertake these reclamation projects or will governments need to be the primary funders of these projects? Finally, will midwestern maize and soybeans, up to now irrigated very little, require more irrigation to adapt to climate change? If so, what impact will this have on water supply and quality in the Midwest across all economic sectors?

typically exceed $1 billion (Staudinger *et al.* 2012). Despite these preventive measures, each year, particularly across the western US, people are killed, large swaths of private property are destroyed, additional greenhouse gases are released, recreational opportunities are lost, and water supply and water quality are degraded due to fire events (Staudinger *et al.* 2012; Bowman *et al.* 2013).

This situation is getting worse. Since the mid-1980s in the western US, the incidence of large forest fires has increased nearly fourfold and the total area burned by fires has risen sixfold (Westerling *et al.* 2006). Much of this increase can be explained by changes in climate, particularly by elevated spring and summer temperatures (Westerling *et al.* 2006). And as Americans put more homes on the edges of large western forests, the consequences of forest fires will become even more dramatic (WebPanel 3).

Forest management and grazing regimes guided by insights from forest ecology could do much to reduce the risk of wildfires. The Arizona Wallow fire of 2011, Arizona's largest fire on record, did not burn ridges where previous thinning treatments had been applied under a forest stewardship project (USBIA 2011). Therefore, well-managed forests with active thinning practices are not only valuable for timber production but can also minimize property loss and the degradation of a diverse suite of ecosystem services (eg McRae *et al.* 2001).

The value that Americans derive from forest stewardship will increase over time as warming trends exacerbate the propensity for severe fires. A US Forest Service (USFS) priority is identifying policies that cost-effectively reduce the risk of and associated damage from wildfire (USFS 2011). However, not all identified policies have to involve physical manipulation of forests. For example, USFS scientists estimated that wildfire prevention education efforts in the state of Florida have created monetary benefits in avoided forest fire damage 10 to 99 times greater than the cost of the additional education (Prestemon *et al.* 2010).

Hazard reduction through coastal protection services

Over the past century, the growing US population has increasingly settled in coastal areas, thereby exposing a greater percentage of Americans and their assets to hurricanes (Figures 3 and 4) and other coastal hazards, such as shoreline erosion and flooding. Now more than one-third of the US population currently lives in coastal watershed counties, and 14 of the 20 largest US urban centers are located along the country's coasts (NOAA 2013). Demographic extrapolations predict that coastal communities will soon become even more densely populated (NOAA 2013). The economic and social impact of coastal hazards will therefore increase even if tropical storm frequency and intensity do not. Moreover, if the frequency and severity of coastal storms increase as expected due to climate change (Emanuel *et al.* 2008), coastal storm-related disruptions will become "the new normal" for more Americans and their cultural institutions and businesses (WebPanel 4; USCCSP 2009). Accordingly, the US Government's financial capacity to manage coastal hazards, including the after-effects of "superstorms", has been listed as a concern by the US Government Accountability Office (GAO 2013).

Undeveloped coastal habitats, such as wetlands, dunes, and mangroves, can protect people and infrastructure against shoreline erosion and flooding caused by the combination of sea-level rise, storm-induced waves, and storm surge (eg WebPanel 5; Arkema *et al.* 2013). As more Americans settle on the coast and climate-change-related storm surges become more frequent, the protection offered by these habitats will become more valuable (Grinsted *et al.* 2012). One of the reasons coastal habitat restoration can provide more cost-effective storm-surge protection than "hard" engineering solutions (eg seawalls, groins) is that habitat has relatively little ongoing maintenance costs and in many places can offer a broad suite of co-benefits (Oxfam America and The Nature Conservancy 2012). If coastal habitat restoration strategy leverages the monetary value that restoration can provide for commercial and recreational uses and wildlife viewing, the benefit-to-cost ratio for "soft" engineering solutions can surpass that of a "hard" solution (eg Aburto-Oropeza *et al.* 2008). Restoring oyster reefs on the Alabama coast, for instance, not only helps protect the shoreline and its residents but also creates jobs and enhances fisheries. One analysis of oyster reef restoration found that the $1 million cost per restored mile will pay for itself in 10 years via avoided future storm-surge damage and increased fishery productivity (WebPanel 6; Oxfam America and The Nature Conservancy 2012; see also Panel 2).

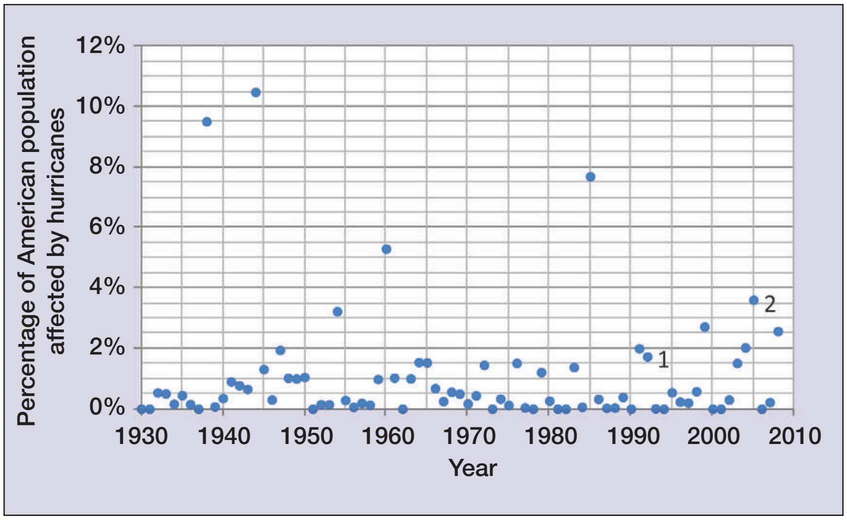

Figure 3. *Percentage of Americans affected by hurricanes each year from 1930 to 2008. The value for year* t *is found by summing the year* t *populations of counties struck by one or more hurricanes in year* t *divided by the number of Americans in year* t*. Since 1985, there have been 6 years where 2% or more of Americans have been affected by hurricanes; from 1930 to 1985, there were only 4 such years. We highlight 2 years in the figure. In 1992, a ~5-m storm surge from Hurricane Andrew contributed to the nation's fourth most costly natural disaster since cost record keeping began in 1980 ("1"). In 2005, Hurricane Katrina generated enough damage to become the nation's most costly disaster since cost record keeping began in 1980 ("2"). See WebPanel 11 for figure sources.*

Marine fishery production

In 2009, there were 1.03 million full- and part-time jobs in the US commercial seafood industry, including its associated harvesting, processing, dealing, wholesaling, distributing, and retailing sectors (NMFS 2011). In that same year, this industry generated $116 billion in sales and contributed $48 billion in value, or 0.34%, to US GDP (NMFS 2011). In aggregate these economic impacts may seem small, but 1.03 million jobs is roughly equivalent to the number of civilian jobs in the state of New Mexico in 2013 (www.bls.gov/news.release/metro.toc.htm). In other words, the livelihoods of many Americans depend on the ecosystem functions that support robust marine fisheries.

Many of the ecosystem functions that US commercial fish species require are found in cooler water. Therefore, most species fished off US coasts are moving poleward as sea-surface temperatures warm due to climate change

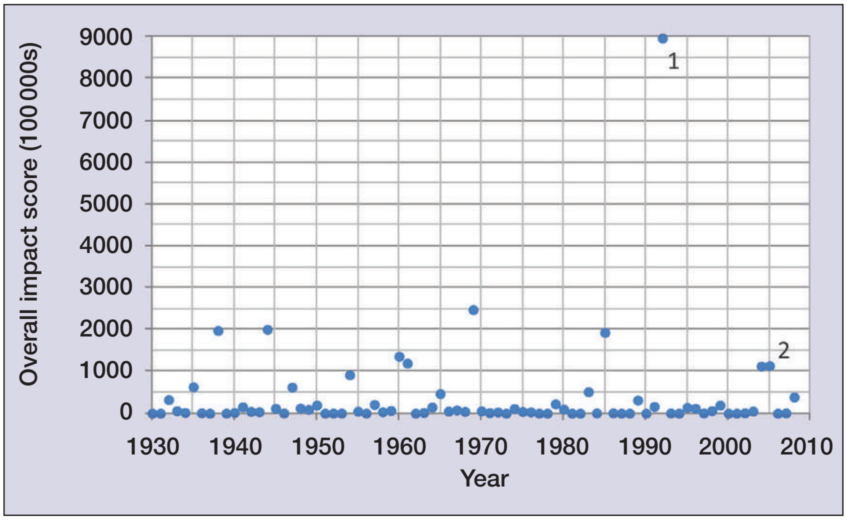

Figure 4. *Overall hurricane impact on Americans from 1930 to 2008. The value for year* t *is found by multiplying the population of a county struck by one or more hurricanes by the cumulative sum of the hurricanes' Saffir-Simpson Category weight and then summing across all affected counties. The weight of category 1, 2, 3, 4, and 5 hurricanes are 1, 4, 16, 64, and 256, respectively. For example, in 1955 North Carolina's Carteret County experienced two category 3 hurricanes. Its population that year was 27 000. Therefore, its "impact" score for that year was (16 + 16) × 27 000 = 864 000. Since 1985, a 22-year time frame, there have been 4 years where the national score was 100 000 000 or better. From 1930 to 1985, a 55-year time frame, there were 5 such years. As in Figure 3, the years 1992 ("1") and 2005 ("2") are highlighted. See WebPanel 11 for figure sources.*

(Nye *et al.* 2009). Fish species' ranges are predicted to continue to shift poleward at a rate of 45–49 km per decade under a moderate climate-change scenario (A1B climate scenario; Cheung *et al.* 2010). Fish and invertebrate populations that cannot easily move with their respective habitable environmental conditions are in danger of extirpation or extinction (Kinlan and Gaines 2003; Shanks 2009). In addition, fish species or fisheries dependent on shelled mollusks and coral reefs – resources increasingly at risk from ocean acidification and elevated water temperatures – are expected to be negatively impacted. In contrast, biomass production in seaweed and seagrass habitats may increase, helping to sustain fish populations that rely on these resources for breeding and feeding (Branch *et al.* 2013).

Some US marine fishing jobs, catches, and values have already moved poleward in reaction to species shifts (McCay *et al.* 2011; Pinsky and Fogarty 2012). Range shifts in exploited species can create major costs in fishery-based industries, including the expense of relocating processing plants and other large infrastructure (Sumaila *et al.* 2011). The quality of US fisheries whose fixed spatial extents are mismatched with their poleward-migrating exploited species will begin to deteriorate unless other harvestable species move into the area from the south or fishers are able to harvest previously ignored marine species (WebPanel 7; Russell 2013). The efficacy with which a coastal community can use an emerging fishery will largely depend on adaptability of local economic, cultural, and regulatory institutions (Ruckelshaus *et al.* 2013a).

Strategies to secure food and livelihoods from marine fisheries in the face of climate change can borrow from existing management approaches and emerging technologies. Ongoing stock assessments used to establish regulated catch limits could begin to more systematically incorporate climate-driven shifts in spatial distributions of fish (eg Link *et al.* 2011). Greater emphasis on integrating remote sensing, ocean observing systems, and oceanographic modeling into fisheries management would improve the ability to adapt to climate change. Finally, protection and restoration of habitats for juvenile and other life stages of marine species can also bolster stock resilience to environmental change (Perry *et al.* 2010). However, there may be little adaptive capacity for species constrained by slow dispersal rates and/or habitat fragmentation, or those already stressed by other factors, such as pollution (Schloss *et al.* 2012). The livelihoods of people involved in these fisheries are particularly vulnerable to climate change.

■ Water supply

Climate change is expected to make US water supplies more variable, both spatially and temporally. Given that evaporation and evapotranspiration rates across the country are also expected to change (Karl *et al.* 2009; Staudinger *et al.* 2012), water scarcity and water-quality issues will be exacerbated in many parts of the US. Because water is essential to so many facets of human life, the impacts of these changes could be profound.

Much of the western US, especially the southwestern US and California, is projected to experience decreasing water yield (precipitation less evapotranspiration) under several future climate scenarios (Walker *et al.* 2011). Western snowpack-driven systems are particularly susceptible to changes in hydrology (Hamlet *et al.* 2005). Snowpack water storage has already declined in many of these systems (Nayak *et al.* 2010), and by 2040 springtime snow water equivalents are expected to be lower than current levels across most of the US (Mote *et al.* 2005; Adam *et al.* 2009). Instead, these systems are anticipated to receive a greater percentage of their precipitation in the form of rain; the cumulative impacts of this shift on the economic and cultural systems of the western US are unknown.

Water scarcity and sustainability in an area are not only determined by the area's water yield; elevated demand due to human population growth and increased municipal, agricultural, and industrial use can exacerbate climate-driven scarcity. Roy *et al.* (2012) have developed a

Panel 2. Protection from coastal hazards

Rising sea levels will likely increase the risk of storm-related coastal flooding and erosion hazards for the 39% of Americans currently living in coastal counties (USCCSP 2009; NOAA 2013). Habitats along the US shoreline (eg marshes, coastal forests, and reefs) provide protection from erosion and storms by attenuating waves and stabilizing shorelines (Shepard *et al.* 2011). Loss of these habitats as a result of climate change, coastal development, and other human activities exacerbates the risks to people and property when storms strike, especially if rising seas or coastal erosion are also regionally prominent. For instance, coastal storms coming ashore in New Jersey could temporarily flood low-lying areas up to 20 times more frequently as a result of the loss of marshes and other protective habitats at the same time that sea level is rising (Cooper *et al.* 2008). The damage from Superstorm Sandy's surge is a good example of the consequences of a large storm and rising seas.

A coastal vulnerability analysis for the US reveals that the greatest number of people at risk from sea-level rise and storms live in the highly populous states of the Northeast, Florida, and California (Figure 5). Intact coastal habitats protect roughly 1.4 million people in the highest risk areas (Arkema *et al.* 2013). Degradation and loss of these ecosystems nationwide would nearly double the number of people most at risk under future climate (Arkema *et al.* 2013). The extent to which natural defense mechanisms operate depends on the relative location of the hazard, habitats, and people. Prioritizing coastal habitats near these areas for conservation and restoration activities could greatly reduce vulnerability among coastal communities.

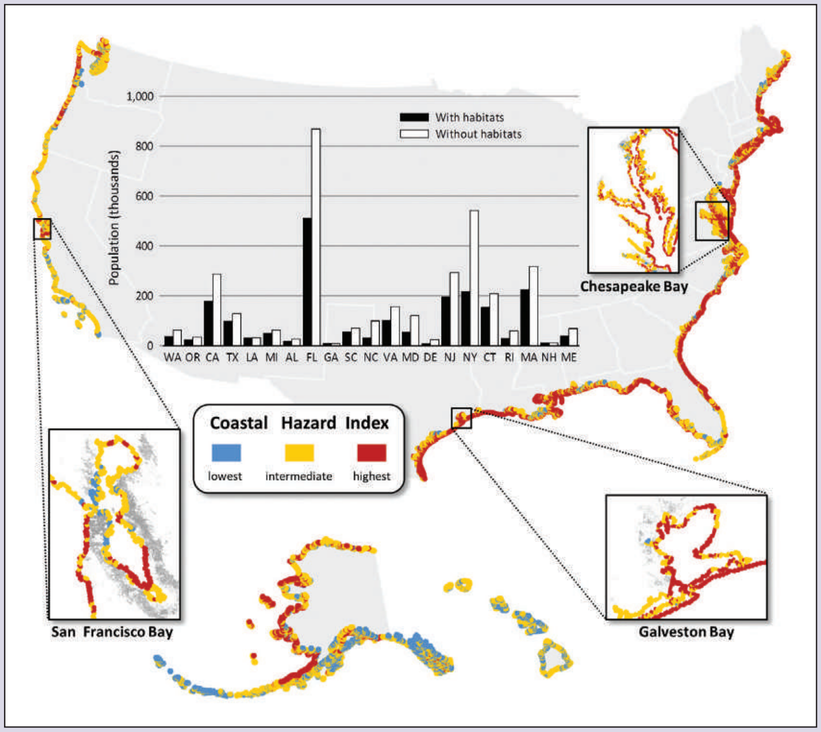

Figure 5. *Exposure of the US coastline and coastal population to sea-level rise in 2100 (A2 scenario) and storms. Red-colored regions have the greatest exposure to coastal hazards. The embedded bar graph displays the population living in areas most exposed to hazards (red 1-km² coastal segments in the map) with protection provided by habitats (black bars), and the increase in population exposed to hazards if habitats were lost due to climate change or human impacts (white bars). Data depicted in the inset maps are zoomed-in views of the nationwide analysis. Exposure to hazards is based on the protection service from coastal habitats, geomorphology, relief, sea-level rise, and potential storm damage from wind, waves, and storm surge (see Supplementary Table 1 in Arkema* et al. *2013). This figure first appeared in the journal* Nature Climate Change *(Arkema* et al. *2013).*

county-level water-supply sustainability index based on attributes of susceptibility to drought and projected increases in water withdrawal, need for storage, and groundwater use. Climate change is projected to double the percentage of US counties with moderate or higher water sustainability risk (from 35% to 75%) by 2050 (Roy *et al.* 2012). Even more notable, the number of counties with high or extreme water sustainability risk will triple (from 10% to 32%), and the number of counties with extreme risk is projected to increase 14-fold. The counties expected to become the most at risk for water sustainability are found in the West, Southwest, and Great Plains regions (Roy *et al.* 2012).

Conservation, improved water management, and more water-efficient technology can help Americans adapt to increasing water scarcity (eg Gober *et al.* 2013). Another potential adaptation to water scarcity is the implementation of water markets throughout the US. Although water pricing could engender public backlash and create equity issues, if done well, it may represent one of the most practical adaptive measures Americans can take (see WebPanel 8).

■ Nature-dependent tourism and outdoor recreation

Many ecosystem processes converge to provide Americans with nature-based recreation. For instance, the quality of a fly-fishing experience on a Montana river is a function of the river's water quality and flow, the water-cooling effect provided by riparian forests, and the aesthetics of the surrounding landscape. Climate change will affect all of these functions and therefore alter this recreational experience.

The size of the nature-based tourism and outdoor recreation industry provides an idea of the US assets that are at risk from climate-change impacts. In 2010 Americans spent $646 billion on outdoor recreation, far exceeding expenditures on pharmaceuticals ($331 billion), motor vehicles and parts ($340 billion), and household utilities ($309 billion). This spending directly supported 6.1 million jobs (WebPanel 9; Allen and Southwick 2012).

Climate-change impacts on outdoor recreation are projected to be most profound in winter sports and beach recreation (WebPanel 10). Abbreviated ski seasons are likely to become the norm in many parts of North America. In particular, the California ski season is expected to shorten from 152 to 103 days, potentially missing the lucrative Christmas–New Year's holiday week (Hayhoe *et al.* 2004). Beach recreation values are likely to drop as beach widths decline due to sea-level rise and greater beach erosion. Narrower beaches make it harder to access fishing sites for anglers and are less attractive to sunbathers (eg Pendleton *et al.* 2011). North Carolina beach erosion, for example, is expected to reduce recreational value by more than $1 billion from 2006 to 2080 (Whitehead *et al.* 2009).

Conversely, climate change is likely to enhance some recreational experiences. For example, while climate change will increase the likelihood of extinction for many native freshwater fish in California, several alien fish, introduced specifically for recreational fishing, could thrive under future conditions (Moyle *et al.* 2013). Furthermore, visitation to Colorado's Rocky Mountain National Park may increase with elevated temperatures (despite the higher wildfire risk; Richardson and Loomis 2005), and weather that is favorable for golfing and some types of boating is projected to increase (Loomis and Crespi 1999). Beach-use days and related local economic benefits may also increase in coastal areas that are spared from beach erosion and that acquire warmer and drier conditions (Loomis and Crespi 1999).

Some threatened recreational experiences may be maintained by adaptive measures, but in other cases Americans may need to accept reduced opportunities and value. Artificial snowmaking at ski resorts is a good example of the limitations and trade-offs associated with adaptive technologies. The ubiquity of snowmaking at US resorts demonstrates that ski-resort managers are willing to invest in technology to extend the downhill ski season in the absence of sufficient natural snowfall. However, this snowmaking technology provides an imperfect substitute for real snow, is expensive, is constrained by water availability and necessary minimum nighttime temperatures, and is impractical for other threatened winter activities such as snowmobiling and cross-country skiing (Scott *et al.* 2008).

Using an ecosystem service balance sheet to guide adaptation

The preceding examples illustrate how valuable US ecosystem services will be impacted – sometimes being enhanced and sometimes diminished – by expected shifts in weather patterns. We have also demonstrated that climate change is a stress that increases the importance of many regulatory services, such as nutrient cycling in soil and wave energy attenuation by coastal habitats. As the nation's climate becomes more disrupted, Americans will be presented with an array of possible responses and adaptations, including many ecosystem-services-based approaches. However, resource and time constraints will limit the number of interventions that can be implemented. Difficult decisions regarding which adaptation strategies to invest in will have to be made. We believe that adaptation decisions involving ecosystem services will be more efficient if the US creates and manages a nationwide and dynamic balance sheet of the natural capital and natural assets that generate ecosystem services (PCAST 2011). By "balance sheet" we mean detailed databases and maps of natural capital and natural assets in the US, the ecosystem services they produce, and potential forecasts of their conditions and provision in the future. By "dynamic" we mean a balance sheet that is updated in real time.

Policy makers, economists, and company shareholders already use such dynamic nationwide balance sheets when analyzing and assessing the effectiveness of various economic policy interventions. The Bureau of Labor Statistics, Bureau of Economic Analysis, and National Agricultural Statistics Service, for instance, offer publically available real-time information on the direction of the US economy, market prices, labor productivity, and commodity production. With this information, areas of economic concern and potential policies to address these concerns can be identified quickly. Similar informational and analytical support on natural capital and natural assets and associated ecosystem services will be necessary if government agencies, businesses, and citizens are to make effective decisions regarding ecosystem service management under a rapidly changing climate. An illustration of the power of natural capital and natural asset balance sheets to guide and prioritize environmental intervention comes from PUMA, a global apparel and sports corporation. PUMA has established an environmental profit and loss account that allows it to determine: (1) "how much would our planet ask to be paid for the services it provides to PUMA if it [were] a business?" and (2) "how much would it charge to clean up the 'footprint' through pollution and damage that PUMA leaves behind?" (PUMA 2011). PUMA claims that it uses its environmental account to structure initiatives to reduce its environmental footprint. In subsequent years, the balance sheet will allow PUMA, its shareholders, and the general public to assess the effectiveness of the company's sustainability initiatives (see www.pwc.com/gx/en/corporate-reporting/sustainability-reporting/pumas-reporting-highlights-global-business-challenges.jhtml).

Consider two ways that a natural capital and ecosystem service balance sheet apparatus could improve US decision making under climate change. First, the Obama Administration has recently incentivized – and, in some cases, directed – US Federal agencies to consider ecosystem impacts and benefits when permitting and undertaking water and infrastructure management (eg *Federal Register* **77**, 56749; 13 Sep 2012). To this end, the US Federal Emergency Management Agency (FEMA) is currently focusing on improving the accuracy of its flood risk maps, the first step in assigning a more accurate value to the protective value of natural floodplains and coastal habitats (King 2013). Combining these more accurate maps with a balance sheet that tracked the current spatial allocation of ecosystem services and expected ecosystem service fluctuations resulting from land-use, demographic, and climate change would allow FEMA to generate a much more thorough assessment of the net return on investment in habitat restoration and protection in various US locations.

Alternatively, consider how such a balance sheet could be used to make agriculture more resilient to extreme weather. Participants in US Farm Bill crop subsidy and insurance programs, the primary policy driver of US agriculture, already need to prove that their land satisfies some basic conservation requirements (USDA–FSA 2013). Eligibility requirements could be strengthened even more by asking participating farmers to engage in soil reclamation projects on their land that are likely to generate more in private and social benefits than costs. Social benefits include reduced soil erosion and improved water quality. The types of soil reclamation best suited for the participant's land would be cataloged in the country's natural capital and ecosystem service balance sheet. In order to facilitate the most advantageous interventions, the more expensive recommended reclamation projects would be eligible for USDA cost-share assistance.

A comprehensive natural capital and ecosystem service balance sheet could also help maintain the profits of private companies and the wages and investment income they produce. More companies are recognizing that their profit margins are heavily reliant on a consistent provision of ecosystem services and that climate-change-induced interruption and modification of relevant ecosystem service flow could threaten their solvency. In reaction, private companies are increasingly considering climate adaptation in their corporate and risk management strategies (Lydenberg *et al.* 2010). For example, the Coca-Cola Company has benefited greatly from the landscape's ability to cleanse surface water prior to its arrival at their bottling plants. The company is now considering how to use landscape services to manage their water cleaning costs under various climate-change scenarios. Furthermore, as one of the world's largest buyers of sugarcane, sugar beet, and maize products, Coca-Cola is closely monitoring the potential impact of climate change on global maize and sugar production and market prices (BSR 2013). Similarly, Dow Chemical is assessing and incorporating the impacts of changing ecosystem services on their corporate strategies. Dow has considered climate scenarios when examining the flood risk at and the water supply chain to its production facility in Freeport, Texas. Both of these companies have paid nongovernmental organizations – the World Wildlife Fund in the case of Coca-Cola and The Nature Conservancy in the case of Dow – to assist in creating a natural capital and natural asset balance sheet and related risk analyses in areas relevant to their respective operations.

Although these two multinational corporations have the resources to pay for this information and analysis, many other US-based companies and local governments do not. A widely and publically available natural capital and ecosystem service balance sheet and related apparatus would provide valuable information to all levels of private and governmental decision making in the face of climate change. To better understand the impact of such a balance sheet for business decision-making nationwide, one only needs to consider the effect that national weather services, providers of a different type of nature-based balance sheet, and their forecasts have had on businesses around the world. Indeed, Qantas Airlines saved AU$27–AU$42 million annually on reduced fuel consumption due to a regulatory change that allowed the airline to set fuel loads based on weather forecasts provided by the Australian weather service (Anaman *et al.* 1997). Likewise, the Australian cotton industry's purchase of Australian weather service products generated a monetary benefit 12.6 times greater than the products' purchase price (Anaman *et al.* 1997). Public provision of detailed and site-specific long-range forecasts on climate change and associated risks and potential ecosystem-service-based adaptations would be similarly valuable.

Conclusions

Climate change translates into change for the way governments, companies, and citizens conduct their daily business. If society begins to adapt to change without an overarching framework to decide which changes are most damaging and what can be tolerated, resources could be squandered and the impacts of climate change exacerbated. A dynamic national tally of natural capital and assets, including associated ecosystem services, promises to serve as an ideal framework to design national, regional, individual, and private-sector responses to climate change. Unfortunately, the scientific and data-oriented foundation to report trends in ecosystem service provision and value is currently lacking (PCAST 2011). Therefore, now is the time for the nation to build a monitoring and reporting system for ecosystem services. Readers of this journal and scientists from many other disciplines will need to be the primary authors of such a system. These stakeholders must conduct the relevant analyses, translate scientific results in ways that are useful to public and private managers, and help draft the architecture of a real-time information database if climate-change adaptation in the US is to be welfare-enhancing and efficient (eg Richter *et al.* 2009; Ruckelshaus *et al.* 2013b).

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