The Effects of Climate Change on U.S. Ecosystems

Agriculture · Land Resources · Water Resources · Biodiversity

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Published May 2008, the Synthesis and Assessment Product 4.3 (SAP 4.3): *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States* provided the basis of this concise report. The SAP 4.3 is the most extensive examination of the impacts of climate change on important U.S. ecosystems undertaken to date and is one of a series of 21 Synthesis and Assessment Products being produced under the auspices of the U.S. Global Change Research Program (USGCRP), which coordinates the climate change research activities of U.S. government agencies.

More information and a full-length report are available from a number of different agencies and organizations:

The National Center for Atmospheric Research (NCAR), which wrote this overview document, also managed creation of the full-length SAP 4.3, which can be found at www.sap43.ucar.edu.
The National Center for Atmospheric Research is sponsored by the National Science Foundation.

The U.S. Department of Agriculture, the lead agency responsible for creating the SAP 4.3, provides an electronic version of the report at www.usda.gov/oce/global_change/sap_2007_FinalReport.htm.

The U.S. Global Change Research Program (USGCRP) also has a link to the full length report, and other SAP efforts. These are available at www.globalchange.gov/publications/reports/scientific-assessments/saps/304

For more information on this report, please contact Rachel Hauser at NCAR's Research Relations Office by email, rhauser@ucar.edu, or phone +1 303 497 1117.

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Introduction

The Earth's climate is changing. The Fourth Assessment Report (AR4) from the Intergovernmental Panel on Climate Change (IPCC) offers the most comprehensive and up-to-date scientific assessment of this issue, stating with "very high confidence" that human activities such as fossil fuel burning and deforestation have altered the global climate. Climate change signals are also manifesting themselves in U.S. ecosystems. U.S. temperature and precipitation records show that the country has become warmer and wetter during the last 100 years, but there is considerable regional variation within this overall picture. Parts of the South have cooled, while northern regions have warmed. Many eastern and southern areas now receive more precipitation than 100 years ago, while other areas, especially in the Southwest, receive less.

A recent U.S. scientific assessment project – one of a series commissioned by the U.S. Global Change Research Program (USGCRP) – examined how these climate changes are affecting agriculture, land resources, water resources and biodiversity in the United States. While this document offers readers a summary version of the original report, a limited amount of new information drawn from supporting scientific materials has been added to provide additional detail on the original findings. The lead sponsor of this activity was the U.S. Department of Agriculture (USDA); the National Center for Atmospheric Research (NCAR) led and coordinated the project. The time horizon considered was 1900 to 2100, but the main focus was on the recent past and the next 25 to 50 years, which fall within the planning horizon of many natural resources managers.

The climate change that will occur during this period is relatively well understood; much of this change will be caused by greenhouse gas emissions that have already happened. It is thus partially independent of current or planned emissions control measures and the large scenario uncertainty that affects longer-term projections.

The team of authors – experts in the fields of agriculture, biodiversity, and land and water resources – conducted an exhaustive review, analysis, and synthesis of the relevant scientific literature, considering more than 1,000 separate publications. This document summarizes their major findings and conclusions.

Robust scientific consensus shows that human-induced climate change is occurring.

Finally, the authors have endeavored to use consistent terms, agreed to by the USGCRP agencies, to describe confidence in the findings and conclusions in this report, particularly when these involve projections of future conditions and accumulation of information from multiple sources. The use of these terms represents the judgment of the authors of this document; for example, "likely" indicates greater than 66% likelihood, while "very likely" is greater than 90% likelihood. Much of the underlying literature does not use such a lexicon and we have not retroactively applied this terminology to previous studies by other authors.

Global Climate Context

It is very likely that the Earth will experience a faster rate of climate change in the 21st century than seen in the last 10,000 years.

Before looking at the effects of climate change on the United States, it's helpful to understand how changing climate is affecting the world as a whole. During the 20th century, global average surface temperature increased by about 0.6°C and global sea level increased about 15 to 20 cm. Global precipitation over land increased about 2 percent during this same period. Looking ahead, human influences will continue to change Earth's climate throughout the 21st century. The IPCC AR4 projects that the global average temperature will rise another 1.1°C to 5.4°C by 2100, depending on how much atmospheric concentrations of greenhouse gases increase during this time. This temperature rise will mean continued increases in sea level and overall rainfall, changes in rainfall patterns and timing, and decline in snow cover, land ice, and sea ice extent. It is very likely that the Earth will experience a faster rate of climate change in the 21st century than seen in the last 10,000 years (Figure 1).

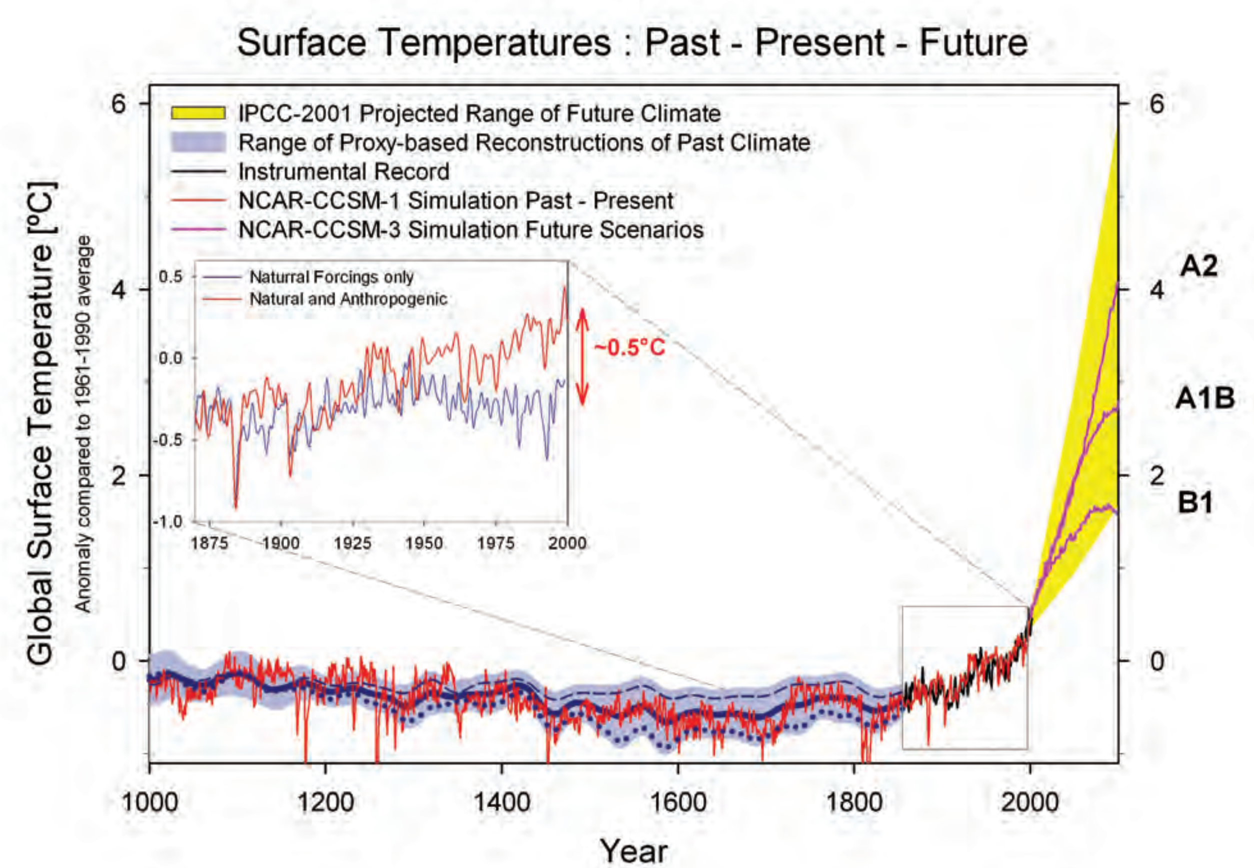

Figure 1. It is very likely that the Earth will experience a faster sustained rate of climate change in the 21st century than has occured in the previous 10,000 years. High-resolution proxy data, surface temperature records, and climate models have been used to establish the structure and magnitude of large scale natural climate variability over the past 1,000 years. However, since the mid-20th century, surface temperatures have warmed significantly—with the greatest warming occurring since the 1970s. Evaluating all observational records and using climate models for testing various processes, this recent change in global climate temperature can only be explained by including the effects of changing greenhouse gas concentrations in the atmosphere. (Image courtesy of the National Center for Atmospheric Research.)

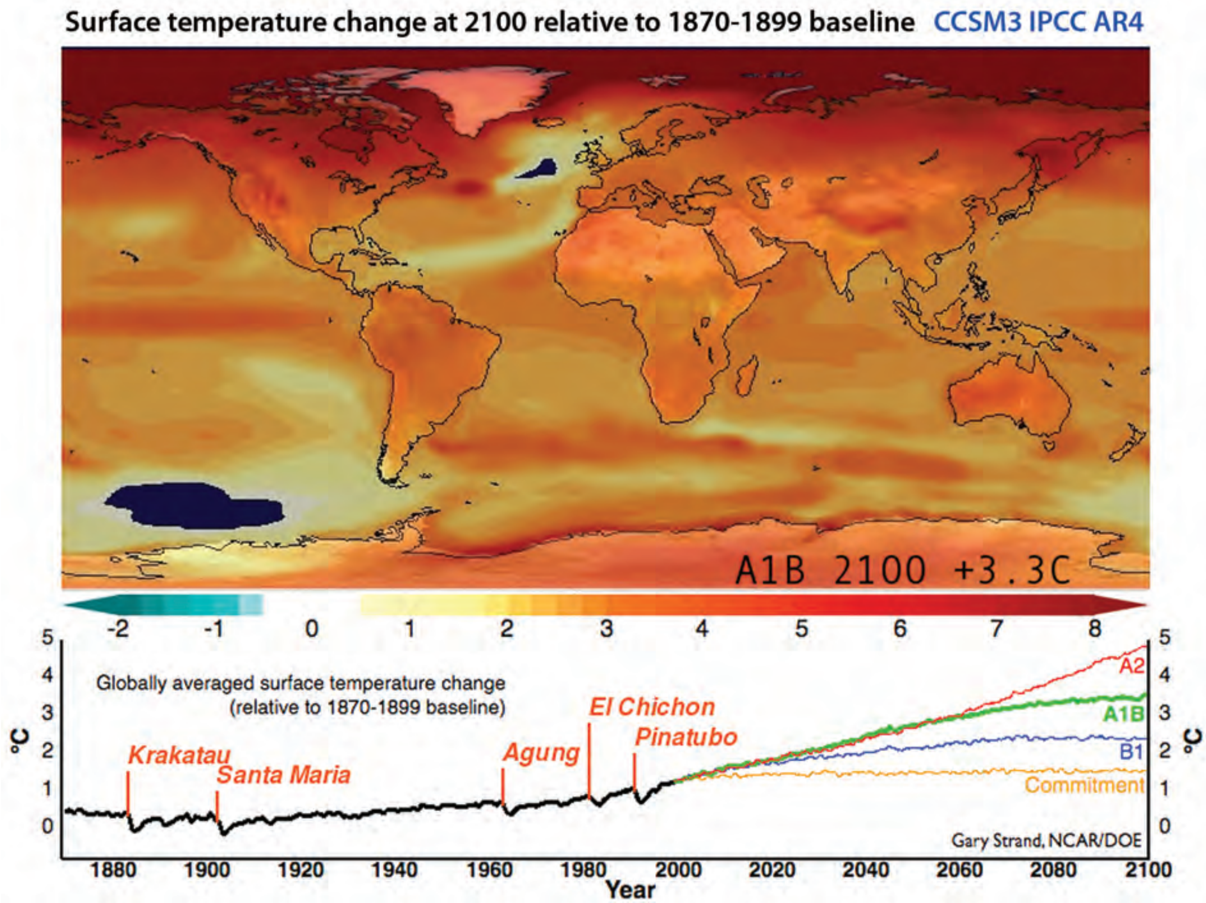

Figure 2 (above). Taken from the average of a set of Community Climate System Model 3 (CCSM3) experiments, the upper image shows global surface temperatures increasing relative to pre-industrial temperatures (1870-1899) based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1B climate change scenario commitment. The lower panel shows the global average temperature change from the same base period, illustrating the impact of five major volcanic eruptions, as well as the different IPCC SRES climate change scenarios, including Commitment (i.e., no changes relative to 2000 in greenhouse gases), B1 (CO_2 level stabilizes at 550 ppm), A1B (CO_2 stabilizes at 720 ppm) and A2 (CO_2 increases to 840 ppm at 2100). (Image courtesy of the National Center for Atmospheric Research.)

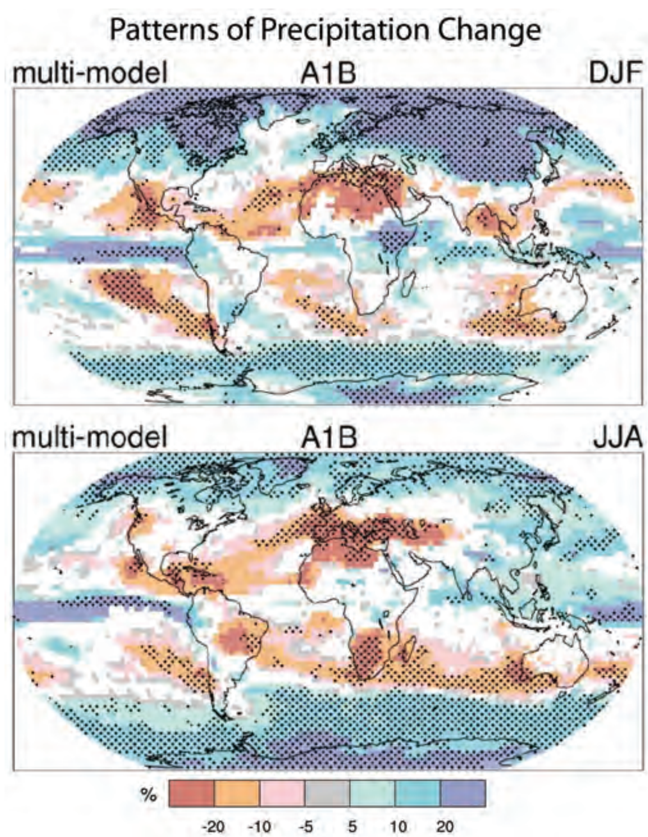

Figure 3 (right). Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999. Values are multi-model averages based on the IPCC A1B (business as usual) emissions scenario for December to February (top) and June to August (bottom). White areas indicate regions where less than 66% of the models agree on the sign of the change, and stippled areas are where more than 90% of the models agree on the sign of the change. (Image from Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Figure SPM.7. Cambridge University Press.)*

U.S. Climate Context

Temperatures in the United States are very likely to increase by another 1°C to more than 4°C.

During the 20th century, the United States warmed and became wetter overall, with changes varying by region (Figures 4 and 5). Parts of the South have cooled, while northern regions have warmed – Alaskan temperatures, for example, have increased 2 to 4°C , which is more than four times the global average.

Much of the eastern and southern United States now receives more precipitation than 100 years ago, while other areas, especially in the Southwest, receive less. The frequency and duration of heat waves have increased, there have been large declines in summer sea ice in the Arctic, and there is some evidence of increased frequency of heavy rainfalls.

Observational and modeling results documented in the IPCC AR4 indicate that these trends are very likely to continue. Temperatures in the United States are very likely to increase by another 1°C to more than 4°C. The West and Southwest are likely to become drier, while the eastern United States is likely to experience increased rainfall. Heat waves are very likely to be hotter, longer, and more frequent, and heavy rainfall is likely to become more frequent.

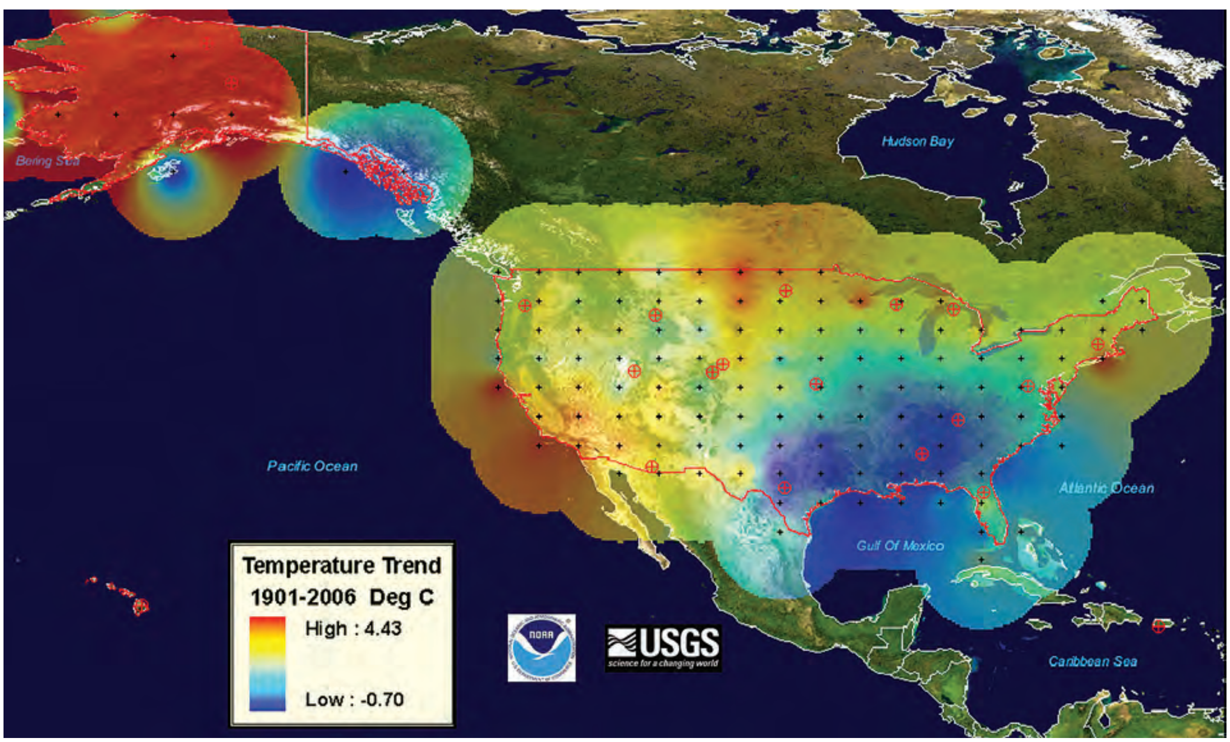

Figure 4. Mapped trends in temperature across the lower 48 states, Alaska, and Hawaii. These data, which show the regional pattern of U.S. warming, are averaged from weather stations across the country using stations that have as complete, consistent, and high quality records as can be found. (Image courtesy NOAA National Climate Data Center and the U.S. Geological Survey.)

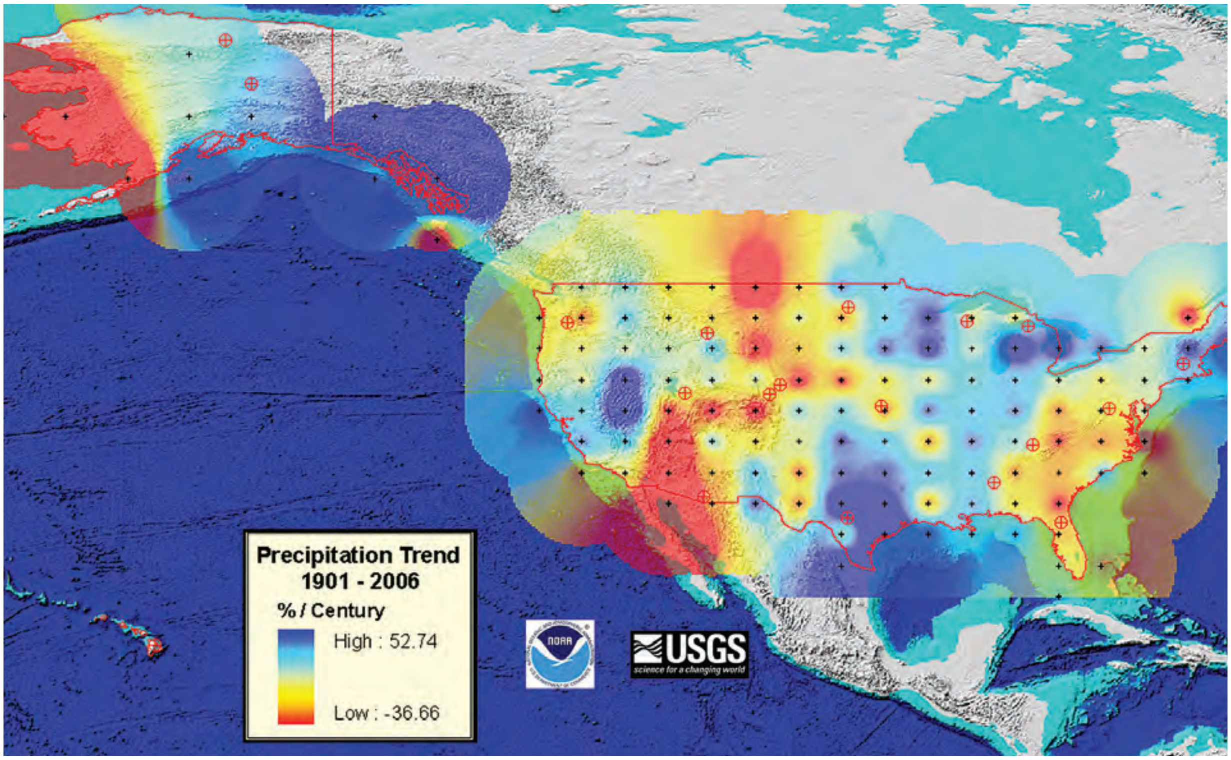

Figure 5. Precipitation changes over the past century from the same weather stations as for temperature. The changes are shown as percentage changes from the long-term average. (Image courtesy NOAA National Climate Data Center and the U.S. Geological Survey.)

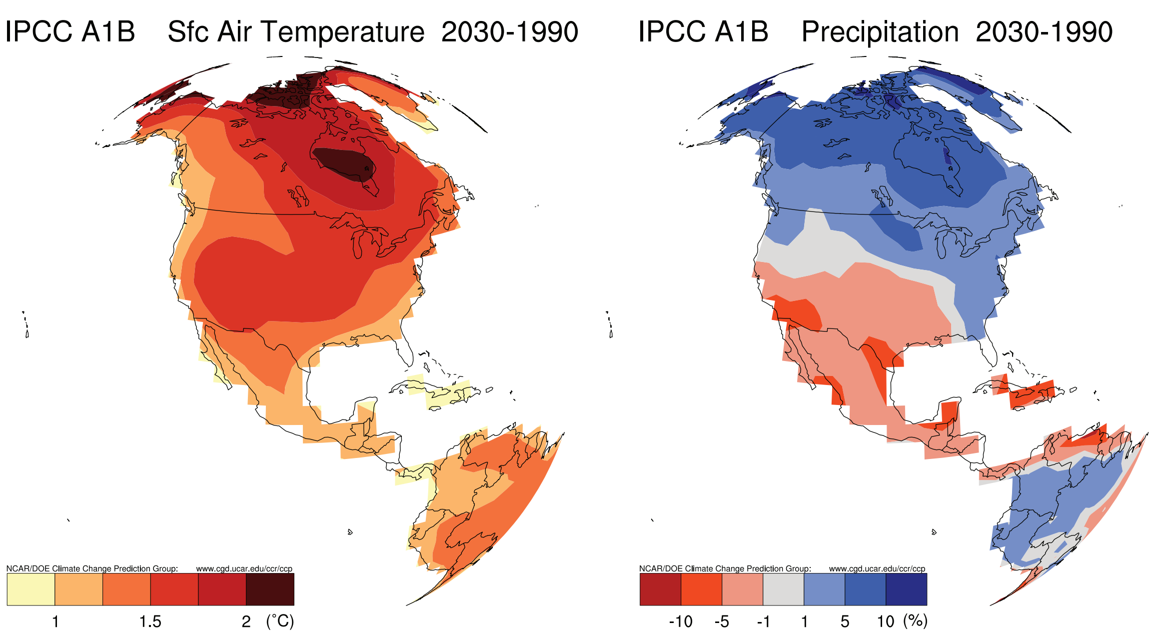

Figure 6. U.S. Temperature and Precipitation Changes by 2030. This figure shows how U.S. temperatures and precipitation would change by 2030 under IPCC emissions scenario A1B, which would increase the atmospheric concentration of greenhouse gases to about 700 parts per million by 2100 (this is roughly double the pre-industrial level). The changes are shown as the difference between two 20-year averages (2020-2040 minus 1980-1999). These results are based on simulations from nine different climate models from the IPCC AR4 multi-model ensemble. The simulations were created on supercomputers at research centers in France, Japan, Russia, and the United States. (Adapted by Lawrence Buja and Julie Arblaster from Tebaldi et al. 2006: Climatic Change, Going to the Extremes; An intercomparison of model-simulated historical and future changes in extreme events, Climatic Change, 79:185-211.)

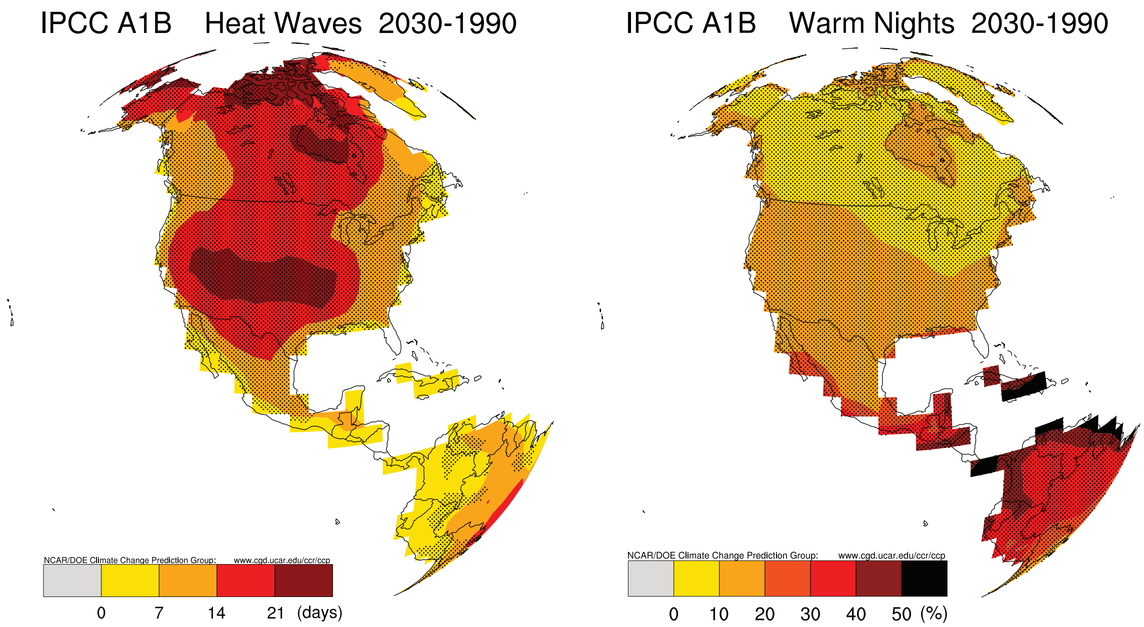

Figure 7. Simulated U.S. Heat Wave Days and Warm Nights in 2030. The left panel shows the projected change in number of heat wave days (days with maximum temperature higher by at least 5°C (with respect to the climatological norm)). The right panel shows changes in warm nights (percent of times when minimum temperature is above the 90th percentile of the climatological distribution for that day). Both panels show results for IPCC emissions scenario A1B, which would increase the atmospheric concentration of greenhouse gases to about 700 parts per million by 2100 (this is roughly double the pre-industrial level). The changes are shown as the difference between two 20-year averages (2020-2040 minus 1980-1999). Shading indicates areas of high inter-model agreement. These results are based on simulations from nine different climate models from the IPCC AR4 multi-model ensemble. The simulations were created on supercomputers at research centers in France, Japan, Russia, and the United States. (Adapted by Lawrence Buja and Julie Arblaster from Tebaldi et al. 2006: Climatic Change, Going to the Extremes; An intercomparison of model-simulated historical and future changes in extreme events, Climatic Change, 79:185-211.)

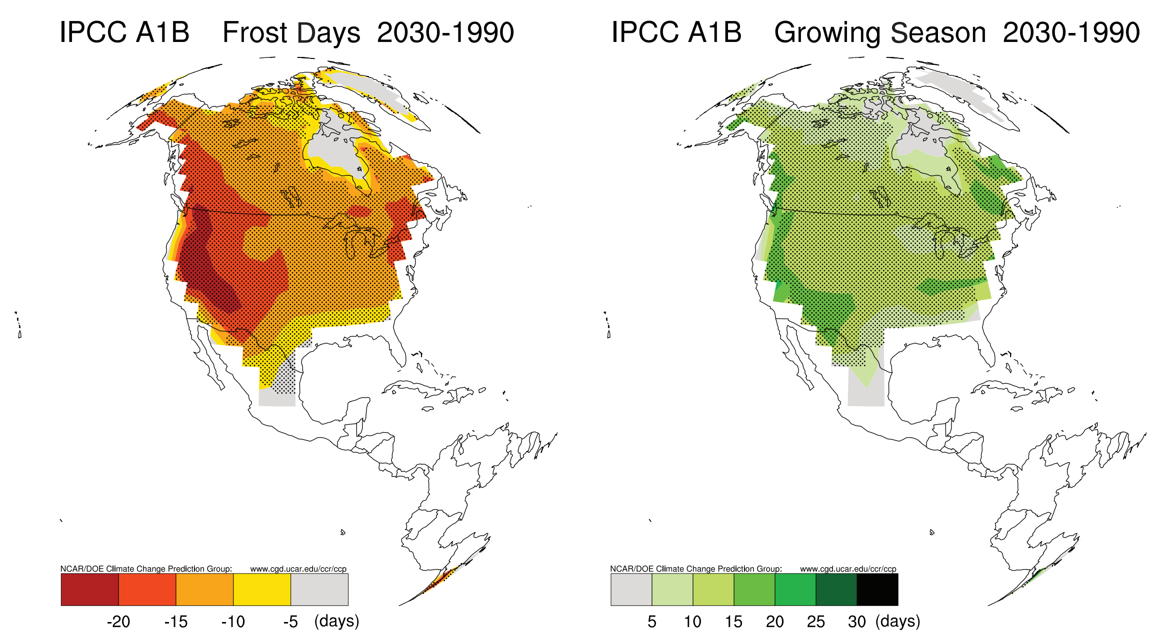

Figure 8. Changes in U.S. Frost Days and Growing Season by 2030. This figure shows decreases in frost days and increases in growing season length that would occur by about 2030 if the world follows IPCC emissions scenario A1B, which would increase the atmospheric concentration of greenhouse gases to about 700 parts per million by 2100 (this is roughly double the pre-industrial level). The changes are shown as the difference between two 20-year averages (2020-2040 minus 1980-1999). Shading indicates areas of high inter-model agreement. These results are based on simulations from nine different climate models from the IPCC AR4 multi-model ensemble. The simulations were created on supercomputers at research centers in France, Japan, Russia, and the United States. (Adapted by Lawrence Buja and Julie Arblaster from Tebaldi et al. 2006: Climatic Change, Going to the Extremes; An intercomparison of model-simulated historical and future changes in extreme events, Climatic Change, 79:185-211.)

Impacts of Climate Change on Agriculture

Valued at about $200 billion in 2002, many U.S. crops and livestock varieties are grown in diverse climates, regions, and soils. But no matter the region, weather and climate factors such as temperature, precipitation, CO_2 concentrations, and water availability directly impact the health and well-being of plants, pasture, rangeland, and livestock. Variation in yield among years is related to growing-season weather for any agricultural commodity; weather also influences insects, disease, and weeds, which in turn affect agricultural production. Some climate change-related effects include:

- The life cycle of grain and oilseed crops will likely progress more rapidly with increased CO_2 and temperature. But, as temperature rises, these crops will increasingly begin to experience failure, especially if climate variability increases and precipitation lessens or becomes more variable.

- Increasing CO_2 increases the growth of C_3 plants (soybean, cotton, beans, tomatoes) more than C_4 plants (corn) and also increases the efficiency of water use in these plants by producing more biomass per unit of water transpired by the plant.

Figure 9. Higher temperatures will negatively affect livestock. Warmer winters will reduce mortality, but this will be more than offset by greater mortality in hotter summers. Hotter temperatures will also result in reduced productivity of livestock and dairy animals.

- Increases in night-time temperature during the reproductive period of plants for either grain or fruit increases the respiration rate and offsets the photosynthetic gains during the day. Plants grown under high night-time temperatures have smaller fruit or grain sizes, thus reducing their productivity.

- The marketable yield of many horticultural crops – e.g., tomatoes, onions, fruits – is very likely to be more sensitive to climate change than grain and oilseed crops.

- Increases in temperature will extend the potential areas for growth of perennial crops in the northern U.S.; however, there is a concurrent increase in the risk of frost damage because plants will begin to grow earlier in the spring. The increase in winter-time temperatures may also have a negative impact on plants that have a chilling requirement before fruit production.

- Climate change is likely to lead to a northern migration of weeds. Many weeds respond more positively to increasing CO_2 than most cash crops, particularly C_3 "invasive" weeds. But recent research also suggests that glyphosate, the most widely used herbicide in the United States, loses its efficacy on weeds grown at the increased CO_2 levels likely in the coming decades.

- Plants alter their chemical composition under increasing CO_2. For example, the toxin in poison ivy, urushiol, is produced by the plant in greater

No matter the region, weather and climate factors such as temperature, precipitation, CO_2 concentrations, and water availability directly impact the health and well-being of plants, pasture, rangeland, and livestock.

abundance and is of higher toxicity under these conditions. This, in turn, has implications for human health.

- Disease pressure on crops and domestic animals will likely increase with earlier springs and warmer winters, through proliferation and higher survival rates of pathogens and parasites. Regional variation in warming and changes in rainfall will also affect spatial and temporal distribution of disease.

Shifts in plant productivity and type will also have significant impact on livestock operations.

- Projected increases in temperature and a lengthening of the growing season will likely extend forage production into late fall and early spring, thereby decreasing need for winter season forage reserves. However, these benefits will very likely be affected by regional variations in water availability.

- Climate change-induced shifts in plant species are already under way in rangelands. Establishment of perennial herbaceous species is reducing soil water availability early in the growing season. Shifts in plant productivity and type will likely also have significant impact on livestock operations.

- Forage quality in pasture and rangeland generally declines with increasing CO_2 because of the interactions between the carbon and nitrogen cycle in plants and the impact on the protein content of the forage. Declining forage quality will reduce the land's ability to supply adequate and nutritious livestock feed.

- Higher temperatures will very likely reduce livestock production during the summer season, but these losses will very likely be partially offset by warmer temperatures during the winter season. For ruminants, current management systems generally do not provide shelter to buffer the adverse effects of changing climate; such protection is more frequently available for non-ruminants (e.g., swine and poultry).

Figure 10. Except in the case of rice and beans, the benefits of CO_2 rise over the next 20 years largely offset the negative effects of temperature for most C_3 crops (wheat and other fine grains, soybeans, legumes, etc.). However, because C_4 crops (for example, corn, sorghum, and cane sugar) have little response to rising CO_2 concentrations, yields will decrease as temperatures rise.

- Monitoring systems for measuring long-term response of agricultural lands are numerous, but integration across these systems is limited. Existing state-and-transition models could be expanded to incorporate knowledge of how agricultural lands and products respond to global change; integration of such models with existing monitoring efforts and plant developmental data bases could provide cost-effective strategies that both enhance knowledge of regional climate change impacts and offer ecosystem management options. In addition, at present, there are no easy and reliable means to accurately ascertain the mineral and carbon state of agricultural lands, particularly over large areas; a fairly low-cost method of monitoring biogeochemical response to global change would be to sample ecologically important target species in different ecosystems.

Impacts of Climate Change on Land Resources

Forests and arid lands are the two broad subtopics considered in this section. Looking first at forests, it is clear that climate strongly influences productivity, species composition, and the frequency and magnitude of forest disturbances. Disturbances such as forest fire, insect outbreaks, storms, and severe drought command public attention and increased management resources. Climate change will increase these disturbances and the attention and resources needed. Similarly in arid lands, disturbance and land use will control the response of these lands to climate change. Many plants and animals in arid ecosystems are near their physiological limits for tolerating temperature and water stress and even slight changes in stress will have significant consequences. In the near term, fire effects will trump climate effects on ecosystem structure and function for arid lands.

Some climate change-related effects on forested and arid lands include:

- The size and number of forest fires, insect outbreaks, and tree mortality in the interior West, the Southwest, and Alaska have very likely increased because of changing climate, and will continue to do so.

It is clear that climate strongly influences productivity, species composition, and the frequency and magnitude of forest disturbances.

Figure 11. Aerial view of the U.S. Forest Service Rocky Mountain Research Station's Fraser Experimental Forest near Winter Park, Colorado, May 2007. The green strips are areas of forest that had been harvested decades earlier, and so have younger, faster growing trees. The red and brown areas show dead and dying trees caused by bark beetle infestation. A more recent photo would show less contrast because, due to drought and beetle epidemic, mortality rates of young trees have also risen. (Image courtesy U. S. Forest Service, Rocky Mountain Research Station.)

Many plants and animals in arid ecosystems are near their physiological limits for tolerating temperature and water stress and even slight changes in stress will have significant consequences.

- Rising CO_2 will very likely increase photosynthesis for forests, but this increase will likely only enhance wood production in young forests on fertile soils.
- Nitrogen deposition and warmer temperatures have very likely increased forest growth where adequate water is available and will continue to do so in the near future.
- The combined effects of rising temperatures and CO_2, nitrogen deposition, ozone, and forest disturbance on soil processes and soil carbon storage remains unclear.
- Higher temperatures, increased drought, and more intense thunderstorms will very likely increase erosion and promote invasion of exotic grass species in arid lands.
- Climate change in arid lands will create physical conditions conducive to wildfire, and the proliferation of exotic grasses will provide fuel, thus causing fire frequencies to increase in a self-reinforcing fashion.
- In arid regions where ecosystems have not co-evolved with a fire cycle, the probability of loss of iconic, charismatic megaflora such as saguaro cacti and Joshua trees is very likely.
- Arid lands very likely do not have a large capacity to absorb CO_2 from the atmosphere and will likely lose carbon as climate-induced disturbance increases.
- River and riparian ecosystems in arid lands will very likely be negatively impacted by decreased streamflow, increased water removal, and greater competition from nonnative species.

Figure 12. Mojave Desert scrub near Las Vegas, NV (foreground), an area invaded by the exotic annual grass red brome (background) following a fire that traveled from desert floor upslope into pinyon-juniper woodlands. (Image courtesy T.E. Huxman.)

- Changes in temperature and precipitation will very likely decrease the cover of vegetation that protects the ground surface from wind and water erosion.
- Current observing systems do not easily lend themselves to monitoring change associated with disturbance and alteration of land cover and land use. Current observing systems also cannot identify climate change as causing ecosystem changes. Identifying the influence of climate change would be easier if climate data and ecosystem response were measured at the same locations using standard protocols, and coupled with a network of experimental manipulations of climate.

Impacts of Climate Change on Water Resources

Plants, animals, natural and managed ecosystems, and human settlements are susceptible to variations in water storage, fluxes, and quality of water, all of which are sensitive to climate change. The effects of climate on the nation's water storage capabilities and hydrologic functions will have significant implications for water management and planning as variability in natural processes increases. Although U.S. water management practices are generally quite advanced, particularly in the West, the reliance on past conditions as the foundation for current and future planning and practice will no longer be tenable as climate variability and change increasingly create conditions well outside of historical parameters and erode predictability.

Some climate change-related effects on U.S. water resources include:

- Most of the United States experienced increases in precipitation and streamflow and decreases in drought during the second half of the 20th century. It is likely that these trends are due to a combination of decadal-scale variability and long-term change.

- Consistent with streamflow and precipitation observations, most of the continental United States experienced reductions in drought severity and duration over the 20th century. However, there is some indication of increased drought severity and duration in the western and southwestern United States.

The effects of climate on the nation's water storage capabilities and hydrologic functions will have significant implications for water management and planning as variability in natural processes increases.

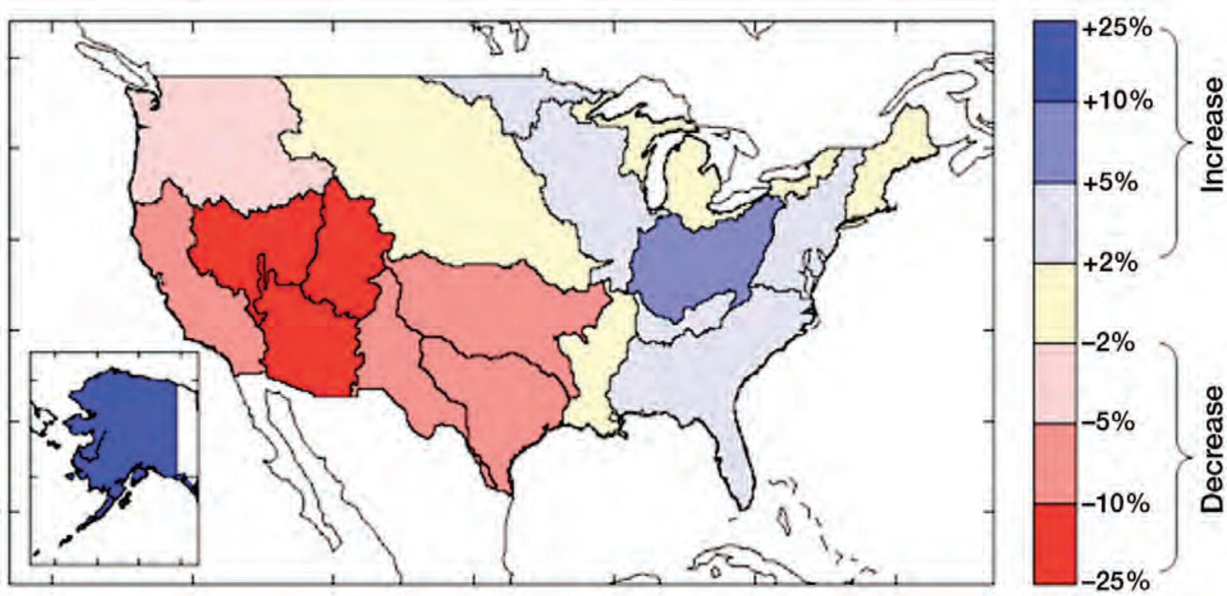

Figure 13. Median changes in runoff interpolated to USGS water resources regions from Milly et al. (2005) from 24 pairs of general circulation model simulations for 2041-2060 relative to 1901-1970. Percentages noted within the mapped regions are the fraction of 24 runs for which differences had same sign as the 24-run median. (Results from the paper, Milly, P.C.D., K.A. Dunne, and A.V. Vecchia, 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature, *438, 347-350, replotted by P.C.D. Milly, USGS.)*

Figure 14. At the Niwot Ridge Long-Term Ecological Research Site in Colorado's Rocky Mountains, scientists study climate and ecosystem interactions.

- There is a trend toward reduced mountain snowpack and earlier spring snowmelt runoff peaks across much of the western United States. This trend is very likely attributable at least in part to long-term warming, although some part may have been played by decadal-scale variability, including a shift in the phase of the Pacific Decadal Oscillation in the late 1970s. Where earlier snowmelt peaks and reduced summer and fall low flows have already been detected, continuing shifts in this direction are very likely and may have substantial impacts on the performance of reservoir systems.

- Water quality is sensitive to both increased water temperatures and changes in precipitation. However, most water quality changes observed so far across the continental United States are likely attributable to causes other than climate change.

- Stream temperatures are likely to increase as the climate warms, and are very likely to have both direct and indirect effects on aquatic ecosystems. Changes in temperature will be most evident during low flow periods, when they are of greatest concern. Stream temperature increases have already begun to be detected across some of the United States, although a comprehensive analysis similar to those reviewed for streamflow trends has yet to be conducted.

- A suite of climate simulations conducted for the IPCC AR4 shows that the United States may experience increased runoff in eastern regions, gradually transitioning to little change in the Missouri and lower Mississippi, to substantial decreases in annual runoff in the interior West (Colorado and Great Basin).

- Trends toward increased water use efficiency are likely to continue in the coming decades. Pressures for reallocation of water will be greatest in areas of highest population growth, such as the Southwest. Declining per capita (and in some cases, total) water consumption will help mitigate the impacts of climate change on water resources.

- Essentially no aspect of the current hydrologic observing system was designed specifically to detect climate change or its effects on water resources. Recent efforts have the potential to make improvements, although many systems remain technologically obsolete, incompatible, and/or have significant data collection gaps in their operational and maintenance structures. As a result, many of the data are fragmented, poorly integrated, and unable to meet the predictive challenges of a rapidly changing climate.

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Impacts of Climate Change on Biodiversity

Biodiversity, the variation of life at the genetic, species, and ecosystem levels of biological organization, is the fundamental building block of the ecosystem services delivered to human societies. It is intrinsically important both because of its contribution to the functioning of ecosystems, and because it is difficult or impossible to recover or replace once it is eroded. Climate change is affecting U.S. biodiversity and ecosystems, including changes in growing season, phenology, primary production, and species distributions and diversity. It is very likely that climate change will increase in importance as a driver for changes in biodiversity over the next several decades, although for most ecosystems it is not currently the largest driver of change. In this section, species diversity and rare and sensitive ecosystems are the broad subtopics considered.

Figure 15. The rapid rates of warming in the Arctic observed in recent decades and projected for at least the next century are dramatically reducing the snow and ice covers that provide denning and foraging habitat for polar bears. (Image courtesy Susanne Miller, U.S. Fish and Wildlife Service.)

Climate change-related effects on U.S. biodiversity include:

- In the higher latitudes of North America, the growing season has lengthened and net primary productivity (NPP) has increased. Over the last 19 years, global satellite data indicate an earlier spring onset across the temperate latitudes by 10 to 14 days.
- In an analysis of 866 scientific papers that explore the ecological consequences of climate change, nearly 60 percent of the 1598 species studied exhibited shifts in distributions and/or phenologies over timeframes of 20 to 140 years. Analyses of field-based phenological responses show shifts as great as 5.1 days per decade, with an average of 2.3 days per decade across all species.
- Subtropical and tropical corals in shallow waters have already suffered major bleaching events that are clearly driven by increases in sea surface temperatures. Increases in ocean acidity, which are a direct consequence of increases in atmospheric carbon dioxide, are calculated to have the potential for serious negative consequences for corals.
- The rapid rates of warming in the Arctic observed in recent decades, and projected for at least the next century, are dramatically reducing the snow and ice covers that provide denning and foraging habitat for polar bears.
- There are other possible, and even probable, impacts and changes in biodiversity (e.g., disruption of the relationships between pollinators, such as bees, and flowering plants), for which we do not yet have a substantial

Climate change is affecting U.S. biodiversity and ecosystems, including changes in growing season, phenology, primary production, and species distributions and diversity.

Over the last 19 years, global satellite data indicate an earlier spring onset across the temperate latitudes by 10 to 14 days.

observational database. However, we cannot conclude that the lack of complete observations is evidence that changes are not occurring.

- It is difficult to pinpoint changes in ecosystem services that are specifically related to changes in biological diversity in the United States. A specific assessment of changes in ecosystem services for the United States as a consequence of changes in climate or other drivers of change has not been done.

- The monitoring systems that have been used to evaluate the relationship between changes in the physical climate system and biological diversity have three components: species-specific or ecosystem-specific monitoring systems, research activities specifically designed to create time-series of population data and associated climatic and other environmental data, and spatially extensive observations derived from remotely sensed data. However, in very few cases were these monitoring systems established with climate variability and climate change in mind, so the information that can be derived from them specifically for climate change-related studies is somewhat limited. It is also not clear that existing networks can be maintained for long enough to enable careful time-series studies to be conducted.

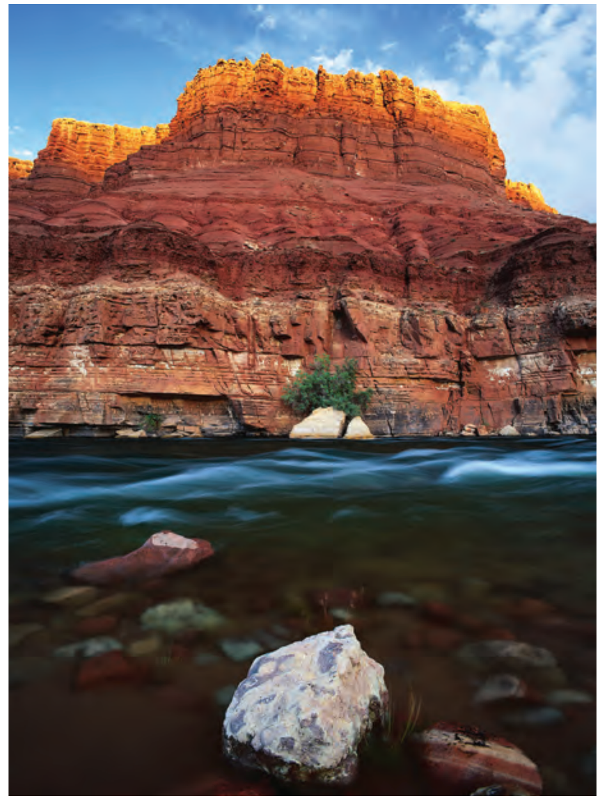

Figure 16. Stream temperatures are likely to increase as the climate warms, and are very likely to have both direct and indirect effects on aquatic ecosystems. Changes in temperature will be most evident during low flow periods, when they are of greatest concern.

Designing Systems to Monitor Climate Change Impacts

Based on the research presented in the preceding pages, it is clear that changes and impacts in many U.S. ecosystems are being driven by changes in the physical climate system, including both long-term changes and climate variability. The authors of this report relied on the results of hundreds of individual studies in establishing this conclusion. In turn, the researchers responsible for many of those individual studies relied on information garnered from existing monitoring systems – systems that in most cases were originally designed for purposes other than looking at the effects of climate change on ecosystems.

A growing need exists for developing strategies to adapt to ecological changes and to manage ecosystems in such a way as to lessen the negative impacts of changing climate, particularly given the very likely possibility of ongoing climate change.

Figure 17. Average rainfall, variability of rainfall, and heavy rainfall events are projected to increase in many regions of the United States.

Going forward, observation and monitoring systems must be able to support analyses that can aid this management challenge, i.e., adapting to change, documenting the rapidity of ecological changes to assist in adjustment of existing management strategies and, most importantly, forecasting when potential thresholds of change might occur and assessing how rapidly changes will occur. Ecological forecasting is one of the specific goals of international programs such as Global Earth Observation System of Systems (GEOSS), but exactly how such programs will fulfill these goals is still in development.

In order to fulfill the goal of providing observations for responding to climate change, there are at least five issues that such systems will need to be able to address:

Monitoring changes in overall status, regardless of cause: Work of the National Research Council (NRC) and the Heinz Center on indicators of the status of U.S. ecosystems cogently articulates this need. Their argument is straightforward: there is both scientific and societal value for the United States to know the extent, status, and condition of its own natural resources and ecosystems. Both the NRC and the Heinz Center present recommendations for specific indicators, derived from scientific concerns and from a broader, stake-holder driven process. In both cases, no attempt is made to attribute changes in the indicators to particular stresses strictly through use of monitoring data. However, both recognize that such analyses are necessary for scientific and policy purposes. The system of indicators

A growing need exists for developing strategies to adapt to ecological changes and manage ecosystems in such a way as to lessen the negative impacts of changing climate, particularly given the very likely possibility of ongoing climate change.

Current research on the relationships between climate variability and change and ecological status and processes could also be used to develop new indicators of the effects of climate change.

is ultimately dependent on existing monitoring systems, most of which have been put in place for other reasons. In addition, the degree to which the ecosystem indicators identified either by the NRC or the Heinz Center process are sensitive to expected changes due to climate variability and change is as yet unknown.

Early warning of changes due to climate: As of now, there are no routine monitoring systems established specifically for early warning of ecosystem shifts or alterations related to climate change. The impacts documented in this report and elsewhere are the results of analyses of existing monitoring systems and research projects, but those systems have not been optimized for early warning purposes. Without changing the configuration of existing in situ monitoring systems, or initiating new systems, it will be difficult to be sure that an adequate early warning system has been constructed, and the ability to determine overall consequences of climate change may be limited.

While unexpected outcomes related to how systems react to changing climate no doubt await, scientists now know more than ever before about the existing responses of ecosystems and species to changes in climate and climate variability. This knowledge will help in defining monitoring systems that are optimized for early warning of subsequent changes. For example, systematic monitoring of ocean pH and alkalinity could be established along with coral observations to identify and track early indications of difficulties in calcification due to increasing CO_2 in surface waters. Another system might sample vegetation along montane transects to detect early changes in flowering phenology and/or change in establishment patterns of seedlings that would result in species range changes to higher elevations as a result of warming temperatures.

In the near-term, stratification of existing systems holds promise for providing reasonable information about early responses. Monitoring of snow pack and streamflow is being used in just this way, as are long time series of ice-out dates in northern lakes and national phenology data. At a minimum, identifying ecosystems known to be at risk of early change (e.g., high latitude ecosystems, high elevation ecosystems, coastal wetlands, migratory bird species), either because similar ecosystems have already exhibited change or because they are in locations that are likely to experience rapid change, and investigating existing monitoring data from them would be more likely to reveal early evidence of expected changes than broad-based monitoring. Over the longer term, studies of existing monitoring data that are stratified with respect to either observation-based or model-based expectations of change would probably lead to better designs for future monitoring, but such studies have not yet been done.

Figure 18. Coral reefs around the world are under a variety of stresses, some related to changing climate, and some not; water temperatures are increasing, water pH is falling, and increasingly intense storms affect the health of coral reef ecosystems.

Monitoring programs optimized for early warning would not be appropriate for other purposes, such as calculating average damages in ecosystems or average changes in ecosystem services, precisely because they would be more likely to detect changes to individual ecosystem characteristics than to the ecosystem overall. This is not a drawback to early warning systems, but it is a caution that information from them cannot simply be used to calculate overall expected damages.

Development and monitoring of indicators of climate change impacts: Scientists are in the early stages of understanding ecological change that is caused by climate variability and change, and it should be expected that this understanding will grow and mature over time. Some indicators of change are already clear from current studies: earlier dates of snowmelt and peak streamflow, earlier ice-out dates on northern lakes, earlier spring arrival dates for migratory birds, northward movement of species distributions, and so forth. Others are more subtle or would become evident over a longer time period, but are measurable in principle: increase in the severity and/or frequency of outbreaks of certain forest or agricultural pests or changes in the frequency of drought conditions. However, since these indicators are already known from current studies, one could certainly design monitoring programs or analyses of existing monitoring data to determine whether they are intensifying or becoming less prevalent. Current research on the relationships between climate variability and change and ecological status and processes could also be used to develop new indicators of the effects of climate change. Any new indicators that are developed will need to be examined for their sensitivity to change in climate drivers, and for the expense of the systems to measure and report them, to determine whether they are good candidates for long-term programs.

Experiments to isolate the impacts of climate change from other impacts: Experiments that directly manipulate climate variables and observe impacts are a critical component in understanding climate change effects and in separating these effects from those caused by other factors. Direct manipulations of precipitation, CO_2, temperature, and nitrogen deposition have yielded much useful information and many surprises (such as the increased growth and toxicity of poison ivy when exposed to higher CO_2). Because many factors change in concert under ambient conditions, manipulations are especially useful at isolating the effect of specific factors. In fact, manipulative experiments that reveal information about underlying ecological processes are crucial to ensuring that a true forecasting capacity is developed.

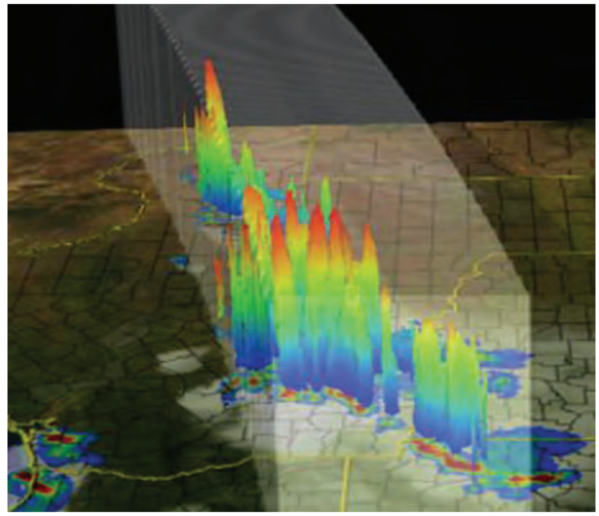

Figure 19. A snapshot of the worldwide inventory of thunderstorms from NASA's Tropical Rainfall Measuring Mission shows storms over Texas on April 30, 2004. The image shows raindrops or larger ice particles that have been carried aloft by strong rising air currents in the storms. Blue, green, and red correspond to low, moderate, and high heights, respectively. (Image courtesy NASA Goddard Space Flight Center.)

Without changing the configuration of existing in situ monitoring systems, or initiating new systems, it will be difficult to be sure that an adequate early warning system has been constructed, and the ability to determine overall consequences of climate change may be limited.

Evaluating damages and benefits from climate change: Over the long term, scientists and decision makers need to understand the extent to which climate change is damaging or enhancing the goods and services that ecosystems provide and how additional climate change would affect the future delivery of such goods and services. This information cannot currently be provided for any ecosystem for several reasons. In some cases sufficient understanding is lacking that would allow researchers to identify the observations that are required. In others, observations known to be useful are lacking. In yet others, observations are available but are not integrated in modeling and analysis frameworks that could enable forecasting of potential changes. But probably the most important difficulty is the lack of a

Ultimately, a national capacity for documenting and evaluating the extent and magnitude of ecosystem changes due to changes in climate will require new system designs that draw on experimentation, modeling and monitoring resources.

national system for ecosystem valuation that takes into account both goods that ecosystems produce that are priced and traded in markets, and those services that are not priced, but are nevertheless valuable to society. Even services that can in principle result in economic gains, such as protection of shorelines from storm surges and flooding by wetlands or mangroves, have not been estimated on large regional or national bases.

Again, in principle it is possible to evaluate both damages and benefits from climate change for any region and/or ecosystem, but such studies will need to be very carefully designed and implemented in order to yield defensible quantification. Until then, it will be necessary to continue to rely on a combination of existing observations made for other purposes and on model output to construct such estimates.

Integration of Ecosystem Observations, Modeling, Experiments and Analysis

The rapid changes in ecosystems that have already been documented pose special challenges to monitoring systems. If their locations cannot be adequately forecast, it is possible for rapid changes to be missed in monitoring data until they become so large that they are obvious. This is especially problematic if the intent of the monitoring program is to provide early warning capabilities. There is currently no analysis in the literature that addresses this problem. A second particular challenge for monitoring ecosystem change due to climate change is the inescapable fact that ecosystems respond to many different factors, of which climate variability and change is only one. Monitoring systems that are established in ways that presuppose one particular driver of change could lead to problematic estimates of change due to other agents.

Ultimately, a national capacity for documenting and evaluating the extent and magnitude of ecosystem changes due to changes in climate will require new system designs that draw on experimentation, modeling and monitoring resources. Expectations derived from modeling time-series can be periodically challenged with observational and experimental data, and the results then fed back to ecosystem models in order to improve their forecasting quantitatively. Such procedures would be analytically similar to data assimilation techniques in wide use in weather and climate modeling, but obviously on very different time scales. It will be necessary for such a system to have systematic sampling of ecosystems with respect to climate variability, and have models that are then capable of ingesting both process observations and observations of ecosystem state and extent.

Key Questions and Answers

What factors influencing agriculture, land resources, water resources, and biodiversity in the United States are sensitive to climate and climate change? Climate change affects average temperatures and temperature extremes; timing and geographical patterns of precipitation; snowmelt, runoff, evaporation, and soil moisture; the frequency of disturbances, such as drought, insect and disease outbreaks, severe storms, and forest fires; atmospheric composition and air quality; and patterns of human settlement and land use change. Thus, climate change leads to myriad direct and indirect effects on U.S. ecosystems. Warming temperatures have led to effects as diverse as altered timing of bird migrations, increased evaporation, and longer growing seasons for wild and domestic plant species. Increased temperatures often lead to a complex mix of effects. Warmer summer temperatures in the western U.S. have led to longer forest growing seasons but have also increased summer drought stress, vulnerability to insect pests, and fire hazard. Changes to precipitation and the size of storms affect plant-available moisture, snowpack and snowmelt, streamflow, flood hazard, and water quality.

How could changes in climate exacerbate or ameliorate stresses on agriculture, land resources, water resources, and biodiversity? What are the indicators of these stresses? Ecosystems and their services (land and water resources, agriculture, biodiversity) experience a wide range of stresses, including pests and pathogens, invasive species, air pollution, extreme events, wildfires and floods. Climate change can cause or exacerbate direct stress through high temperatures, reduced water availability, and altered frequency of extreme events and severe storms. It can ameliorate stress through warmer springs and longer growing seasons, which, assuming adequate moisture, can increase agricultural and forest productivity. Climate change can also modify the frequency and severity of stresses. For example, increased minimum temperatures and warmer springs extend the range and lifetime of many pests that stress trees and crops. Higher temperatures and/or decreased precipitation increase drought stress on wild and crop plants, animals and humans. Reduced water availability can lead to increased withdrawals from rivers, reservoirs, and groundwater, with consequent effects on water quality, stream ecosystems, and human health.

What current and potential observation systems could be used to monitor these indicators? A wide range of observing systems within the United States provides information on environmental stress and ecological responses. Key systems include National Aeronautics and Space Administration (NASA) research satellites, operational satellites and ground-based observing networks from the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce, Department of Agriculture (USDA) forest and agricultural survey and inventory systems, Department of Interior/U.S. Geological Survey (USGS) stream gauge networks, Environmental Protection Agency (EPA) and state-supported water quality observing systems, the Department of Energy (DOE) Ameriflux network, and the Long-Term Ecological Research (LTER) network and the proposed National Ecological Observing Network (NEON) sponsored by the National Science Foundation (NSF). However, many key biological and physical indicators are not currently monitored, are monitored haphazardly or with incomplete spatial coverage, or are monitored only in some regions. In addition, the information from these disparate networks is not well integrated. Almost all of the networks were originally instituted for specific purposes unrelated to climate change and cannot necessarily be adapted to address these new questions.

Climate change presents new challenges for operational management. Understanding climate impacts

Warmer summer temperatures in the western United States have led to longer forest growing seasons but have also increased summer drought stress, vulnerability to insect pests, and fire hazards.

For the moment, there is no viable alternative to using the existing systems for identifying climate change and its impacts on U.S. agriculture, land resources, water resources, and biodiversity, even though these systems were not originally designed for this purpose.

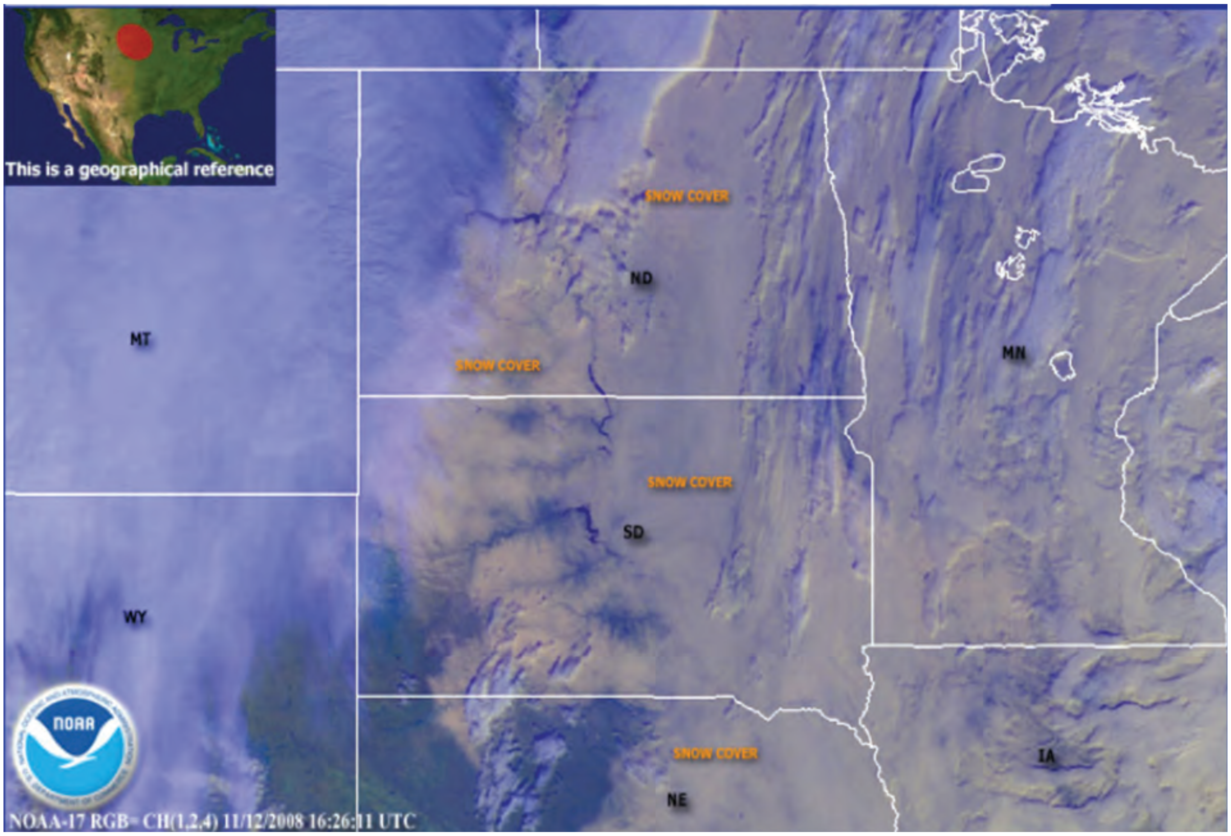

Figure 20. A wintry blast of punishing wind and snow pummeled portions of the Northern Plains on November 12, 2008. Snow cover can be seen in this NOAA-17 satellite image across sections of North Dakota, South Dakota, and Nebraska. (Image courtesy NOAA.)

requires monitoring many aspects of climate and a wide range of biological and physical responses. Putting climate change impacts in the context of multiple stresses and forecasting future services requires an integrated analysis. Beyond the problems of integrating the data sets, the nation has limited operational capability for integrated ecological monitoring, analyses, and forecasting. A few centers exist, aimed at specific questions and/or regions, but no coordinating agency or center has the mission to conduct integrated environmental analysis and assessment by pulling this information together.

Operational weather and climate forecasting provides an analogy. Weather-relevant observations are collected in many ways, ranging from surface observations through radiosondes to operational and research satellites. These data are used at a handful of university, federal, and private centers as the basis for analysis, understanding, and forecasting of weather through highly integrative analyses blending data and models. This operational activity requires substantial infrastructure and depends on federal, university, and private sector research for continual improvement. By contrast, no such integrative analysis of comprehensive ecological information is carried out, although the scientific understanding and societal needs have probably reached the level where an integrative and operational approach is both feasible and desirable.

Can observation systems detect changes in agriculture, land resources, water resources, and biodiversity that are caused by climate change, as opposed to being driven by other causes? In general, the current suite of observing systems is reasonably able overall to monitor ecosystem change and health in the United States, but neither the observing systems nor the current state of scientific understanding is adequate to rigorously quantify climate contributions to ecological change and separate these from other influences. Monitoring systems for measuring long-term response of agriculture to climate and other stresses are numerous, but integration across these systems is limited. There is no coordinated national network for monitoring changes in land resources associated with climate change, most disturbances, such as storms, insects, and diseases, and changes in land cover/land use. No aspect of the current hydrologic observing system was designed specifically to detect climate change or its effects on water resources. The monitoring systems that have been used to evaluate the relationship between changes in the physical climate system and biological diversity were likewise not designed with climate variability or change in mind.

So for the moment, there is no viable alternative to using the existing systems for identifying climate change and its impacts on U.S. agriculture, land resources, water resources, and biodiversity, even though these systems were not originally designed for this purpose. There has obviously been some considerable success so far in doing so, but there is limited confidence that the existing systems provide a true early warning system capable of identifying potential impacts in advance. The authors of this report also have very limited confidence in the ability of current observation and monitoring systems to provide the information needed to evaluate the effectiveness of actions that are taken to mitigate or adapt to climate change impacts. Furthermore, we emphasize that improvements in observations and monitoring of ecosystems, while desirable, are not sufficient by themselves for increasing our understanding of climate change impacts. Experiments that directly manipulate climate and observe impacts are critical for developing more detailed information on the interactions of climate and ecosystems, attributing impacts to climate, differentiating climate impacts from other stresses, and designing and evaluating response strategies. Much of our understanding of the direct effects of temperature, elevated CO_2, ozone, precipitation, and nitrogen deposition has come from manipulative experiments. Institutional support for such experiments is a concern.

Experiments that directly manipulate climate and observe impacts are critical for developing more detailed information on the interactions of climate and ecosystems, attributing impacts to climate, differentiating climate impacts from other stresses, and designing and evaluating response strategies.

Overarching Conclusions

Going forward, understanding current and near-future – the next 25 to 50 years – impacts of climate and related environmental changes on agriculture, water resources, land resources and biodiversity will be essential.

Effects of climate change on U.S. ecosystems are proving to be both rapid and large. In addition to altered temperature and precipitation patterns, and rising levels of CO_2, environmental disturbances such as insect outbreaks, wildfire, and pollution, among other factors, are contributing to ecosystem stress. Some of the likely climate change-related effects that will impact U.S. ecosystems are described below.

Climate changes – temperature increases, increasing CO_2 levels, and altered patterns of precipitation – are* very likely *already affecting U.S. water resources, agriculture, land resources, and biodiversity. Even after accounting for other factors in each of the four resource areas, studies show that altered climate patterns are the direct result of climate system variability and change. For instance, the number and frequency of forest fires and insect outbreaks are increasing in the interior West, the Southwest, and Alaska. Precipitation, streamflow, and stream temperatures are increasing in most of the continental United States. The western United States is experiencing reduced snowpack and earlier peaks in spring runoff. The growth of many crops and weeds is being stimulated. And migration of plant and animal species is changing the composition and structure of arid, polar, aquatic, coastal, and other ecosystems.

Climate change will* very likely *continue to have significant effects on these resources over the next few decades and beyond. Because the lifespan of most greenhouse gases ranges from a decade to a century, warming caused by greenhouse gases already in the atmosphere will continue even with a reduction in new emissions. This means that, in turn, the magnitude and frequency of ecosystem changes in the United States will very likely continue

Figure 21. Wildfire management in the United States costs up to $1 billion per year. Despite the use of radio communications, rapid helicopter transport, and new types of chemical firefighting apparatus, about 2 million acres (approximately 1%) of U.S. forests burn annually from wildfires.

Figure 22. In arid regions where ecosystems have not coevolved with a fire cycle, the probability of loss of iconic, charismatic megaflora such as saguaro cacti and Joshua trees is very likely.

to increase – and accelerate – during the next 50 years. When it comes to agriculture, this will mean more frequent occasions when temperatures are above the optimum for crops' reproductive development; increasing instances of extreme temperature events will also affect production of meat and dairy products. As for water resources, management of Western reservoir systems is very likely to become more challenging as runoff patterns continue to change. Arid areas are very likely to experience increases in erosion and fire risk; in arid ecosystems that have not coevolved with a fire cycle, the probability of loss of iconic, charismatic megaflora such as Saguaro cacti and Joshua trees will greatly increase.

It is very likely that many other stresses and disturbances are also affecting these resources. For many ecosystem changes, there are multiple environmental drivers – land use change, nitrogen cycle changes, point and nonpoint source pollution, wildfires, invasive species – that are also changing. Atmospheric deposition of nitrogen compounds continues to be an important issue, along with persistent ozone pollution in many parts of the country. It is very likely that these additional atmospheric effects cause biological and ecological changes that interact with changes in the physical climate system. In addition, land cover and land use patterns are changing, e.g., the increasing fragmentation of U.S. forests as exurban development spreads to previously undeveloped areas, further raising fire risk and compounding the effects of summer drought, pests, and warmer winters. There are several dramatic examples of extensive spread of invasive species throughout rangeland and semiarid ecosystems in western states, and indeed throughout the United States. It is likely that the spread of these invasive species, which often change ecosystem processes, will exacerbate the risks from climate change alone; for example, in some cases invasive species increase fire risk and decrease forage quality.

All existing monitoring systems, however, have been put in place for other reasons, and none have been optimized specifically for detecting the effects and consequences of climate change.

Climate change impacts on ecosystems will very likely affect the services that ecosystems provide, such as cleaning water and removing carbon from the atmosphere. However, sufficient understanding to estimate the timing, magnitude, and consequences of many of these effects does not exist. Items commonly priced and traded in markets, like food and fiber, are among the ecosystem services and products that will very likely be affected by climate change. Other services, for example carbon sequestration capacity, are only beginning to be understood and traded in markets. Still others, such as regulation of water quality and quantity and maintenance of soil fertility, are not yet priced and traded but are valuable nonetheless. Researchers and decision makers agree that ecosystems services and products are important to society and while studies assessing how climate change will affect individual species and ecosystems abound, no integrated analysis of how climate change will affect ecosystem services exists. A comprehensive understanding of impacts on these services is required, and will only be possible through quantification of anticipated alterations in ecosystem function and productivity.

Understanding climate impacts requires monitoring many aspects of climate and a wide range of biological and physical responses.

Existing monitoring systems, while useful for many purposes, are not optimized for detecting the impacts of climate change on ecosystems. Many operational and research monitoring systems exist in the United States and are useful for studying the consequences of climate change on ecosystems and natural resources. Systems range from resource- and species-specific monitoring systems that land-management agencies depend on, to research networks, such as the LTER sites, which the scientific community uses to better understand ecosystem processes. All existing monitoring systems, however, have been put in place for other reasons, and none have been optimized specifically for detecting the effects and consequences of climate change. As a result, it is likely that only the largest and most visible consequences of climate change are being detected. In some cases, marginal changes and improvements to existing observing efforts, such as USDA's snow and soil moisture measurement programs, can provide valuable new data detection of climate impacts. But more refined analysis and/or monitoring systems designed specifically for detecting climate change effects would provide more detailed and complete information and probably capture a range of more subtle impacts. Such systems, in turn, could lead to early-warning systems and more accurate forecasts of potential future changes. It must be emphasized, however, that improved observations, while needed, are not sufficient for improving understanding of ecological impacts of climate change. Ongoing, integrated and systematic analysis of existing and new observations would enable forecasting of ecological change, garner greater value from observational activities, and contribute to more effective evaluation of measurement needs.

Figure 23. Instruments for measuring exchange of carbon dioxide and water between a forest and the atmosphere at the Niwot Ridge Long Term Ecological Research Site. (Image courtesy Michael G. Ryan.)

Going forward, understanding current and near-future – the next 25 to 50 years – impacts of climate and related environmental changes on agriculture, water resources, land resources and biodiversity will be essential. Enhanced awareness of how climate change is affecting ecosystems on national and regional scales will help scientists, policy makers and local and national leaders more effectively develop mitigation and adaptation strategies for dealing with these issues.

The U.S. Global Change Research Program (USGCRP) coordinates the climate change research activities of U.S. government agencies. Among its responsibilities is publication of a series of Synthesis and Assessment Products (SAPs) that integrates federal research on climate and global change, as sponsored by 13 federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council and the Office of Management and Budget.

SAP 4.3, *The Effects of Climate Change on Agriculture, Biodiversity, Land, and Water Resources in the United States*, on which this paper is based, is one of 21 SAPs produced by the USGCRP aimed at providing current assessments of climate change science to inform public debate, policy, and operational decisions. These reports are also intended to help the USGCRP develop future program research priorities.

The USGCRP's guiding vision is to provide the nation and the global community with the science-based knowledge needed to manage the risks and capture the opportunities associated with climate and related environmental changes. The SAPs are important steps toward achieving that vision and help to translate the USGCRP's extensive observational and research database into informational tools that directly address key questions being asked of the research community.

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