CHAPTER 6

Synthesis

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6.1 INTRODUCTION

The preceding chapters have focused on the observed and potential impacts of climate variability and change on U.S. agriculture, land resources, water resources, and biodiversity. This section synthesizes information from those sectoral chapters to address a series of questions that were posed by the CCSP agencies in the prospectus for this report and formulate a set of overarching conclusions.

6.2 KEY QUESTIONS AND ANSWERS

CCSP Question: 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, increased vulnerability to insect pests and increased fire hazard. Changes to precipitation and the size of storm events affect plant-available moisture, snowpack and snowmelt, streamflow, flood hazard, and water quality.

Further Details: The direct effects of changes to air temperature and precipitation are relatively well understood, though some uncertainties remain. This report emphasizes that a second class of climate changes are also very important. Changes to growing season length are now documented across most of the country and affect crops, snowmelt and runoff, productivity, and vulnerability to insect pests. Earlier warming has profound effects, ranging from changes to horticultural systems to expansion of the mountain pine beetleís range. Changes to humidity, cloudiness, and radiation may reflect both the effect of anthropogenic aerosols and the global hydrological systemís response to warming at the surface, humidity, and, hence, evaporation. Since plants and, in some cases, disease organisms are very sensitive to the near-surface humidity and radiation environment, this is emerging as an important ìhiddenî global change. Finally, changes to temperature

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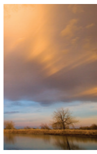
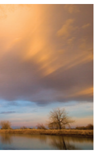


and water are hard to separate. Increasing temperatures can increase evapotranspiration and reduce the growing season by depleting soil moisture sooner, reduce streamflow and degrade water quality, and even change boundary layer humidity.

Disturbance (such as drought, storms, insect outbreaks, grazing, and fire) is part of the ecological history of most ecosystems and influences ecological communities and landscapes. Climate affects the timing, magnitude, and frequency of many of these disturbances, and a changing climate will bring changes in disturbance regimes to forests and arid lands. Ecosystems can take from decades to centuries to re-establish after a disturbance. Both human-induced and natural disturbances shape ecosystems by influencing species composition, structure, and function (productivity, water yield, erosion, carbon storage, and susceptibility to future disturbance). Disturbances and changes to the frequency or type of disturbance present challenges to resource managers. Many disturbances command quick action, public attention, and resources.

Climate change may also ameliorate stress. Carbon dioxide "fertilization," increased growing-season length, and increased rainfall may increase productivity of some crops and forests, increase carbon storage in forests, and reduce water stress in arid land and grazing land ecosystems.



Climate and air quality –chemical climate–also interact. Nitrogen deposition has major chemical effects in ecosystems. It can act as a fertilizer increasing productivity, but can also contribute to eutrophication. High levels of deposition have been associated with loss of species diversity and increased vulnerability to invasion, and there is some evidence that climate change exacerbates these effects. On the other side of the ledger, increases in atmospheric CO_2 and nitrogen availability can increase crop yields if soil water is available.

Climate change can also interact with socioeconomic factors. For example, how crop responses to changing climate are managed can depend on the relative demand and price of different commodities. Climate change mitigation practices, such as the promotion of biofuel crops, can also have a major impact on the agricultural system by increasing the demand and prices for some crops.

CCSP Question: 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 effects of pests and pathogens, invasive species, air pollution, extreme events and natural disturbances such as wildfire and flood. Climate change can cause or exacerbate direct stress through high temperatures, reduced water availability, and altered frequency of extreme events and severe storms. Climate change can also modify the frequency and severity of other stresses. For example, increased minimum temperatures and warmer springs extend the range and lifetime of many pests that stress trees and cops. Higher temperatures and/or decreased precipitation increase drought stress on wild and crop plants, fruit and nut trees, 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.

Further Details: Changes to precipitation frequency and intensity can have major effects. More intense storms lead to increased soil erosion, flooding, and decreased water quality (by transporting more pollutants into water bodies through runoff or leaching through soil layers), with major consequences for life and property. Changing timing, intensity and amount of precipitation can reduce water availability or the timing of water availability, potentially increasing competition between biological and consumptive water use at critical times. Flushing of pollutants into water bodies or concentration of contaminants during low-flow intervals can increase the negative consequences of effects of other stresses, such as those resulting from development, land use intensification, and fertilization.

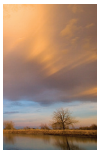
Climate change may also ameliorate stress. Carbon dioxide ìfertilization,î increased growing-season length, and increased rainfall may increase productivity of some crops and forests, increase carbon storage in forests, and reduce water stress in arid land and grazing land ecosystems. Increased minimum temperatures during winter can reduce winter mortality in crops and wild plants and reduce low-temperature stresses on livestock. Increased rainfall can increase groundwater recharge, increase water levels in lakes and reservoirs, and flow levels in rivers. Increased river levels tend to reduce water temperatures and, other things being equal, can help limit the warming of water that might otherwise occur.

Indicators of climate change-related stress are incredibly diverse. Even a short list includes symptoms of temperature and water stress, such as plant and animal mortality, reduced productivity, reduced soil moisture and streamflow, increased eutrophication and reduced water quality, and human heat stress. Indicators of stress can also include changes in species ranges, occurrence and abundance of temperature- or moisture-sensitive invasive species and pest/pathogen organisms, and altered mortality and morbidity from climate-sensitive pests and pathogens. Many stresses are tied to changes in seasonality. Early warning indicators include timing of snowmelt and runoff, as early snowmelt has been related to increased summer-time water stress, leading to reduced plant growth, and increased wildfire and insect damage in the western U.S. Phenology can provide warning of stresses in many ways. Changes to crop phenology may presage later problems in yield or vulnerability to damage, changes to animal phenology (for example, timing of breeding) may come in advance of reduced breeding success and long-term population declines. Changes in the abundance of certain species, which may be invasive, rare, or merely indicative of changes, can provide warning of stress. For example, some C4 plants may be indicative of temperature or water stress, while other species reflect changes to nitrogen availability. Changes to the timing of animal migration may indicate certain types of stress, although some migration behavior also responds to opportunity (e.g., food supply or habitat availability).

CCSP Question: 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, 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 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 are challenged by adapting to new questions.

Climate change presents new challenges for operational management. Understanding climate impacts requires both monitoring many aspects of climate and a wide range of biological and physical responses. Understanding climate change impacts in the context of multiple stresses and forecasting future services requires an integrated analysis approach. 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 as



the basis for analysis, understanding, and forecasting of weather through highly integrative analyses blending data and models in a handful of university, federal and private centers. This activity requires substantial infrastructure to carry out operationally and depends on multi-agency 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.

Further Details: Operational and research satellite remote sensing provides a critical capability. Satellite observations have been used to detect a huge range of stresses, including water stress (directly and via changes to productivity), invasive species, effects of air pollution, changing land use, wildfire, spread of insect pests, and changes to seasonality. The latter is crucial, as much of what we know about changing growing season length comes from satellite observations. Changing growing seasons and phenology are crucial indicators of climate and climate stress on ecosystems. Aircraft remote sensing complements satellite remote sensing, and provides higher resolution and, in some cases, additional sensor types that are useful in monitoring ecosystems. Remote sensing also provides essential spatial context for site-based measurements, that, when used in the appropriate analysis framework, allows the results of local studies to be applied over regions large enough to be useful in management.

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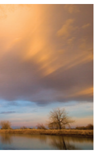


Ground-based measurements, such as USDA forest and agricultural surveys ,provide regular information on productivity of forest, rangeland, and crop ecosystems, stratified by region and crop type. Somewhat parallel information is reported on diseases, pathogens, and other disturbances, such as wind and wildfire damage. Current systems for monitoring productivity are generally more comprehensive and detailed than surveys of disturbance and damage. Agricultural systems are monitored much more frequently than are forest ecosystems, due to differences in both the ecological and economic aspects of the two systems.

Climate stress itself is monitored in a number of ways. NOAA operates several types of observing networks for weather and climate, providing detailed information on temperature and precipitation, somewhat less highly resolved information on humidity and incoming solar resolution, and additional key data products, such as drought indices and forecasts, and flood forecasts and analyses. DOEís ARM network provides key process information on some atmospheric processes affecting surface radiation balance, but at a limited number of sites. The USDA SNOTEL network provides partial coverage of snowfall and snowmelt in high elevation areas, though many of the highest and snowiest mountain ranges have sparse coverage. Several even more detailed meteorological networks have been developed, such as the Oklahoma Mesonet, which provide dense spatial coverage, and some additional variables.

Broad purpose climate and weather networks are complemented by more specialized networks. For example, the Ameriflux network focuses on measuring carbon uptake by ecosystems using micrometeorological techniques, and also provides very detailed measurements of the local microclimate. The National Atmospheric Deposition Network monitors deposition of nitrogen and other compounds in rainwater across the continent, while several sparser networks monitor dry deposition. Ozone is extensively monitored by the Environmental Protection Agency, though rural sites are sparse compared to urban because of the health impacts of ozone. The impact of ozone on vegetation, though believed to be significant, is less well observed. Water resources are monitored as well. Streamflow is best observed through the USGS networks of stream gauges. The number of watersheds, of widely varying scale, and the intensity of water use in the United States make monitoring in-stream water extremely complicated. Establishing basic trends thus requires very careful analysis. Lake and reservoir levels are fairly well measured. Groundwater, though critical for agricultural and urban water use in many areas, remains poorly observed and understood, and very few observations of soil moisture exist.

In addition to observing networks developed for operational decision making, several important research networks have been established. The Ameriflux network was described above. The LTER network spans the United States, and includes polar and oceanic sites as well. LTER provides understanding of critical processes, including processes that play out over many years, at sites in a huge range of environments, including urban sites. While the LTER network does not emphasize standardized measurements (but rather addresses a core set of issues, using site-adapted methods), the proposed new NEON program will implement a set of standardized ecological sensors and protocols across the county.

Because climate change is just one of the multiple stresses affecting ecosystems, the fact that the existing observing systems are at best loosely coordinated is a major limitation. Interoperability of data remains an issue, despite efforts in standardization and metadata, and co-location of observations of drivers and responses to change occurs only haphazardly. This contributes to the difficulties discussed below of quantifying the relative contributions of climate change and other stressors.

CCSP Question: 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 causal activities?

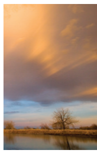
In general, the current suite of U.S. observing systems provides a reasonable overall ability to monitor ecosystem change and health in the United States, but neither the observing systems or the current state of scientific understanding are adequate to rigorously quantify climate contributions to ecological change and separate these from other influences. It is very difficult, and in most cases, not practically feasible, to quantify the relative influences of individual stresses, including climate change, through observations alone.

In the case of **agriculture**, monitoring systems for measuring long-term response of agricultural lands are numerous, but integration across these systems is limited. 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.

For **land resources**, current observing systems are very likely inadequate to separate the effects of changes in climate from other effects. There is no coordinated national network for monitoring changes associated with disturbance (except for forest fires) and alteration of land cover and land use. Attempts to date lack spatial or temporal resolution, or the necessary supporting ground truth measurements, to themselves adequately distinguish climate change influences. Separating the effects of climate change from other impacts would require a broad network of indicators, coupled with a network of controlled experimental manipulations.

Essentially no aspect of the current hydrologic observing system was designed specifically for purposes of detecting climate change or its effects on **water resources**. Many of the existing systems are technologically obsolete, are designed to achieve specific, often non-compatible management accounting goals, and/or their operational and maintenance structures allow for significant data collection gaps. As a result, the data is fragmented, poorly integrated, and very likely unable to meet the predictive challenges of a rapidly changing climate.

In the case of **biodiversity**, there is a collection of operational monitoring systems that are sponsored by federal agencies, conservation groups, state agencies, or groups of private citizens that are focused on particular taxa (e.g. the Breeding Bird Survey), or on particular ecosystems (e.g. Coral Reef Watch), or even particular phenomena (e.g. the National Phenology Network). These tend to have been established for very particular purposes, e.g. for tracking the abundance of migratory songbirds, or the status and abundance of game populations within individual states, or the status and abundance of threatened and endangered species. There is a second category of monitoring programs whose initial justification has been to investigate particular research problems, whether or not those are primarily oriented around biodiversity. The third category of monitoring systems is those that offer the extensive spatial and variable temporal resolution of remotely sensed information from Earth-orbiting satellites. None of these existing monitoring systems are likely to be completely adequate for monitoring changes in biodiversity associated with climate variability and change.



Although there are lists of specifications for monitoring systems that would be relevant and important for this purpose (e.g. IGOL 2007), there is at present no analysis in the literature that has addressed this question directly.

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. Institutional support for such experiments is a concern.

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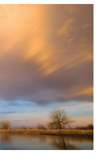

Further Details: One of the great challenges of understanding climate change impacts is that these changes are superimposed on an already rapidly changing world. Ecosystems across the United States are subject to a wide variety of stresses, most of which inevitably act on those systems simultaneously. It is rare in these cases for particular responses of ecosystems to be diagnostic of any individual stress – ecosystem-level phenomena, such as reductions in net primary productivity, for example, occur in response to many different stresses. Changes in migration patterns, timing, and abundances of bird and/or butterfly species interact with changes in habitat and food supplies.

In some cases, effects due to climate variability and change can be quite different from those expected from other causes. For example, the upward or northward movements of treeline in montane and Arctic environments are almost certainly driven by climate, as no other driver of change is implicated. Other changes, such as those in wildfire behavior, are influenced by climate, patterns of historical land management, and current management and suppression efforts. Disentangling these influences is difficult. Some changes are so synergistic that our current scientific understanding cannot separate them solely by observations. For example, photosynthesis is strongly and interactively controlled by levels of nitrogen, water availability, temperature, and humidity. In areas where these are all changing, estimating quantitatively the effects of, say, temperature alone is all but impossible. In regions of changing climate, separating effects of climate trends from other influencing factors with regard to biodiversity and species invasions is very challenging, and requires detailed biological knowledge, as well as climate, land use, and species data.

Separating climate effects from other environmental stresses is difficult but in some cases feasible. For example, when detailed water budgets exist, the effects of land use, climate change and consumptive use on water levels can be calculated. While climate effects can be difficult to quantify on small scales, sometimes, regional effects can be separated. For example, regional trends in productivity, estimated using satellite methods, can often be assigned to regional trends in climate versus land use, although on any individual small-scale plot, climate may be primary or secondary. In other cases, scientific understanding is sufficiently robust that models in conjunction with observations can be used to estimate climate effects. This approach has been used to identify climate effects on water resources and crop productivity, and could be extended to forests and other ecological systems as well.

While it is not yet possible to precisely determine and separate the effects of individual stresses, it is feasible to quantify the actual changes in ecosystems and their individual species, in many cases through observations. There are many monitoring systems and reporting efforts set up specifically to do this, and while each may individually have gaps and weaknesses, there are many opportunities for improvement. This report identifies a number of opportunities, and many other documents have addressed the nationís need for enhanced ecological observations as well. Many networks exist, but for the integrative challenges of understanding and quantifying climate change impacts, they provide limited capability. Most existing networks are fairly specialized, and at any given measurement site, only one or a few variables may be measured. The ongoing trend of more co-location of sensors, and development of new, much more integrative networks (such as NEON and the NOAA Climate Reference Network) is positive. By measuring drivers of change and ecological responses, the processes of change can be understood and quantified, and the ability to separate and ultimately forecast climate change enhanced.

6.3 DESIGNING SYSTEMS TO MONITOR CLIMATE CHANGE IMPACTS

This assessment makes clear that there are many changes and impacts in many US ecosystems that are being driven by changes in the physical climate system, including both long-term changes and climate variability. Documentation of such changes has largely been a function of assessing results from individual studies that have been creative in their use of information from existing monitoring systems, all of which were originally designed for other purposes. But because the observed changes are proving to be both large and rapid, and because management agencies and organizations are ill-prepared to cope with such changes (GAO 2007), there is a growing need to develop strategies for adapting to ecological changes, and for managing ecosystems to ameliorate climate impacts. In addition, because changes in climate and subsequent impacts in ecosystems are very likely to continue to occur, adaptive management strategies for adapting to change are going to be quite important (GAO 2007). Observation and monitoring systems, therefore, must be able to support analyses that would contribute to this management challenge, i.e. adapting to change, documenting the rapidity of ecological changes so that management strategies can be adjusted, and most importantly, forecasting when potential thresholds of change might occur, and 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 being developed.

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

Monitoring changes in overall status, regardless of cause: This need has been most cogently articulated by the work of the NRC (NRC 2000 [Orians report]), and the Heinz Center on indicators of status of US ecosystems (Heinz Center 2004). The argument is straightforward; there is both scientific and societal value to the US 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 that either derived from scientific concerns (NRC) or from a broader, stake-holder driven process (Heinz Center). In either case, no attempt is made to attribute changes in the indicators to particular stresses strictly through use of the monitoring data. Both recognize, however, that such analyses are necessary for both scientific and policy purposes. The system of indicators 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.

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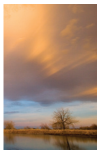

Early warning of changes due to climate: As of now, there are no routine monitoring systems established specifically for early warning of changes due to climate change. The impacts documented in this report and elsewhere are the results of analyses of existing monitoring systems and research projects, 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 we have constructed an adequate early warning system and the ability to determine overall consequences of climate change may be limited.

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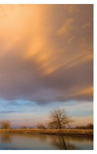
Fortunately, enough is now known about the existing responses of ecosystems and species to changes in climate and climate variability to define monitoring systems that are optimized for early warning of subsequent changes. For example, one could set up systematic monitoring of ocean pH and alkalinity along with coral observations to track whether or not there were early indications of difficulties in calcification due to increasing pCO_2 in surface waters. One might also systematically 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 systems known to be at risk of early change (e.g. high latitude ecosystems, high elevation systems, coastal wetlands, migratory bird species), either because similar systems 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.



Monitoring programs that are 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 than the overall ecosystem average. 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: We are early in our understanding of ecological changes due to climate variability and change, and we should expect that understanding to 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 (NRC 2000).

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 impacts and in separating the effects of climate 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.

Evaluating damages and benefits from climate change: Over the long term, we 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 we lack sufficient understanding to identify the observations that are required. In others, we lack observations that we know would be helpful. In yet others, we have observations but are not integrating these in modeling and analysis frameworks that could enable forecasting of potential changes. But probably the most important difficulty is that we do not have a national system for ecosystem valuation that takes into account both goods that ecosystems produce that are priced and are 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 wetlands or mangroves protection of shorelines from storm surge and flooding, 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, we will need to continue to rely on a combination of existing observations made for other purposes and on model output to construct such estimates.

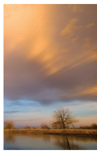
6.4 INTEGRATION OF ECOSYSTEM OBSERVATIONS, MODELING, EXPERIMENTS AND ANALYSIS

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.

6.5 OVERARCHING CONCLUSIONS

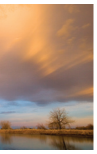
Climate changes – temperature increases, increasing CO_2 levels, and altered patterns of precipitation – are already affecting U.S. water resources, agriculture, land resources, and biodiversity, and will continue to do so *(very likely).* The results of the literature review undertaken for this assessment document case after case of changes in these resources that are the direct result of variability and changes in the climate system, even after accounting for other factors. 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 U.S. The western U.S. is experiencing reduced snowpack and earlier spring runoff peaks. The



growth of many crops and weeds is being stimulated. Migration of plant and animal species is changing the composition and structure of arid, polar, aquatic, coastal and other ecosystems.

Climate change will continue to have significant effects on these resources over the next few decades and beyond *(very likely).* Warming is very likely to continue in the United States during the next 25-50 years, regardless of the efficacy of greenhouse gas emissions reduction efforts, due to greenhouse gas emissions that have already occurred. U.S. ecosystems and natural resources are already being affected by climate system changes and variability. It is very likely that the magnitude and frequency of ecosystem changes will continue to increase during this period, and it is possible that they will accelerate. As temperature rises, crops will increasingly begin to experience higher temperatures beyond the optimum for their reproductive development. 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 erosion and fire risk. In arid region ecosystems that have not co-evolved with a fire cycle, the probability of loss of iconic, charismatic mega flora such as saguaro cacti and Joshua trees will greatly increase.

Many analyses of the impacts of climate change on individual species and ecosystems have been published in the scientific literature, but there is not yet adequate integrated analysis of how climate change could affect ecosystem services.



Many other stresses and disturbances are also affecting these resources *(very likely).* For many of the changes documented in this assessment, there are multiple environmental drivers – land use change, nitrogen cycle change, point and non-point source pollution, wildfires, invasive species, and others – that are also changing. Atmospheric deposition of biologically available nitrogen compounds continues to be an important issue, along with persistent, chronic levels of 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 semi-arid 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.

Climate change impacts on ecosystems will affect the services that ecosystems provide, such as cleaning water and removing carbon from the atmosphere *(very likely)*, but we do not yet possess sufficient understanding to project the timing, magnitude, and consequences of many of these effects. One of the main reasons for needing to understand changes in ecosystems is the need to understand the consequences of those changes for the delivery of services that our society values. Many analyses of the impacts of climate change on individual species and ecosystems have been published in the scientific literature, but there is not yet adequate integrated analysis of how climate change could affect ecosystem services. A comprehensive understanding of the way such services might be affected by climate change will only be possible through quantification of anticipated alteration in ecosystem function and productivity. As described by the Millennium Ecosystem Assessment, some products of ecosystems, such as food and fiber, are priced and traded in markets. Others, such as carbon sequestration capacity, are only beginning to be understood and traded in markets. Still others, such as the regulation of water quality and quantity, and the maintenance of soil fertility, are not priced and traded, but are valuable nonetheless. Yet although these points are recognized and accepted in the scientific literature and increasingly among decision makers, there is no analysis specifically devoted to understanding changes in ecosystem services in the United States from climate change and associated stresses. It is possible to make some generalizations from the existing literature on the physical changes in ecosystems, but interpreting what this means for services provided by ecosystems is very challenging and can only be done for a limited number of cases. This is a significant gap in our knowledge base.

Existing monitoring systems, while useful for many purposes, are not optimized for detecting the impacts of climate change on ecosystems. There are many operational and research monitoring systems that have been deployed in the United States that are useful for studying the consequences of climate change on ecosystems and natural resources. These range from the resource- and species-specific monitoring systems, which land-management agencies depend on, to research networks, such as the Long-Term Ecological Research (LTER) sites, which the scientific community uses to understand ecosystem processes. All of the 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 snow and soil moisture measurement programs, could 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. This in turn would hold promise of developing early warning systems and more accurate forecasts of potential future changes. But it must be emphasized 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 could enable forecasting of ecological change, thus garnering greater value from observational activities, and contribute to more effective evaluation of measurement needs.