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Answers to Guiding Questions

What factors influencing agriculture, land resources, water resources, and biodiversity in the United States are sensitive to climate and climate change?

Climate change over the past several decades has had myriad effects on ecosystems of the United States. For example, warming temperatures have altered the timing of bird migrations, increased evaporation, and altered growing seasons for wild and domestic plant species. Increased temperature can also lead to counteracting 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 the amount of moisture available for plant growth, snowpack and snowmelt, streamflow, flood hazards, and water quality. In any case, the balance of counteracting effects cannot be determined solely on theoretical grounds, but must be understood for each particular resource and region.

Direct changes to air temperature and precipitation are relatively well understood, though significant 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 very likely had profound effects ranging from changes to horticultural systems to changes in the mountain pine beetle's range and population density. Changes to humidity, cloudiness, and radiation may reflect the influence of both anthropogenic aerosols and the way in which the global hydrological system responds to warming, by affecting solar radiation 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 has emerged as an important hidden global change. Finally, changes to temperature 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.

Climate and air quality – i.e. the chemical climate – also interact. Excess nitrogen deposition has major effects in ecosystems, where it can act as a fertilizer, increasing productivity. However, in some aquatic ecosystems, it can overfertilize, resulting in lower biodiversity, lower productivity, more decaying organic matter, and less ability to support new growth. High levels of deposition have been associated with loss of species diversity, and increased vulnerability to invasion. When climate changes and high nitrogen deposition interact, even greater susceptibility to invasion and biodiversity loss may possibly occur. On the other side of the ledger, stimulation of crop yields by rising atmospheric carbon dioxide increases as nitrogen availability increases. Higher nitrogen deposition to croplands may allow larger yield responses, or smaller protein-concentration decreases with increasing carbon dioxide.

Climate change can also interact with socioeconomic factors. For example, managing crops in a changing climate will depend on the relative demand and price of different commodities. Mitigation practices, such as the promotion of biofuel crops, can also have a major impact on the agricultural system.

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 crops. Higher temperatures and/or decreased precipitation increase drought stress on wild and crop plants, animals, and humans. Reduced water availability can lead to conflicts over water for multiple uses, as people withdraw water from rivers, reservoirs, and groundwater, with consequent effects on water quality, stream ecosystems, and human health.

Changes to precipitation frequency and intensity can have major effects. More intense storms lead to increased soil erosion, decreased water quality (by flushing more pollutants into water bodies), and flooding, with major consequences for life and property. Changing the timing, intensity, and amount of precipitation can reduce water availability, or the timing of water availability, potentially increasing competition between biological and consumptive use of water 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 “fertilization,” increased rainfall, and increased growing season length may increase the productivity of crops and 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 ameliorate increased water temperatures.

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 stream flow, 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 – early snowmelt has been related to increased summer 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 change, can provide warning of stress. For example, the increasing abundance of so-called C4 plants may be indicative of temperature or water stress, and other species indicate changes to nitrogen availability. Changes to the timing of migration may indicate certain types of stress, although some migration behavior also responds to opportunity (e.g., food supply or habitat availability).

What current and potential observation systems could be used to monitor these indicators?

Within the United States, a wide range of observing systems provide access to information on environmental stress, although many key biological and physical indicators are not monitored, are monitored haphazardly, or are monitored only in some regions. 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: 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.

Ground-based measurements remain central as well. USDA forest and agricultural survey information 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 the differences in both ecological and economic aspects of the two types of system.

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. The SNOTEL network provides a 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 networks have been developed, such as the Oklahoma Mesonet, which provide dense spatial coverage and some additional variables. The basic meteorological networks are complemented by more specialized networks. For example, the Ameriflux network focuses on measuring carbon uptake by ecosystems using micrometeorological techniques, and also includes very detailed measurements of the local microclimate. The National Atmospheric Deposition Network monitors deposition of nitrogen and other compounds in rainwater across the continent, and 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 calculated to be significant, is less well-observed.

Water resources are monitored through a number of networks 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 makes monitoring instream water surprisingly complicated, and establishing basic trends has required very careful analysis. Lake and reservoir levels are fairly well observed. 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 has already been mentioned. The National Science Foundation's Long Term Ecological Research (LTER) network spans the United States, and includes polar and oceanic sites. 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), a new initiative, the National Ecological Observatory Network (NEON), will implement a set of standardized ecological sensors and protocols across the county.

While there are many observing systems at work, the information from these disparate networks is not well integrated. Many of the networks were originally instituted for specific purposes unrelated to climate change and are challenged by adapting to these new questions. Beyond the problems of integrating the data sets, the nation has limited operational capability for integrated ecological monitoring, analyses and forecasting. Centers exist that aim to answer specific questions and/or provide services in specific regions, but no coordinating agency or center pulls all this information together. This is clearly an unmet need.

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?

One of the great challenges of understanding climate change impacts is that climate changes are superimposed on an already-rapidly changing world. In some cases, climate change effects 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 changes to 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 they defy any effort to separate them strictly by observations. For example, photosynthesis is strongly and interactively controlled by levels of nitrogen, water stress, temperature, and humidity. In areas where these are all changing, estimating quantitatively the effects of, say, temperature alone is all but impossible. Separating effects of climate trends in regions of changing climate on biodiversity and species invasions is very challenging and requires detailed biological knowledge on top of climate, land use and species data to accomplish.

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, our 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 issues as well.

In many cases, either the observations or the understanding are lacking that would allow us to identify climate contributions to ecological change, and separate these from other influences. This report identifies a number of opportunities where this opportunity exists, and many other documents have addressed the nation's need for enhanced ecological observations as well. As a synthesis, many networks exist, but for the integrative challenges of climate change, 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 to more co-location of sensors, and the development of new, much more integrative networks (such as NEON and the Climate Reference Network) is positive and should be enhanced. By measuring drivers of change and ecological responses, the processes of change can be understood and quantified, and our ability to separate and ultimately forecast climate changes enhanced. In this same vein, centers and programs focused on such integrative analyses also need to be created or enhanced.

Overarching Conclusions

A series of observational and modeling results documented in the IPCC AR4 show that U.S. climate has changed and that this change accelerated in the last several decades of the 20th century. It is very likely that the trends exhibited over the past several decades will continue for the next several decades. There are several reasons for this, among them the realization that greenhouse gas concentrations in the atmosphere are themselves very likely to increase during that time period. Even if aggressive, global control measures were instituted very soon, the lifetime of energy sector infrastructure would make rapid reductions in greenhouse gas concentrations very, very difficult to accomplish. In addition, there is substantial thermal inertia already built up in the climate system. Finally, we have already seen increases in the frequency and duration of heat waves, continued decline in summer sea-ice in the Arctic, and there is some evidence of increased frequency of heavy rainfalls. We are very likely to experience a faster rate of climate change in the next 100 years than has been seen over the past 10,000 years.

- Climate change is affecting US water resources, agriculture, land resources, and biodiversity
- Many other stresses – land use change, nitrogen cycle change, point and non-point source pollution, invasive species – are also affecting these resources
- It is difficult to precisely quantify the effects of individual stresses on ecosystems, but not so difficult to observe and assess ecosystem change and health
- There is no specific analysis of consequences of climate change for ecosystem services in the US.
- Existing monitoring systems, while useful for many purposes, are not optimized for detecting the ecological consequences of climate change.

Climate change is very likely affecting U.S. water resources, agriculture, land resources, and biodiversity, and will continue to do so.

This assessment reviews the extensive literature on water resources, agriculture, land resources, and biodiversity, much of which has been published within the past decade, and certainly since the publication of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change. The results are striking. In case after case, there are carefully documented changes in these resources that are the direct result of variability and changes in the climate system, even after accounting for other factors (more on this point below). Given that U.S. ecosystems and natural resources are already beginning to experience changes due to climate system changes and variability, it is very unlikely that such changes will slow down or stop over the next several decades. It is likely that these changes will increase over the next several decades in both frequency and magnitude, and it is possible that they will accelerate.

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For many of the changes documented in this assessment, there are multiple environmental drivers that are also changing. Atmospheric deposition of biologically available nitrogen compounds continues to be an important issue in many parts of the country, for example, along with persistent chronic levels of ozone pollution in many parts of the country. It is very likely that these additional atmospheric effects also cause biological and ecological consequences that interact with the observed changes in the physical climate system. In addition, there are patterns of land-use change, e.g. the increasing fragmentation of U.S. forests as homeowners build new households in areas that had previously been outside of suburban development, thus raising fire risk, that also interact with the effects of summer drought, pests, and warmer winters, which also raise fire risk. There are several dramatic examples of extensive spread of invasive species throughout rangeland and semi-arid ecosystems in the Western states, and indeed throughout the United States. It is likely that the spread of these invasive species, which often change ecosystem processes – e.g., in some cases increasing fire risk and decreasing forage quality – to interact with climate changes in a way that exacerbates the risks from climate change alone.

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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 the migration patterns, timing, and abundances of bird and/or butterfly species interact with changes in habitat and food supplies. It is very difficult, and in most cases not practically feasible, to quantify the relative influences of individual stresses through observations alone. However, it is quite 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, the overall ability to monitor ecosystem change and health in the United States is quite reasonable, and has an opportunity to improve. A combination of field observations from such monitoring systems, experimental research, and modeling studies is a more viable strategy for understanding the relative contributions of climate change and other stresses on ecosystem changes, and overall ecosystem health.

There is no specific analysis of consequences of climate change for ecosystem services in the United States.

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. Using ecosystem services in the same way as the Millennium Ecosystem

Assessment describes, for example, means that 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 to our society 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. We are able to make some generalizations from the existing literature on the physical changes in ecosystems, but only in some cases can we make a useful translation to services. This is a significant gap in our knowledge base.

Existing monitoring systems, while useful for many purposes, are not optimized for detecting the ecological consequences of climate change.

As this assessment demonstrates, 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 that land-management agencies depend on, to research networks, such as the LTERs, that 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 of have been optimized specifically for detecting changes as a consequence of climate change. As a result, it is likely that we are only detecting the largest and most visible consequences of climate change. It is likely that more refined analysis, and/or monitoring systems designed specifically for detecting climate change effects, would be more effective as early warning systems.

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