Executive Summary

Introduction and Context

This report is an assessment of the effects of climate change on U.S. land resources, water resources, agriculture, and biodiversity, based on extensive examination of the relevant scientific literature, and measurements and data collected and published by U.S. government agencies. It is one of a series of 21 Synthesis and Assessment Products being produced under the auspices of the U.S. Climate Change Science Program (CCSP), which coordinates the climate change research activities of U.S. government agencies. The lead sponsor of this particular assessment product is the U.S. Department of Agriculture (USDA). The team of authors includes scientists and researchers from universities, national laboratories, non-government organizations, and government agencies, coordinated by the National Center for Atmospheric Research (NCAR).

Scope of this Report

As agreed by the CCSP agencies, the topics addressed in this product are:

- Agriculture
    - Cropping systems
    - Pasture and grazing lands
    - Animal management

- Land Resources
    - Forests
    - Arid lands

- Water Resources
    - Quantity, Availability, and Accessibility
    - Quality

- Biodiversity
    - Species diversity
    - Rare and sensitive ecosystems

Guiding Questions for this Report

- What factors influencing agriculture, land resources, water resources, and biodiversity in the United States are sensitive to climate and climate change?
- How could changes in climate exacerbate or ameliorate stresses on agriculture, land resources, water resources, and biodiversity?
- What are the indicators of these stresses?
- What current and potential observation systems could be used to monitor these indicators?

- 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?

Time Horizon for this Report

Climate change is a long-term issue, and climate change will affect the world for the foreseeable future. Many studies of climate change have focused on the next 100 years as model projections out to 2100 have become a *de facto* standard, as reported in the assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC), and many other documents. In this report, we focus on the nearer-term future – the next 25 to 50 years. We report some results out to 100 years to frame the report, but we emphasize the coming decades.

Climate Context

There is a robust scientific consensus that human-induced climate change is occurring, as documented in the recently released Fourth Assessment Report of the IPCC (IPCC AR4), which states with "very high confidence," that human activity has caused the global climate to warm. The IPCC report describes an increasing body of observations and modeling results which show that human-induced changes in atmospheric composition are changing the global climate:

- The global-average surface temperature increased by about 0.6°C over the 20^{th} century. Global sea level increased by about 15-20 cm during this period.
- Global precipitation over land increased about two percent over the last century with considerable variability by region (Northern Hemisphere precipitation increased by about five to 10 percent during this time, while West Africa and other areas experienced decreases).

Looking ahead, it is clear that human influences will continue to change Earth's climate and the climate of the United States throughout the 21^{st} century. The IPCC AR4 describes a large body of modeling results that show that changes in atmospheric composition will result in further increases in global average temperature, sea level, and rainfall, and continued decline in snow cover, land ice, and sea ice extent. We are very likely to experience a faster rate of climate change in the 21^{st} century than seen in the last 10,000 years.

- If atmospheric concentration of CO2 increases to about 550 parts per million (ppm), global average surface temperature would likely increase by about 1.1 - 2.9°C by 2100.
- If atmospheric concentration of CO2 increases to about 700 ppm, global average surface temperature would likely increase about 1.7 - 4.4°C by 2100.
- If atmospheric concentration of CO2 increases to about 800 ppm, global average surface temperature would likely increase about 2.0 - 5.4°C by 2100.

- Even if atmospheric concentration of CO_2 were stabilized at today's concentrations of about 380 ppm, global average surface temperatures would likely continue to increase by another 0.3 - 0.9°C by 2100.

The climate changes that we can expect are very likely to continue to have significant effects on the ecosystems of the United States, and the services those ecosystems provide to us, its inhabitants. The balance of this report documents some of the observed historical changes and provides insight into how the continuing changes may affect our nation’s ecosystems.

AGRICULTURE

Agriculture within the United States is varied and produces a large value ($200 billion in 2002) of production across a wide range of plant and animal production systems. Because of this diversity, changes in climate will likely impact agriculture in many regions of the United States. Agriculture within the United States is complex: many crops are grown in different climates and soils, and different livestock types are produced in numerous ways. There are 116 different plant commodity groups listed by the USDA National Agricultural Statistics Service, and four different livestock groupings (dairy, poultry, specialty livestock, and livestock that contain a variety of different animal types, or products derived from animal production, e.g. cheese or eggs). Climate affects crop, vegetable, and fruit production, pasture production, rangeland production, and livestock production systems significantly because of the direct effects of temperature, precipitation, and CO_2 on plant growth, and the direct effect of temperature and water availability to livestock. Variations in production between years in any of the commodity is a direct result of weather within the growing season, and often an indirect effect from weather effects on insects, diseases, or weeds.

Findings

Crops

- In general, the optimal temperature for reproductive growth and development of grain and oilseed crops is lower than that for vegetative growth. As a consequence, life cycle will progress more rapidly, very likely resulting in less time for grain-filling, and thus reduced yield as temperature rises. Furthermore, these crops are characterized by an upper failure-point temperature at which pollination and grain-set processes fail.

- The net effect of 0.8°C increase in temperature, and a 60 ppm increase in atmospheric concentration of CO_2 (from about 380 to 440 ppm) on yield is likely to affect production of maize (-1.5 percent), soybean (+9.1 percent in the Midwest, +5.0 percent in the South), wheat (+2.4 percent), rice (-1.6 percent), sorghum (-5.2 percent), cotton (+5.7 percent), peanut (+3.4 percent), and dry bean (+0.3 percent). Changes in evapotranspiration associated with increased temperature and CO_2 could lead to a further 0.2 to 0.9 percent increase in yield under rainfed production. There will be a similar small reduction in crop water requirement under irrigated production.

- As temperature rises, crops will increasingly begin to experience upper failure point temperatures, especially if climate variability increases, and if rainfall is reduced or becomes more variable. Under this situation, yield responses to temperature and CO_2 would move more toward the negative side. There are cases of negative interactions on pollination associated with the rise in canopy temperature caused by lower stomatal conductance.

- The marketable yield of many horticultural crops is likely to be more sensitive to climate change than grain and oilseed crops because even short-term, minor environmental stresses can negatively affect visual and flavor quality. Perennial fruit and nut crop survival and productivity will be highly sensitive to winter, as well as summer, temperatures.

- The potential habitable zone of many weed species is largely determined by temperature. While other factors such as moisture and seed dispersal will affect the spread of invasive weeds such as kudzu, climate change is likely to lead to a northern migration in at least some cases.

- Many weeds respond more positively to increasing CO_2 than most cash crops, particularly C_3 invasive weeds that reproduce by vegetative means (roots, stolons, etc.). Recent research also suggests that glyphosate, a common herbicide, loses its efficacy on weeds grown at elevated CO_2.

- Disease pressure from leaf and root pathogens may increase in regions where increases in humidity and frequency of heavy rainfall events occur, and decrease in regions that encounter more frequent drought.

Rangelands

- The evidence from manipulative experiments, modeling exercises, and long-term observations of rangeland vegetation over the past two centuries provide indisputable evidence that warming, altered precipitation patterns, and rising atmospheric CO_2 can have profound impacts on the ecology and agricultural utility of rangelands.

- Modeling exercises suggest generally positive net primary productivity responses of Great Plains native grasslands to combined rising CO_2 and temperature, which is supported by experimental results suggesting enhanced productivity in shortgrass steppe under warming and elevated CO_2. An important exception to these findings is California annual grasslands, where production appears only minimally responsive to CO_2 or temperature.

- Plants with the C_3 photosynthetic pathway – including forbs, woody plants and possibly legumes – will be favored by rising CO_2, although interactions of species responses with rising temperature and precipitation patterns may affect these functional group responses. For instance, warmer temperatures and drier conditions will tend to favor C_4 species, which may cancel out the CO_2-advantage of C_3 grasses.

- There is already some evidence that climate change-induced species changes are underway in rangelands. For example, the encroachment of woody shrubs into former grasslands is likely due to a combination of over-grazing, lack of fire, and rising levels of atmospheric CO_2. Spread of the annual grass, *Bromus tectorum* (cheatgrass), through the Intermountain region of western North America appears driven at least in part by the species sensitivity to rising atmospheric CO_2. It seems likely that plant species changes will have as much or more impact on livestock operations as alterations in plant productivity.

- One of our biggest concerns is in the area of how grazing animals affect the responses of ecosystems to climate change, but the paucity of data presently available on livestock-plant interactions under climate change severely compromises our ability to predict the consequences of climate change on livestock grazing.

- Another important knowledge gap concerns the responses of rangelands to multiple global changes. The only experiment described in the peer-reviewed literature suggests highly complex interactions of species responses to combined global changes, which may ultimately impact nutrient cycling and have important implications for plant community change, and carbon storage.

- Such results underscore an emerging acknowledgement that while there is certainty that rangeland ecosystems are responding to global change, our ability to understand and predict responses to future changes are limited.

Animal Production Systems

- Increase in air temperature reduces livestock production during the summer season with partial offsets during the winter season. Current management systems usually do not provide as much shelter to buffer the effects of adverse weather for ruminants as for non-ruminants. The climate changes that matter the most for ruminants are (1) general increase in temperature levels; (2) increases in nighttime temperatures; and (3) increases in the occurrence of extreme events (e.g., hotter daily maximum temperature, and more/longer heat waves).

- Climate changes affect certain parasites and pathogens, which could result in adverse effects on host animals. Other interactions may exist, for example, animals stressed by heat or cold may be less able to cope with other stressors (restraint, social mixing, transport, etc). Improved stressor characterization is needed to provide a basis for refinement of sensors providing input to control systems.

- Innovations in electronic system capabilities will undoubtedly continue to be exploited for the betterment of livestock environments. However, inclusion and weighting of multiple factors (e.g. endocrine function, immune function, behavior patterns, performance measures, health status, vocalizations) is not an easy task when developing integrated stress measures. Establishing threshold limits for impaired functions, which may result in reduced performance or health, are essential. Modeling of physiological systems as our knowledge base expands will help the integration process.

- The capabilities of livestock managers to cope with the various effects are quite likely to keep up with the projected rates of change in global temperature and related climatic factors. However, coping will entail costs, such as application of environmental modification techniques, use of more suitably adapted animals, or even shifting of animal populations.

Land Resources

Climate strongly influences forest productivity, species composition, and the frequency and magnitude of disturbances that impact or reset forests. Below, we list the key points from our literature review, coupled with the observed and projected trends in climate. Four key findings stand out. First, we are already experiencing the effects of increased temperature and decreased precipitation in the Interior West, the Southwest, and Alaska. Forest fires are growing larger and more numerous, insect outbreaks are currently impacting more than three times the forested area as fire, and are moving into historically new territory, and drought and insects have killed pinyon pine over large areas of the Southwest. Second, an increased frequency of disturbance is at least as important to ecosystem function as incremental changes in temperature, precipitation, atmospheric CO_2, nitrogen deposition, and ozone pollution. Disturbances partially or completely reset the forest ecosystems causing short-term productivity and carbon storage loss, allowing better opportunities for invasive alien species to become established, and commanding more public and management attention and resources. Third, interactions between changing climate, changing atmospheric chemistry, disturbance, and forest ecosystems are important, but poorly understood – so predicting the future of forest ecosystems is difficult. Finally, we do not have the observing systems in place to separate the effects of climate from those of other agents of change. We particularly lack a coordinated national network for monitoring forest disturbance.

Findings

- Climate effects on disturbances such as fire, insect outbreaks, and wind and ice storms are very likely important in shaping ecosystem structure and function.

- Temperature increases and drought have very likely influenced the massive insect outbreaks in the past decade.

- If warming continues as anticipated over the next 30 years:

    - The number of large, stand-replacing fires are likely to increase
    - The range and frequency of large insect outbreaks are likely to increase
    - Tree growth and forest productivity are likely to increase slightly on average, and the growth season will very likely lengthen
    - The impact of expected warming on soil processes and soil carbon storage is still unclear.

- Rising CO_2 will very likely increase photosynthesis for forests.

    - On high fertility sites, increased photosynthesis will likely increase wood growth and carbon stored in wood.

    - On low to moderate fertility sites, increased photosynthesis will possibly be rapidly respired
    - The response of photosynthesis to CO_2 for older forests is uncertain, but possibly will be lower than that of the younger forests that have been studied
    - Effects of elevated CO_2 on soil carbon storage are poorly understood because soil carbon formation is slow. Long-term, elevated CO_2 experiments are very likely necessary to predict soil responses

- Nitrogen deposition has very likely increased forest growth, and will continue to do so. Nitrogen deposition will likely increase the response of forest growth to CO_2.

- If existing trends in precipitation continue (drier in the Interior West and Southwest, and higher in portions of the East), forest productivity will likely increase in portions of the eastern U.S., and decrease in portions of the western U.S. If the frequency of droughts increases, forest productivity will very likely be reduced, and tree mortality likely increase where drought occurs.

- Storm damage very likely reduces productivity and carbon storage. If projected increases in hurricanes and ice storms are realized, storm damage will very likely increase.

- Monitoring the effects of climate change.

    - Current observing systems are very probably inadequate to separate the effects of changes in climate from other effects. Separating the effects of climate change would require a broad network of indicators coupled with a network of controlled experimental manipulations.
    - Major indicators of climate change in forests are effects on physiology, such as productivity, respiration, growth, net ecosystem exchange, and cumulative effects on tree rings, phenology, species distributions, disturbances, and hydrology. No national climate observation system provides measures of these indicators.
    - Major observation systems that can provide some information for forests include the USDA Forest Service Forest Inventory & Analysis Program, AmeriFlux, U.S.A National Phenology Network, Long Term Ecological Research network, and the upcoming National Ecological Observatory Network (NEON), coupled with remote sensing.
    - No coordinated system exists for monitoring forest disturbance.
    - The effects of climate change on disturbance and resulting species composition, and the attribution of changes in disturbance to climate change is one area where a well-designed observation system is a high priority need.
    - A national climate observation system should be able to identify early indicators of climate effects on ecosystem processes, and observations of structural and species changes.
    - Large-scale experimental manipulations of climate, CO_2, and nitrogen have supplied the most useful information on separating the effects of climate from

site and other effects. Experimental manipulations of precipitation and water availability are rare, but these supply critical information on long-term responses of different species.

Arid Lands

Arid lands occur in tropical, subtropical, temperate, and polar regions, and are defined based on physiographic, climatic, and floristic features. Arid lands are characterized by low (typically < 400 mm) and highly variable annual precipitation, along with temperature regimes where potential evaporation far exceeds precipitation inputs. In addition, growing season rainfall is often delivered via intense convective storms, such that significant quantities of water run off before infiltrating into soil; and precipitation falling as snow in winter may sublimate or run off during snowmelt in spring, while soils are frozen. As a result of these combined factors, production per unit of precipitation can be low. Given that many organisms in arid lands are near their physiological limits for temperature and water stress tolerance, slight changes in temperature and precipitation (e.g., higher temperatures that elevate potential evapotranspiration; more intense thunderstorms that generate more run off) that affect water availability and water requirements could have substantial ramifications for species composition and abundance, as well as the ecosystem goods and services these lands can provide for humans.

The response of arid lands to climate and climate change is contingent upon the net outcome of non-climatic factors interacting at local scales (Figure 1.9). Some of these factors may reinforce and accentuate climate effects (e.g., livestock grazing); others may constrain, offset or override climate effects (e.g., soils, atmospheric CO_2 enrichment, fire, non-native species). Climate effects should thus be viewed in the context of other factors, and simple generalizations regarding climate effects should be viewed with caution. Today's arid lands reflect a legacy of historic land uses, and future land use practices will arguably have the greatest impact on arid land ecosystems in the next two to five decades. In the near-term, climate fluctuation and change will be important primarily as it influences the impact of land use on ecosystems and how ecosystems respond to land use.

Findings

Species Distributions and Community Dynamics

- Responses to climate trends in the Sonoran Desert (decrease in the frequency of freezing temperatures, lengthening of the freeze-free season, and increased minimum temperatures (Weiss and Overpeck 2005) likely include contraction of the overall boundary of the Sonoran Desert in the southeast, and expansion northward, eastward, and upward in elevation, as well as changes to plant species ranges. Realization of these changes will be co-dependent on what happens with precipitation and disturbance regimes (e.g., fire). Similar scenarios can be expected for other deserts.

- Experimental data suggest shrub recruitment at woodland-grassland ecotones along elevation gradients will likely be favored by increases in summer precipitation, but are likely to be unaffected by increases in winter precipitation (Weltzin and McPherson 2000). This suggests increases in summer precipitation, should they occur, would favor down-slope migration of woodland boundaries.

- Droughts early in the 21st Century are likely to increase rates of perennial plant mortality in arid lands, accelerate rates of erosion, and create opportunities for exotic plant invasions.

- Proliferation of non-native annual and perennial grass are virtually certain to predispose sites to fire, resulting in a loss of native woody plants and charismatic mega flora. Low elevation, arid ecosystems are very likely to henceforth experience climate-fire synchronization where none previously existed.

- By virtue of their profound impact on the fire regime and hydrology, invasive plants in arid lands are likely to trump direct climate impacts on native vegetation where they gain dominance. The climate-driven dynamics of the fire cycle is likely to become the single most important feature controlling future plant distributions in U.S. arid lands.

- Greater temperatures predicted to co-occur with drought are very likely to increase mortality for the dominant woody vegetation typical of North American deserts, and open the door for establishment of exotic annual grasses.

- Due to climate-fire interactions, wide-spread conversion of shrubland to degraded, non-native grasslands is likely for the hot deserts of North America.

- The main invasion of exotic buffelgrass in southern Arizona occurred with warmer winters beginning in the 1980s. Buffelgrass range will very likely extend further north and upslope as minimum temperatures continue to increase (Arriaga et al. 2004). This upslope and northward extension will likely to be promoted by introduction of cold-resistant cultivars.

- Exurban development is virtually certain to be a major source for exotic species introductions by escape from horticulture.

Ecosystem Processes

- Plant productivity is strongly water limited, and is thus vulnerable to changes with changes in regional precipitation.

- Arid soils contain relatively little soil organic matter, and collectively make only a small contribution to the global pool of carbon in soils (Schlesinger 1977; Jobbagy and Jackson 2002).

- Low plant productivity limits the amount of carbon sequestration that can be expected per unit area; but given the large geographic extent of drylands, their contribution to carbon storage is potentially significant.

- The risk of loss of ecosystem carbon pools is high; greatest losses are very likely to be associated with desertification processes and annual plant invasions.

- Arid land soils are often deficient in nitrogen, so (1) erosional losses of soil nitrogen will further restrict regional productivity; and (2) vegetation, especially exotic grasses, will be very responsive to nitrogen deposition.

- Nitrogen deposition is spatially variable, being greater in areas downwind from major urban centers.

- Emissions of volatile organic carbon gases are very likely to have increased as a result of the displacement of grasslands by desert shrubs during the past 100 years

Riparian Systems

- Climate change is likely to place increasing pressure on montane water sources to arid land rivers, and increase competition among all major water depletions in arid land river and riparian ecosystems.

- The net result of climate warming is likely to be greater depletion of water along riverine corridors.

- The balance of competition between native and non-native species in riparian zones is likely to continue to shift toward favoring exotics as temperatures increase, as the timing and amount of water shifts, and as the intensity of disturbances are magnified.

- Major disturbances that structure arid land riverine corridors (e.g., floods, droughts) are likely to increase in number and intensity.

- Land use change, increased nutrient availability, increasing human water demand, and continued pressure from non-native species will act synergistically with climate warming to restructure the rivers and riparian zones of arid lands.

Erosion

- Climate change directly impacts the erosivity of precipitation and winds.

- Increases in precipitation intensity and the proportion of precipitation that comes in high-intensity storms will very likely increase water erosion from uplands and delivery of nutrient-rich sediment to riparian areas.

- Increases in wind speed and gustiness will very likely increase wind erosion, dust emission, and transport of nutrient-rich dust to downwind ecosystems, causing more rapid spring melt and shorter availability of snowmelt for human use.

- Climate change indirectly influences erodibility of the surface via effects on vegetation cover.

- Higher temperatures and decreased soil moisture will very likely reduce the stability of surface soil aggregates, making the surface more erodible.

WATER RESOURCES

Water is essential to life, and is central to society's welfare and to sustainable economic growth. Plants, animals, natural and managed ecosystems, and human settlements are sensitive to variations in the storage, fluxes, and quality of water at the land surface – notably storage in soil moisture and groundwater, snow, and surface water in lakes, wetlands, and reservoirs, and precipitation, runoff, and evaporative fluxes to and from the land surface, respectively – which are, in turn, sensitive to climate change.

Water managers have long understood the implications of variability in water sources at time scales ranging from days, to months and years on the reliability of water resources systems, and have developed many sophisticated methods to simulate and respond to such variability in water system design and operation. The distinguishing feature of current methods, however, is that they assume that an observed record of streamflow is statistically stationary, that is, the probability distribution(s) from which observations are drawn does not change with time. *In the era of climate change, this assumption is no longer tenable.* The challenge for water managers at this point is to determine reasonable ways of assessing plausible ranges of future conditions for purposes of hydrologic design and operation. Such assessment is also needed to understand how changes in the availability and quality of water will affect animals, plants, and ecosystems. Improved representation of the hydrological cycle in regional and global scale climate and weather models is needed to provide more accurate, finer scale projections of future conditions.

Findings

- Much of the continental U.S. has become wetter in recent decades. Measurements collected by the National Oceanic and Atmospheric Administration show that precipitation over much of the continental U.S. increased. Most U.S. stream flow measurements show increases in extremely low through median flows (i.e., in the low end through the middle of the streamflow distribution). Simulations of soil moisture also show a trend of increased wetness over most of the country, but this is unfortunately not verifiable from observations due to short record lengths.

- The rate and severity of flooding in the continental U.S. has almost certainly not increased. Data from the U.S. Geological Survey Hydroclimatic Data Network, which covers a range of basin sizes (mostly thousands, to tens of thousands of square km drainage area), does not provide any evidence of upward trends at the upper end of the streamflow distribution (i.e., high flows have not increased).

- Drought severity and duration declined over most of the United States during the 20th century. However, there are some trends in the opposite direction in the western and southwestern U.S., where increased temperatures, and resultant increases in evaporative demand more than counteracted increased precipitation.

- Evaporation appears to have increased over most of the United States during the latter half of the 20th century. Pan evaporation declined over this period, which is consistent with the "complementary hypothesis" that states that trends in actual and pan evaporation should be in opposite directions (i.e., actual evaporation should be increasing if pan evaporation is decreasing). Furthermore, some analyses support this hypothesis by showing trends toward increased precipitation minus runoff (inferred actual evaporation) at the river basin level.

- Snowpack in the mountainous headwaters regions of the western U.S. generally declined over the second half of the 20th century, especially at lower elevations and in locations where average winter temperatures are close to or above 0°C.

- Reduced winter snow accumulation and earlier spring melt have resulted in a tendency toward earlier runoff peaks in the spring. This shift has not occurred in rainfall-dominated watersheds in the same region.

- Warmer summer temperatures in the western U.S. have led to longer growing seasons, but have also increased summer drought stress. This has led to conditions that are conducive towards increased fire hazard. This tendency is, however, confounded by the effects of fire suppression over the same period.

- Stream temperature increases have begun to be detected across much of the United States, although a comprehensive analysis similar to those reviewed for long-term streamflow trends has yet to be conducted. Stream temperature is a change agent that has both direct and indirect effects on aquatic ecosystems. Higher temperatures during low flow periods are a particular concern for water quality and many aquatic species.

- U.S. consumptive use of water *per capita* has declined over the last two decades, and total water use has declined slightly as well. This is a result of various improvements in water use efficiency, related to both legal mandates and water pricing, as well as some changes in water laws that have facilitated reallocation of water, especially in the western U.S., and especially during droughts.

- It is likely that a combination of large temperature increases and modest increases in precipitation over the next 100 years will lead to declines in streamflows in some areas of the United States This finding is based on results averaged across many climate model simulations. However, because of the uncertainty in climate model projections of precipitation change, the regional-scale hydrologic consequences are highly uncertain across most of the United States

- In watersheds dominated by spring and summer snowmelt, such as the mountainous western U.S, the already observed shifts to earlier snowmelt peaks, and reduced summer and fall low flows are very likely to continue. This is likely to have substantial impacts on the performance of reservoir systems, especially when the active reservoir storage volume is much less than mean annual streamflow, as is the case across much of the western U.S.

- The trend of increasing U.S. water use efficiency and declining water consumption is likely to continue in the coming decades, helping to mitigate the impacts of climate change on water resources. Pressures for reallocation of water will be greatest in areas of the highest population growth, notably the Southwest.

BIODIVERSITY

Based on review of the literature, we have concluded that there are observable impacts of climate change on terrestrial ecosystems in North America, including changes in the timing of growing season length, phenology, primary production, and species distributions and diversity. Some important effects on components of biological diversity have already been observed and are increasingly well-documented over the past several decades. This statement is true both for ecosystems in the United States, and also, as the IPCC (2007) demonstrates, for ecosystems and biological resources around the world.

There are a suite of other impacts and changes in biodiversity that are theoretically possible, and even probable (e.g., mismatches in phenologies between pollinators and flowering plants), but for which we do not yet have a substantial observational database. However, we cannot conclude that the lack of a complete observational database in these cases is evidence that they are not occurring – it is just as likely that it is simply a matter of insufficient numbers or lengths of observations.

It is difficult to pinpoint changes in ecosystem services that are specifically related to changes in biological diversity in the United States. The Millennium Ecosystem Assessment (2005) concludes that climate change is likely to 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. But 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.

Findings

- Growing season and phenology: There is evidence indicating a significant lengthening of the growing season and higher net primary productivity in the higher latitudes of North America where temperature increases are relatively high. This evidence comes largely from global satellite data. The exception to this trend comes from forested regions that have been subject to persistent drought. In these systems, the combination of drought stress, warm winters, pests, and fires has led to extensive mortality, especially in the Intermountain West, and Southwest.

- Biogeographical and phenological shifts: Evidence from two meta-analyses and a major synthesis on species from a broad array of taxa suggests that there is very likely a significant impact of recent climatic warming in the form of long-term, large-scale alteration of animal and plant populations.

- Migratory birds: A climate change signature is very likely contributing to the advancement of spring migration phenology, but the indirect effects may be more important than the direct effects of climate in determining the impact on species persistence and diversity.

- Butterflies: Butterflies are also very likely to be exhibiting distributional and/or range shifts in response to warming. Across all studies included in her synthesis, Parmesan (2006) found that the range 30 to 75 percent of butterflies species had expanded northward, less than 20 percent had contracted southward, and the remainder was stable.

- Coastal and near-shore systems: Tropical, temperate, and Arctic regions have all documented changes that are due to climate variability/change and sea-level rise. These range from range shifts in offshore fish species, to coral bleaching, to reductions in sea-ice extent and thickness.

- Corals: Corals and tropical regions where they live are experiencing increasing water temperatures, increasing storm intensity, and a reduction in pH, all while experiencing a host of other ongoing challenges from development/tourism, fishing and pollution.

- Coastal lands: Climate change will also very likely lead to increasing coastal erosion through several processes, such as increasing coastal storm intensity, shifts to fewer more intense storm events in some regions and loss of sea ice cover during traditional storm seasons. While these issues have been well addressed in terms of human infrastructure and settlement vulnerability to climate change, they have been less well explored in terms of biodiversity.

- Arctic: Ice loss to date is already causing measurable changes in polar bear and ringed seal populations. There are also shifts in species ranges in the Arctic, both on land and in the water, and changes in phenology.

- Pests and Pathogens: Evidence is beginning to accumulate that links the spread of pathogens to a warming climate. For example, the chytrid fungus (*Batrachochytrium dendrobatidis*) is a pathogen that is rapidly spreading worldwide, and decimating amphibian populations. To date, geographic range expansion of pathogens related to warming temperatures have been the most easily detected, perhaps most readily for arthropod-borne infectious disease. However, a recent literature review found additional evidence gathered through field and laboratory studies that support hypotheses that latitudinal shifts of vectors and diseases are occurring under warming temperatures.

- Invasive plants: Projected increases in CO_2 are likely to stimulate the growth of most plants species, and some invasive plants are expected to respond with greater growth rates than non-invasive plants. Some invasive plants may have higher growth rates, and greater maximal photosynthetic rates relative to native plants under increased CO_2. However, definitive evidence of a general benefit of CO_2 enrichment to invasive plants over natives has not emerged. Nonetheless, invasive plants in general may better tolerate a wider range of environmental conditions and may be more successful in a warming world because they can migrate and establish in new sites more rapidly than native plants, and they are not usually limited by pollinators or seed dispersers.

- Marine fisheries: Linkages between the North Atlantic Oscillation, zooplankton ,and fisheries have also been described for the Northwest Atlantic waters off of eastern Canada, and the United States: Pershing and Green (2007) report a decrease in salinity, and an increase in biomass of small copepods (zooplankton).

- Particularly sensitive systems: Hibernating and migratory species that reproduce at high altitudes during the summer are also being affected by ongoing environmental changes. For example, marmots are emerging a few weeks earlier than they used to in the Colorado Rocky Mountains, and robins are arriving from wintering grounds weeks earlier in the same habitats. Species such as deer, bighorn sheep, and elk, which move to lower altitudes for the winter, are likely also to be affected by changing temporal patterns of snowpack formation and disappearance.

- Polar bears: The rapid rates of warming in the Arctic observed in recent decades and projected for at least the next century are dramatically reducing snow and ice cover that provide denning and foraging habitat for polar bears. During previous climate warmings, polar bears apparently survived in some unknown refuges. Whether they can withstand the more extreme warming ahead is doubtful.

- Monitoring systems: Despite the fact that there are many existing monitoring systems that are useful for observing climate change and ecosystem status, the United States does not have a robust capability for assessing the impacts of climate change on biodiversity

    - There is a plethora of species-specific or ecosystem-specific monitoring systems, variously sponsored by the U.S. federal agencies, state agencies, conservation organizations, and other private organizations. However, in very few cases were these monitoring systems established with climate variability and climate change in mind.

- Augmenting the monitoring systems are a set of more specific research activities that have been specifically designed to create time-series of population data, and associated climatic and other environmental data. These systems, however, tend to lack the institutional stability to create, manage, and maintain long time-series of observations.
- There are also spatially extensive observations derived from remotely sensed data. These are primarily focused on land-cover, and thus are good indicators of major, single-driver changes in biodiversity patterns, or on estimating ecosystem functioning, such as producing estimates of net primary productivity, or growing season changes, and thus reflect functional changes more easily than structural changes. However, similarly to the in situ monitoring networks, the space-based observations' future is not assured. The National Research Council (2007) recently released a major survey of data and mission needs for the Earth sciences to address this issue, so we will not pursue it further here.

SYNTHESIS

The following section presents information drawn from the individual chapters summarized above, organized into answers to the guiding questions posed by the CCSP agencies and a set of overarching conclusions.

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

Climate has myriad effects on U.S. ecosystems. Warming temperatures have led to effects as diverse as altered timing of bird migrations, increased evaporation and altered growing seasons for wild and domestic plant species. Increased temperatures often 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 plant-available moisture, snowpack and snowmelt, streamflow, flood hazard, and water quality.

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 profound effects, ranging from changes to horticultural systems to changes in the mountain pine beetle's range. Changes to humidity, cloudiness, and radiation may reflect both anthropogenic aerosols, and the global hydrological system's response to warming affect 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 – chemical climate – also also interact. Nitrogen deposition has major chemical effects in ecosystems, can act as a fertilizer increasing productivity, but also eutrophying ecosystems. 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 occur. On the other side of the ledger, crop yield increases, as rising atmospheric CO_2 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, how crop-responses to changing climate are managed can 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 cops. 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.

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 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 a 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 growing-season length, and increased rainfall may increase 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 the 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, so-called C4 plants may be indicative of temperature or water stress, while other species indicate 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).

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. The National Oceanic and Atmospheric Administration (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. 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 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 makes monitoring in-stream 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 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), a new initiative, the 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, aimed at specific questions and/or 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 these changes are superimposed on a 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 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 it defies our current scientific understanding to separate them 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. 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, 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 inhibiting our ability to identify climate contributions to ecological change and separate these from other influences. This report identifies a number of opportunities to do just this, 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 of more co-location of sensors, and 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 change is 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.

Many other stresses – land use change, nitrogen cycle change, point and non-point source pollution, invasive species – are also affecting these resources.

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, which 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 Western states, and indeed throughout the United States. It is likely that the spread of these invasive species, which often change ecosystem processes, will react to changing climate in a way that exacerbates the risks from climate change alone. For example, in some cases invasive species increase fire risk, and decrease forage quality.

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.

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. 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, as well as overall ecosystem health.

There is no specific analysis of the 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, as described by the Millennium Ecosystem Assessment, 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, which land-management agencies depend on, to research networks, such as the LTERs, 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 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.