# SAP 4.3

# The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity

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# REPORT Abstract

# 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?

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- 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 20th 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 21st 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 21st century than seen in the last 10,000 years.

- If atmospheric concentration of $CO_2$ 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 $CO_2$ increases to about 700 ppm, global average surface temperature would likely increase about 1.7 - 4.4°C by 2100.

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- 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 CO2 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.

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# 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.

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- 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

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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

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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.

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  - 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

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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.

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- 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).

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- 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.

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- 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

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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

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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

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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

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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

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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.

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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

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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

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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.

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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

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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.

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## 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

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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.

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# 1 Introduction

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. It is one of a series of 21 Synthesis and Assessment Products that are being produced under the auspices of the U.S. Climate Change Science Program (CCSP), which coordinates U.S. government climate change research across agencies. The lead sponsor of this particular assessment product is the U.S, Department of Agriculture. The team of authors includes scientists and researchers from universities, non-government organizations, and government agencies, coordinated by the National Center for Atmospheric Research (NCAR). They have reviewed and discussed hundreds of peer-reviewed papers, guided by a prospectus agreed upon by the CCSP agencies (*see appendix X*), to produce a synthesis of information on resource conditions, observation systems, and monitoring capabilities that can be used to gauge future change. Much of this literature was produced under the sponsorship of agency programs in the ecosystems, land use, and water research elements of the CCSP, and this assessment is properly seen as the product of ongoing support of research in these areas by the CCSP agencies.

## 1.1 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

## 1.2 Guiding Questions for this Report

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This synthesis and assessment report builds on an extensive scientific literature and series of recent assessments of the historical and potential impacts of climate change and climate variability on managed and unmanaged ecosystems, and their constituent biota and processes. It discusses our ability to identify, observe, and monitor the stresses that influence agriculture, land resources, water resources, and biodiversity, and evaluates the relative importance of these stresses and how they are likely to change in the future. It identifies changes in resources conditions that are now being observed, and examines whether these changes can be attributed in whole or part to climate change. It also highlights changes in resource conditions that recent scientific studies suggest are most likely to occur in response to climate change, and when and where to look for these changes. The assessment is guided by five overarching questions:

- 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?

## *1.3 Ascribing Confidence to Findings*

The authors of this document have used language agreed to by the CCSP agencies to describe their confidence in findings that project future climate changes and impacts, as shown in Figure 1.1 below. Our intent is to use a limited set of terms in a consistent fashion.

**Figure 1.1** Language for Discussing Confidence in Findings

## *1.4 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 rather on the nearer-term future, the next 25-50 years. We report key results out to 100 years to frame the report, but we emphasize the coming decades.

This focus is chosen for two reasons. First, for many natural resources, planning and management already addresses these time scales through the development of long-lived infrastructure, forest rotations, and other significant investments. Second, climate projections are relatively certain over the next few decades. Emission scenarios for the next few decades do not diverge from each other very much because of the "inertia" of the energy system. Most projections of greenhouse gas emissions assume that it will take decades to make major changes in the energy infrastructure, and only begin to diverge rapidly until several decades have passed (30-50 years).

As a result, projections of high- and low-emission scenarios only begin to separate strongly in the 2030s-2040s, and climate scenarios then diverge slightly later. Averaging over climate models, a rate of a few tenths of a degree per decade can be assumed likely for the next two to four decades. As emissions diverge in the 2030s-2050s, so do climate projections and, as a result, uncertainty about future climates rapidly becomes larger.

This is captured in Figure 1.2 below, which shows that overall climate uncertainty is lowest in the mid-century. The near-term is affected by the weather forecast problem. Given a few tenths of a degree warming per decade, hard-to-forecast interannual variability (El Niño and similar phenomena) can contribute similar amounts of warming or cooling. Later in the century, variability between emission scenarios and resulting climate dominate and, since this depends on human choices and behavior, this is extremely hard to predict. Thus, the mid-term uncertainty is lowest. We focus this report on the mid-term, where the experience gained in observation studies likely remains relevant, where today's management effects will remain relevant, and where the uncertainty is relatively low.

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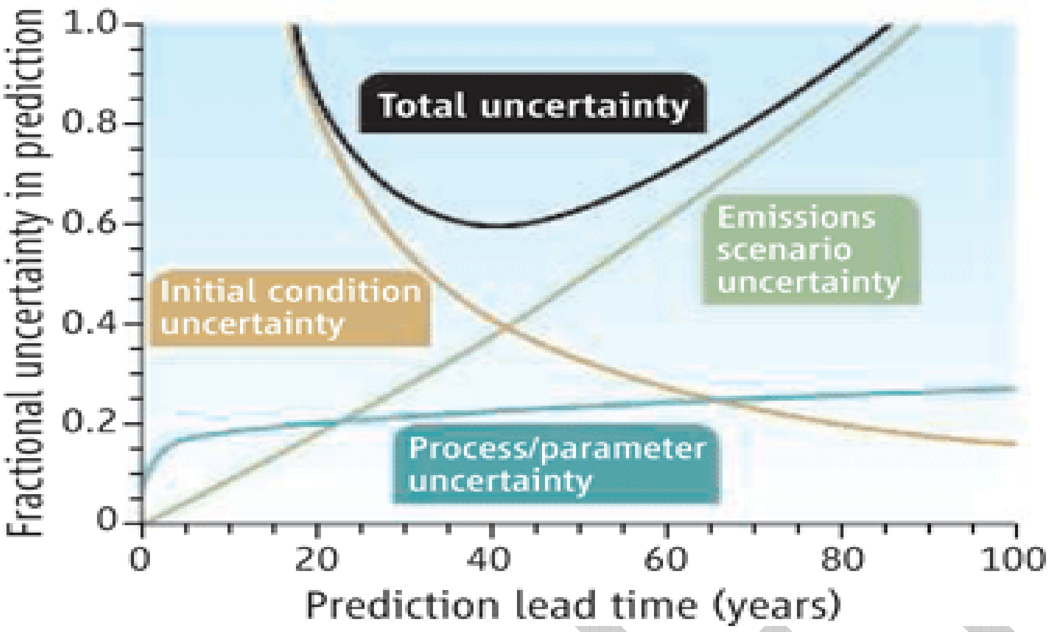

**Figure 1.2** **Uncertainty of Climate Projections:** Contributions to uncertainty in the predicted decadal mean temperature vary with the lead time of the prediction. Climate predictions focusing on lead times of ~30 to 50 years have the lowest fractional uncertainty. From "A Changing Climate for Prediction," Peter Cox and David Stephenson, *Science*, 13 July 2007, pp. 207-208.

## *1.5 Global Climate Context*

There is a robust scientific consensus that human-induced climate change is occurring. The recently released Fourth Assessment Report of the IPCC (IPCC AR4) states with "very high confidence," that human activity has caused the global climate to warm (Solomon et al. 2007). Many well-documented observations show that fossil fuel burning, deforestation, and other industrial processes are rapidly increasing the atmospheric concentrations of $CO_2$ and other greenhouse gases. The IPCC report describes an increasing body of observations and modeling results, summarized below, which show that these changes in atmospheric composition are changing the global climate and beginning to affect terrestrial and marine ecosystems.

- The global-average surface temperature increased by about 0.6°C over the 20th century. Global sea level increased by about 15-20 cm during this period.
- Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000 meters, and that the ocean has been absorbing more than 80 percent of the heat added to the climate system.
- Long-term temperature records derived from ice sheets, glaciers, lake sediments, corals, tree rings, and historical documents show that 1995-2004 was the warmest decade worldwide in the last one to two thousand years. Nine of the 10 warmest years on record have occurred in the last decade.

- 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 percnet during this time, while West Africa and other areas experienced decreases).
- Mountain glaciers are melting worldwide, the Greenland ice sheet is melting, the extent and thickness of Arctic sea-ice is declining, and lakes and rivers freeze later in the fall and melt earlier in the spring. The growing season has lengthened by about one to four days per decade in the last 40 years in the Northern Hemisphere, especially at high latitudes.
- The ranges of migrating birds, and some fish, and insect species are changing. Tropical regions are losing animal species, especially amphibians, to warming and drying.

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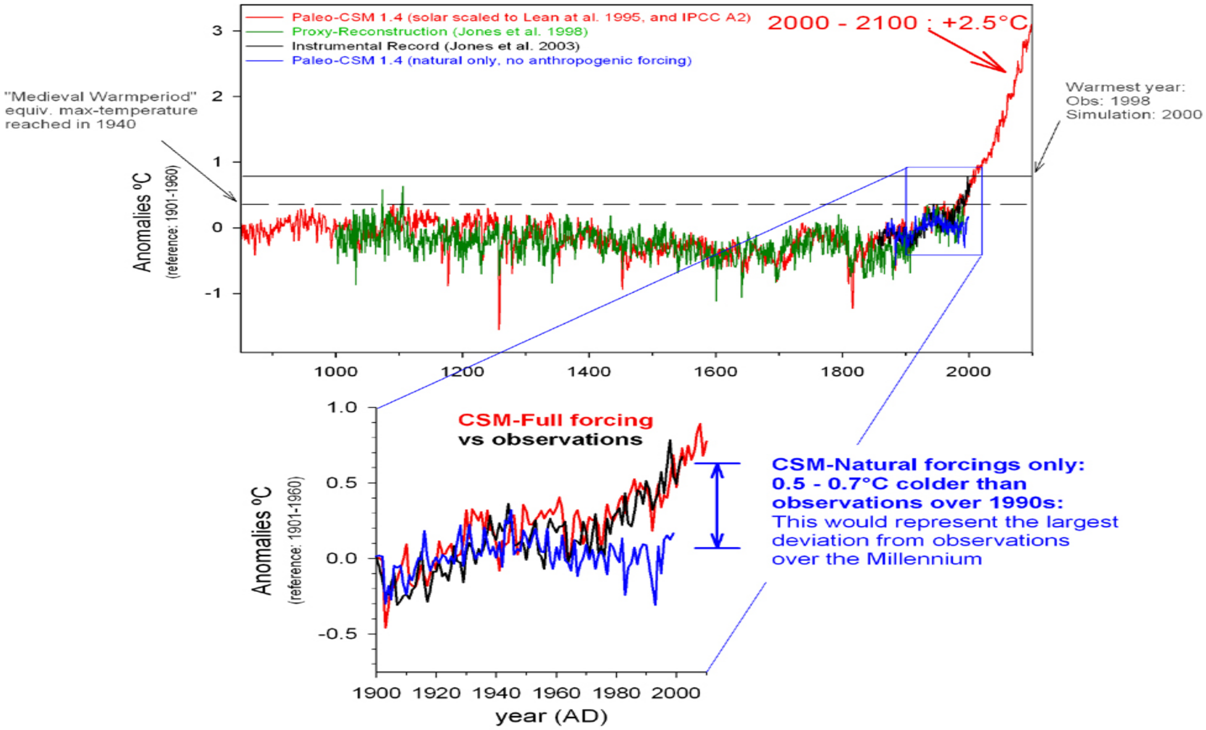

**Figure 1.3** **Temperatures of the Last Millennium and the Next Century.** The effects of historical reconstructions of solar variability and volcanic eruptions were modeled using an NCAR climate model and compared to several reconstructions of past temperatures. The model reproduces many temperature variations of the past 1,000 years, and shows that solar and volcanic forcing has been a considerable impact on past climate. When only 20th Century solar and volcanic data are used, the model fails to reproduce the recent warming, but captures it quite well when greenhouse gases are included.

Change is a persistent feature of climate, and the anthropogenic climate change now occurring follows on millennia of natural climate changes. We now know that the climate of the past thousand or so years has varied significantly with hemispheric-to-global variations in temperature and precipitation resulting from the effects of the sun, volcanoes, and the climate system's natural variability (Ammann et al. 2007). This long-term variability is witnessed by many paleoclimate records, including natural archives in tree rings, corals, and glacial ice. Some of these historical variations can even be reproduced by today's advanced climate models, which can convincingly capture the effects of solar variability and volcanoes over the past thousand years. Interestingly, the model that captures the past thousand years of global temperature patterns successfully (Figure 3) using only solar and volcanic inputs fails to simulate the 20th century unless greenhouse gases are factored in (Ammann et al. 2007).

Looking ahead, it is clear that human influences will continue to change Earth's climate throughout the 21st century. The IPCC AR4 describes a large body of modeling results, which show that changes in atmospheric composition will result in further increases in global average temperature and sea level, and continued decline in snow cover, land ice and sea ice extent. Global average rainfall, variability of rainfall, and heavy rainfall events are projected to increase. Heat waves in Europe, North America, and other regions will become more intense, more frequent, and longer lasting. We are very likely to experience a faster rate of climate change in the 21st 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 - 2.9ºC by 2100.
- If atmospheric concentration of CO2 increases to about 700 ppm, global average surface temperature would likely increase about 1.7 - 4.4ºC by 2100.
- If atmospheric concentration of CO2 increases to about 800 ppm, global average surface temperature would likely increase about 2.0 - 5.4º C by 2100.
- Even if atmospheric concentration of CO2 were stabilized at today's concentrations of about 380 ppm, global average surface temperatures would likely continue to increase by another 0.3 – 0.9ºC by 2100, as shown in Figure 1.4.

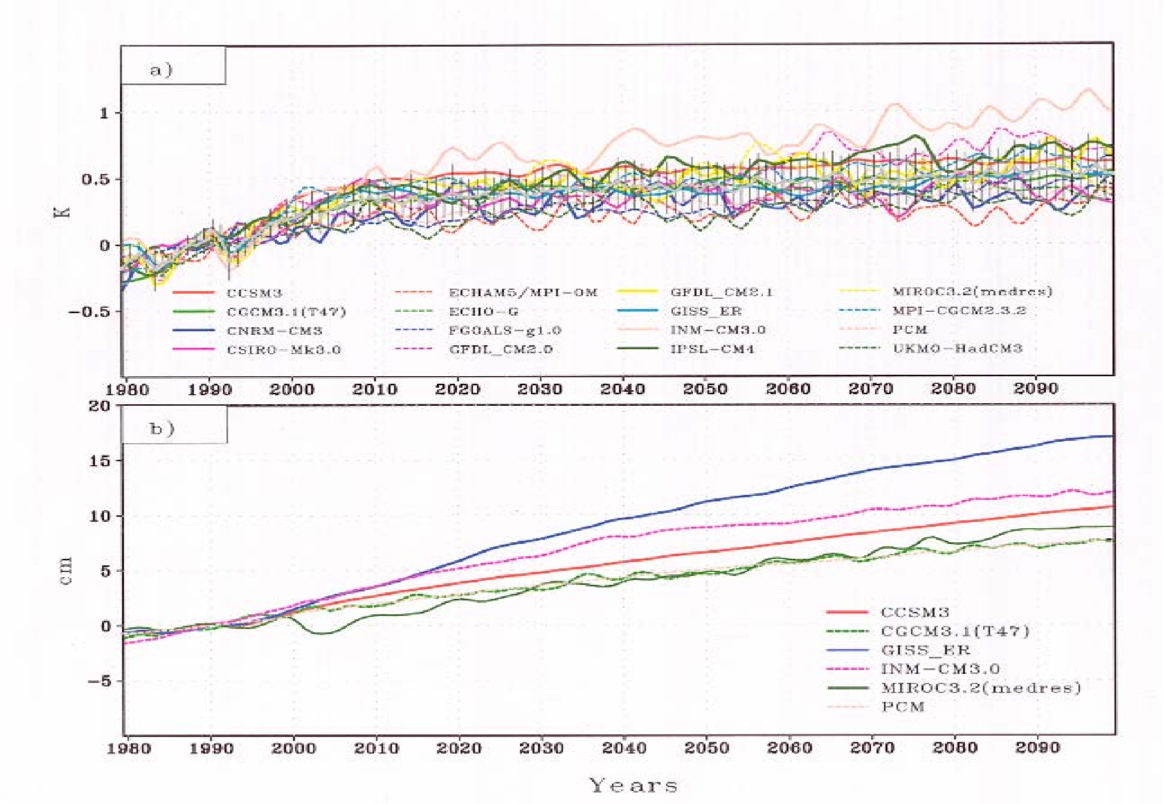

**Figure 1.4 The Climate Change Commitment.** A wide range of modeling studies indicates that substantial increases in temperature (panel a), and sea level rise (panel b) will occur over the next century even if atmospheric concentrations are stabilized at today's levels (*Science*,18 March 2005:Vol. 307. no. 5716, pp. 1766 - 1769).

## *1.6 U.S. Climate Context*

Records of temperature and precipitation in the United States show changes that are consistent with the global-scale changes discussed above. The US has warmed up significantly overall, but change varies by region. (Figure 1.5). Parts have cooled, and Northern regions, especially Alaska, have warmed the most. Much of the Eastern and Southern U.S. now receive more precipitation than 100 years ago, while other areas, especially in the US Southwest, now receive less (Figure 1.6).

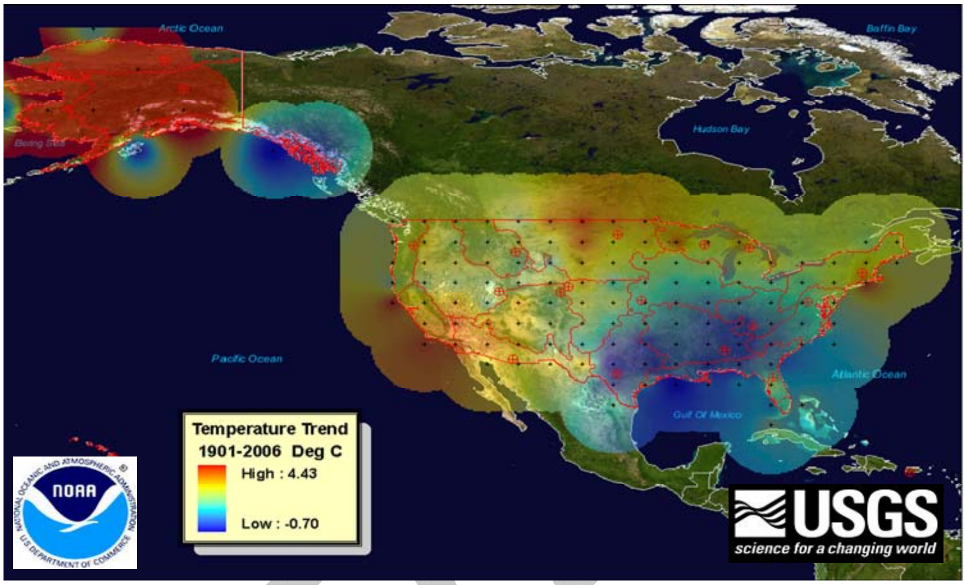

**Figure 1.5 Mapped trends in temperature across the lower 48 states, and Alaska**. These data, which show the regional pattern of US warming, are averaged from weather stations across the country using stations that have as complete, consistent, and high quality records as can be found. Data and mapping courtesy of NOAA's National Climate Data Center, and the U.S. Geological Survey.

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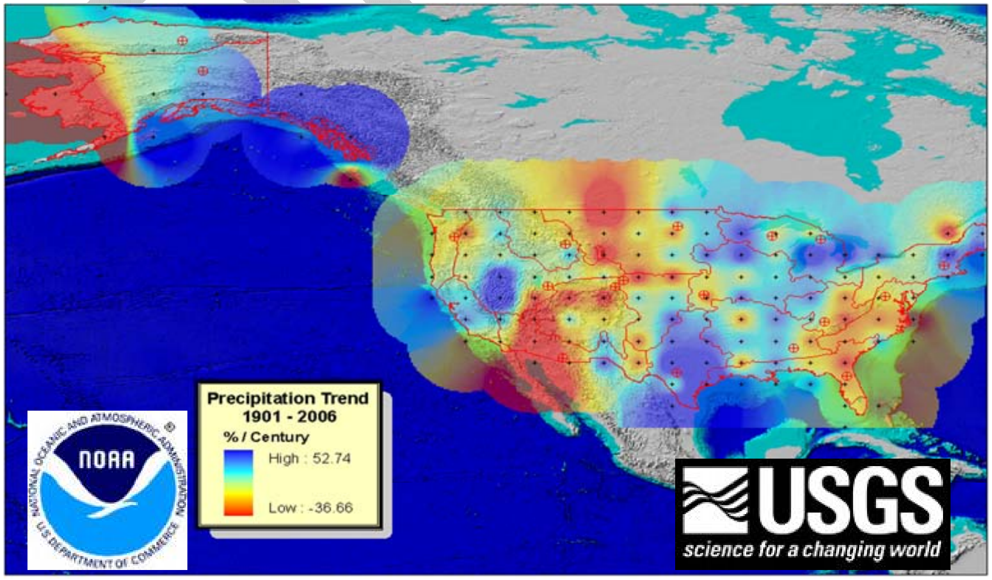
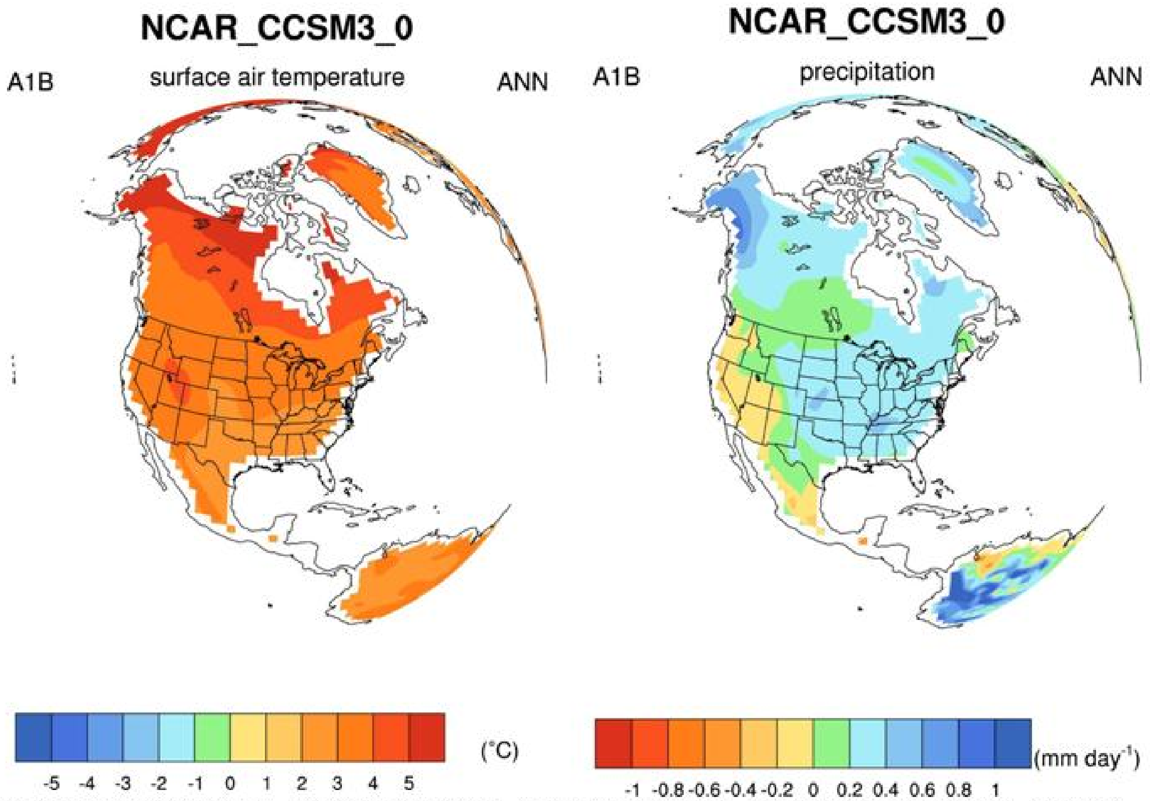


**Figure 1.6** **Precipitation changes** over the past century from the same weather stations as for temperature. The changes are shown as percentage changes from the long-term average.

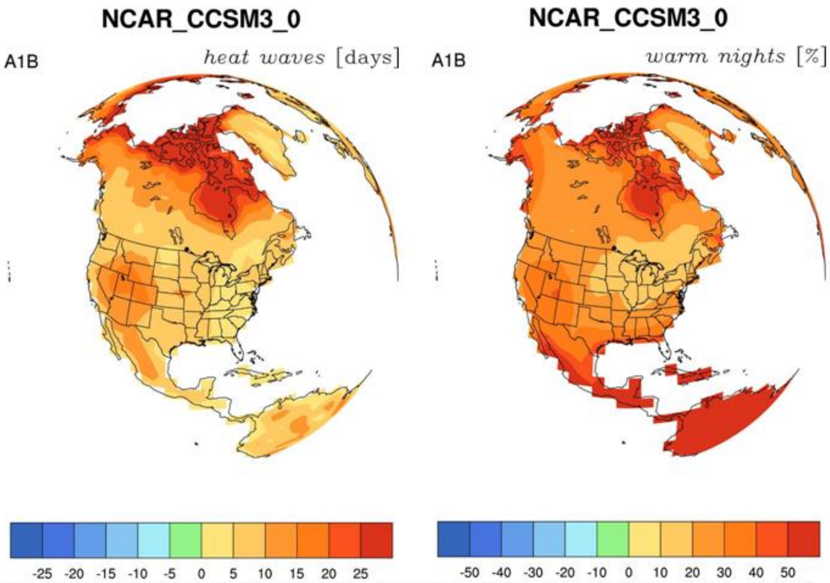
The scenarios of global temperature change discussed in the global climate context section above would result in large changes in U.S. temperatures, and precipitation, with considerable variation by region. Below, Figure 8 shows results of an NCAR Community Climate System Model simulation for IPCC scenario A1B, generally considered a mid-range projection. The expected increases in average U.S. temperatures vary from 1-2°C more than 4°C – and remember that Alaska, for example, has already warmed by more than 2°C.



Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html

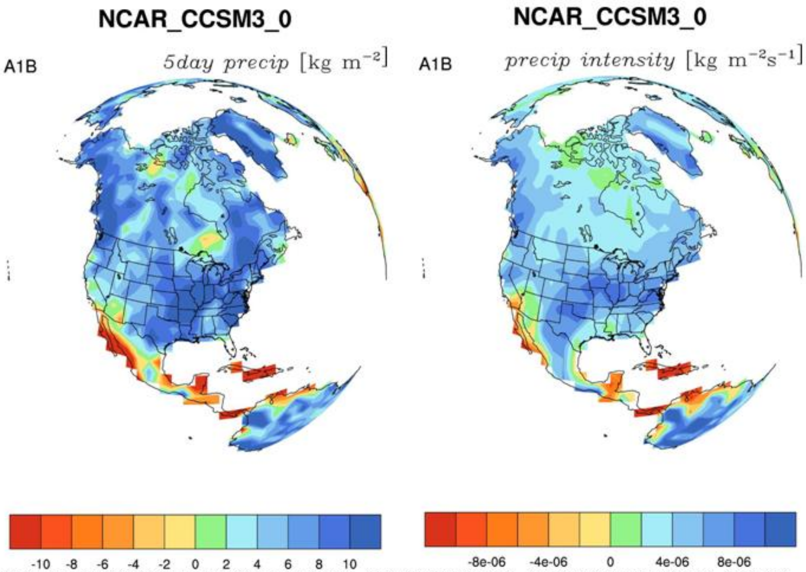
**Figure 1.7** **US Temperature and Precipitation Changes by 2100.** This figure shows how U.S. temperature and precipitation would change by 2100 if the atmospheric concentration of greenhouse gases increases to about 700 parts per million, which is roughly double the pre-industrial level. The change is shown as the difference between two twenty-year averages (2080-2099 minus 1980-1999).

The average temperature and precipitation are not the only factors that matter for ecosystems. Extreme climate conditions, such as droughts, heavy rainfall, snow events, and heat waves affect individual species and ecosystems structure and function. Change in the incidence of extreme events could thus have major impacts on U.S. ecosystems and must be considered when assessing vulnerability to and impacts of climate change. Figure 9 shows how the U.S. temperature increases simulated by the NCAR Community Climate System Model (CCSM) for IPCC scenario A1B (a moderate emissions growth scenario) will result in an increased number of heat waves and warm nights in the last decade of this century. Figure 10 shows the expected change in heavy precipitation events.



Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html

**Figure 1.8 Simulated US Heat Wave Days and Warm Nights in 2100.** The left panel shows the expected change in number of heat wave days (days with maximum temperature higher by at least 5°C (with respect to the climatological norm) between 2000 and 2100. The right panel shows changes in warm nights (percent of times when minimum temperature is above the 90th percentile of the climatological distribution for that day) between 2000 and 2100.



Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html

**Figure 1.9 Changes in US Precipitation by 2100.** This figure shows increases in heavy rainfall expected for the United States if atmospheric concentrations of greenhouse increase to about 700 parts per million. The left panel shows changes in maximum 5-day precipitation totals, while the right panel shows a simple daily precipitation intensity index (annual total precipitation divided by the number of wet days).

## 1.7 Ecological and Biological Context

Climate has many impacts on terrestrial ecosystems, some of which create further feedbacks to climate through greenhouse gas fluxes, albedo changes, and other processes. Ecosystem responses to climate have implications for sustainability, biodiversity, and the ecosystem goods and services available to people. Much of the research on terrestrial ecosystems and climate change has focused on their role as carbon sources or sinks. The observation that atmospheric $CO_2$ was growing more slowly than expected from fossil fuel use and ocean uptake led to the conclusions of a "missing sink," and that increased plant photosynthesis was due to elevated atmospheric $CO_2$ (Gifford, RM. The Global Carbon Cycle: a Viewpoint on the Missing Sink. *Australian Journal of Plant Physiology* 21, 1–15).

It is now evident that several mechanisms, and not just $CO_2$ fertilization, play a role (Feedbacks of Terrestrial Ecosystems to Climate Change, (*Christopher B. Field, David B. Lobell, Halton A. Peters, Nona R. Chiariell,* Annual Review of Environment and Resources 2007 32). These include recovery from historic land use, fertilizing effects of nitrogen in the environment, expansion of woody vegetation, storage of carbon in landfills, reservoirs, and other depositional sites, and sequestration in long-lived timber products (Schimel D., House J.I., Hibbard K., Bousquet P., Peylin P., et al. (2001), Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems, *Nature*, 414, 169-172).

Responses of photosynthesis and growth to warming are nonlinear and typically rise to an optimum temperature, then decrease as it is exceeded. The response of plants from different ecosystems is usually adapted to local conditions, such that local warming increases photosynthesis under conditions that are cool relative to local conditions and decreases under conditions that are hot (relative to the local mean). Extreme hot and cold events affect photosynthesis and growth, and may reduce uptake or even cause mortality. Warming can lead to either increased or decreased plant growth.

Comprehensive analyses show that climate change can cause the shift of many species to higher latitudes and/or altitudes, as well as changes in phenology. Not all species can successfully adjust, and models show biomes that are shifting in a warm, high-$CO_2$ world lose an average of a tenth of their biota. When this is not offset by redundancy in function among species, linkages between climate and ecosystem function will break down.

Climate will affect ecosystems through fire, pest outbreaks, diseases, and extreme weather, as well as through changes to photosynthesis and other physiological processes. Disturbance regimes are a major control of climate-biome patterns. Fire-prone

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ecosystems cover about half the land area where forests would be expected, based on climate alone, and lead to grasslands and savannas in some of these areas. Plant pathogens, and insect defoliators are pervasive as well, and, annually, affect more than 40 times the acreage of United States forests damaged by fire. Disturbance modifies the climatic conditions where a vegetation type can exist.

The majority of studies on ecosystem responses and feedbacks to climate change treat the system as if factors external to the biosphere were affecting the system in a univariate way (i.e., by releasing $CO_2$ or warming the climate). More recent thinking recognizes that that deforestation, agriculture, and the spread of invasive species can influence or even dominate how systems respond to climate

While the vast majority of the ecosystems and climate change literature focuses on plants and soil processes, significant impacts on animal species are also known. A substantial literature documents impacts on the timing of bird migrations, on the latitudinal and elevational ranges of species and on more complex interactions between species, e.g., when predator and prey species respond to climate differently, breaking their relationships (Camille Parmesan and Gary Yohe, A globally coherent fingerprint of climate change impacts across natural systems, *Nature* 421, 37-42 2003) | doi:10.1038/). The seasonality of animal processes can also respond, and this effect can have dramatic consequences, as occurs, for example, with changes in insect pest or pathogen-plant host interactions. Domestic animals also respond significantly to climate, both through direct physiological impacts on livestock, and through more complex effects of climate on livestock and their habitats. While the effects of climate change on animals has been less studied than effects on plants, the impacts on ecosystem goods and services from people may be as large or larger.

## 1.8 Attribution of Ecosystem Changes

It is important to note that the changes due to climate change occur against a background of rapid changes in other factors affecting ecosystems. These include changing patterns of land management, intensification of land use and exurban development, new management practices (e.g., biofuel production), species invasions and changing air quality (Lodge, D.M., S. Williams, H. MacIsaac, K. Hayes, B. Leung, L. Loope, S. Reichard, R.N. Mack, P.B. Moyle, M. Smith, D.A. Andow, J.T. Carlton, and A. McMichael. 2006. Biological invasions: recommendations for policy and management [Position Paper for the Ecological Society of America]. Ecological Applications 16:2035-2054). Because many factors are affecting ecosystems simultaneously, it is difficult and in some cases impossible to factor out the magnitude of each impact separately. In a system affected by, for example, temperature, ozone, and changing precipitation, assigning a percentage of an observed change to each factor is generally impossible. Research is ongoing on improved techniques for separating influences, but in some cases, drivers of change interact with each other, making the combined effects different from the sum of the separate effects. Scientific concern about such multiple stresses is rising rapidly.

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## 1.9 Summary

The changes in temperature and precipitation over the past century now form a persistent pattern, and show features consistent with our scientific understanding of climate change: for example, scientists expect larger changes near the poles than near the equator. This pattern can be seen in the dramatically higher rates of warming in Alaska compared to the rest of the country. However, most of the warming is concentrated in the last decades of the century. Prior to that, large natural variations due to solar and volcanic effects were comparable in magnitude to the then-lower greenhouse gas effects. These natural swings sometimes enhanced, and sometimes hid the effects of greenhouse gases. The warming due to greenhouse gases is now quite large and the “signal” of the greenhouse warming has more clearly emerged from the “noise” of our planet’s natural variations. The effects of greenhouse gases have slowly accumulated, but in the past few years, their effects have become evident. Recent data show clearly both the trends in climate, and climate’s effects on many aspects of our nation’s ecology.

The changes that are likely to occur will continue 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 will document some of the observed historical changes and provide insights into how the continuing changes may affect our nation’s ecosystems.

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# 2 Agriculture

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## 2.1 Introduction

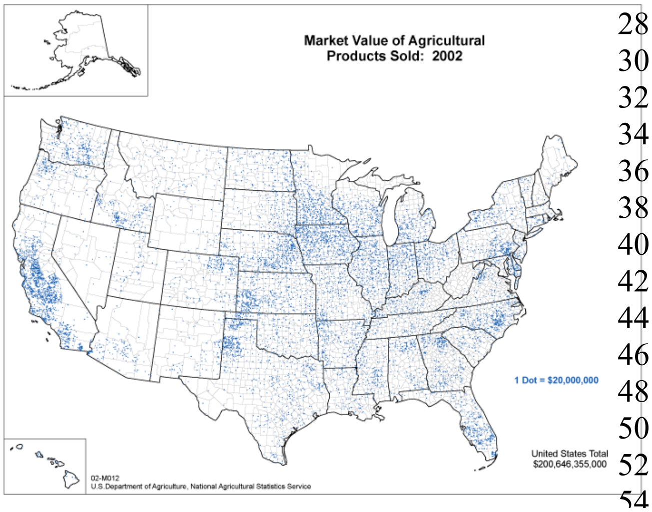


**Figure 2.1** Market value of all agricultural products sold in 2002. (USDA National Agricultural Statistics Service).

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 U.S. regions. U.S. agriculture 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 United States Department of Agriculture (USDA) National Agricultural Statistics Service, and four different livestock groupings (i.e., 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). The extensive and intensive nature of U.S. agriculture is best represented in the context of the value of the production of crops and livestock. Market value of agricultural production within the United States represents a combination of all crops and their distribution (Figure 2.1). U.S. agriculture was distributed among these different commodities with 52 percent of the value generated from livestock, 21 percent from fruit and nut, 20 percent from grain and oilseed, two percent from cotton, and five percent from other commodity production, not including pastureland or rangeland production. Figure 2.2 illustrates that crops and livestock represent approximately equal portions of the commodity value (Figure 2.2).

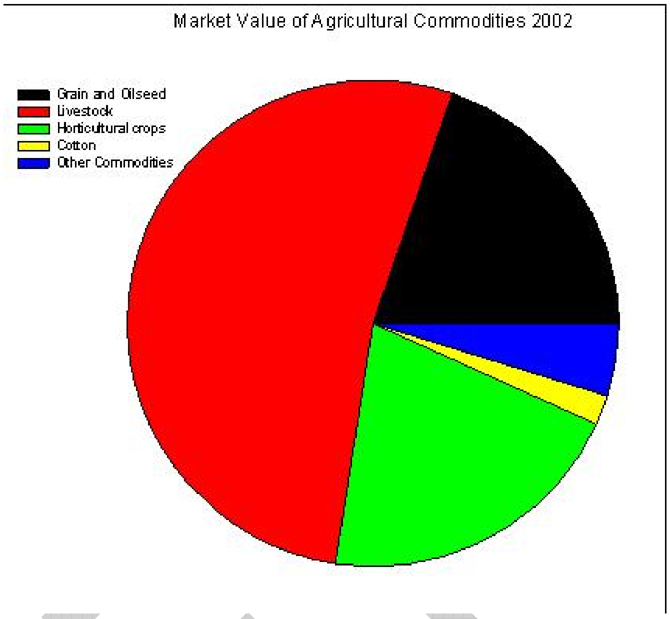


**Figure 2.2**. Market value distribution of livestock, grain and oilseed, horticultural crops, cotton and other crops for the United States in 2002. (USDA National Agricultural Statistics Service).

Distribution of crops across the United States is dependent upon the suitability of the soil and climate for efficient production. Corn (*Zea mays* L.) is the most widely distributed crop across the United States, next to pastureland and rangeland. Wheat, while grown in most states has a concentration in the upper Great Plains and Northwest United States. In contrast to grain crops, orchard crops are restricted to regions in which there are moderate winter temperatures (Figure 2.3). For example, citrus crops are grown in the southern regions of the United States where winter temperatures are mild, and occurrence of freezing temperatures is minimal.

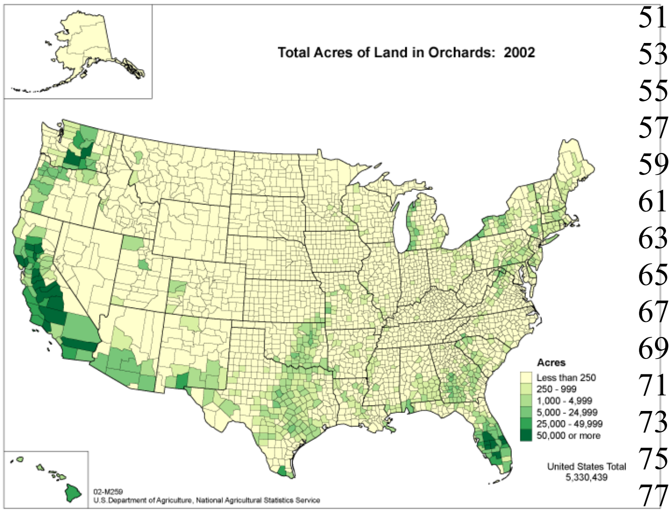


**Figure 2.3**. Distribution of orchards across the United States in 2002. (USDA National Agricultural Statistics Service).

However, orchards are distributed in the Northeast U.S. and intensive areas along the Great Lakes to take advantage of the moderating effect of the lakes. The local microclimate, induced by the regional climate, creates areas in which orchards that have specific requirements for winter chilling create opportunities for these crops as part of the production system. Shifts in the climate that cause changes in these conditions will have a major impact on fruit production and risks due to variations in temperature during the spring (flowering) and fall (fruit maturity).

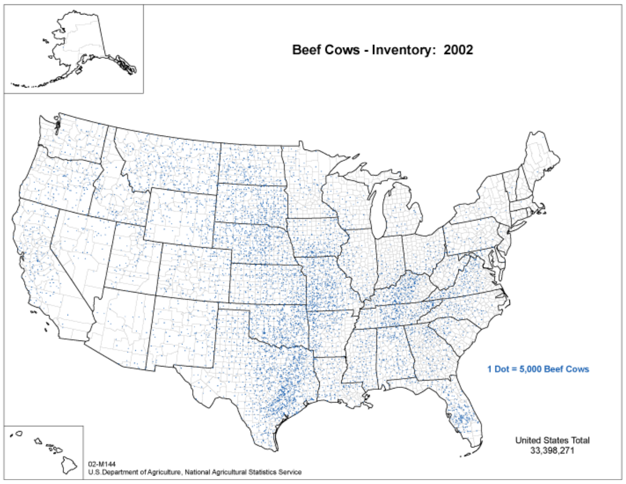


**Figure 2.4**. Distribution of beef cow inventory across the United States in 2002. (USDA National Agricultural Statistics Service).

Distribution of beef cows across the United States is indicative of a livestock commodity produced across a range of climates (Figure 2.4). Every state has some beef cows with the majority in states that have an abundance of native or planted pastures, which provide easily accessible feed supplies for the grazing animals. Linkage exists between the amount of pasture and grazing land (Figure 2.5) and beef cow numbers because of the combination of production systems and the use of animals to directly consume grass or hay. In contrast, areas classified as rangeland, v precipitation, are concentrated in the western p

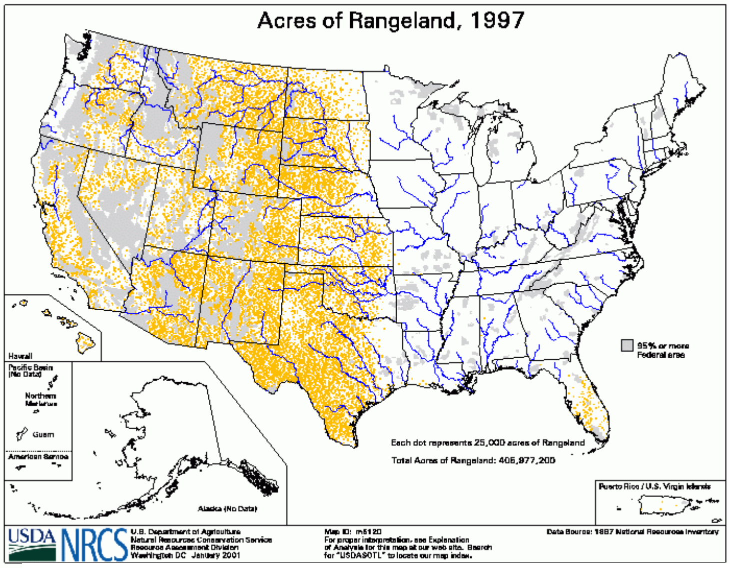
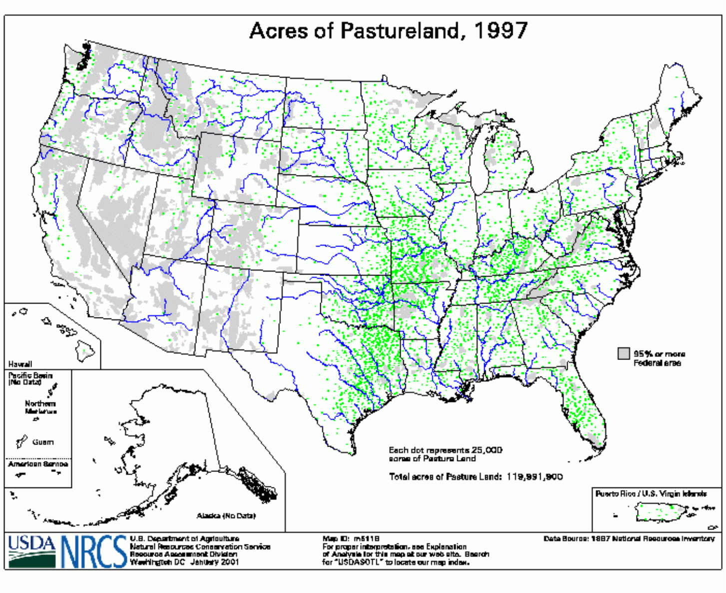


**Figure 2. 5**. Distribution of pastureland across the United States in 1997 (www.nrcs.usda.gov/technical)



1997 (www.nrcs.usda.gov/technical)

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 impacts of temperature and water availability to livestock. Variations in production among 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.

There has been a decline in land classified as rangeland, pastureland, or grazed forest land over the past 25 years. These changes are unrelated to climate change but illustrate changes in U.S. land use characteristics (Table 2.1). These shifts seem to more related to changes in population growth since much of the decline has occurred in the eastern United States. (Table 2.2).

Climate has direct and indirect impacts on agriculture and the goal in this section is to provide a synthesis of the potential impacts of climate on agriculture that can be used a baseline to understand the consequences of climate variability.

**Table 2.1. Non-Federal grazing land**

| | **Rangeland** | **Pastureland** (millions of acres) | **Grazed Forest land** (millions of acres) | **Total** (millions of acres) |
|---|---|---|---|---|
| **Year:** 1982 | 415.5 | 131.1 | 64.3 | 610.9 |
| 1992 | 406.7 | 125.2 | 61.0 | 592.9 |
| 1997 | 404.9 | 119.5 | 58.0 | 582.4 |
| 2001 | 404.9 | 119.2 | 55.2 | 579.3 |
| 2003 | 405.1 | 117.0 | 54.3 | 576.4 |

**Table 2.1**. Non-federal grazing land (in millions of acres). Source: www.nrcs.usda.gov/technical/land/nri03/national_landuse.html

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**Table 2.2. Changes in pasturelands**

| | 1982 | 1992 | 2003 |
|---|---|---|---|
| Arkansas-White-Red | 18.6 | 19.0 | 19.8 |
| California / Great Basin | 2.3 | 2.2 | 2.3 |
| Great Lakes | 5.8 | 4.7 | 4.4 |
| Lower Colorado / Upper Colorado | 0.8 | 0.9 | 0.9 |
| Lower Mississippi | 5.6 | 5.4 | 5.0 |
| Missouri | 20.4 | 19.2 | 18.0 |
| New England / Mid Atlantic | 7.4 | 6.3 | 5.6 |
| Ohio / Tennessee River | 20.9 | 19.8 | 17.7 |
| Pacific Northwest | 4.6 | 4.7 | 4.3 |
| Souris- Red-Rainy / Upper Mississippi | 14.5 | 12.7 | 11.7 |
| South Atlantic-Gulf | 15.5 | 15.9 | 13.9 |
| Texas- Gulf / Rio Grande | 14.7 | 14.4 | 13.4 |
| | 131.1 | 125.2 | 117.0 |

**Table 2.2.** Changes in pasturelands by major water resource areas (in millions of acres). Source: www.nrcs.usda.gov/technical/land/nri03/national_landuse.html

Temperature changes will affect U.S. agriculture. There are direct effects of temperature on crop and livestock production. In these analyses, a 0.8 ºC temperature increase was assumed to be consistent with projections for the United States for the next 30 years as reported in Intergovernmental Panel on Climate Change (IPCC) 2001. There is certainty in this degree of change over the next 30 years, although regional differences will vary. This value represents one of several potential scenarios for temperature change and characterizes the mid-range of the values. If temperature increases are less than this value, some effects will not be realized within the next decades; however, if this value is conservative, then impacts on agriculture will be hastened. Temperature ranges selected in the analyses for the various crops and livestock were based on reported temperature ranges from NOAA records across the United States. Further changes in climate beyond these 30 years are expected, and it is important to realize that long-term climate impact on agriculture and regional variations will occur.

A major temperature effect will be increased likelihood of extreme events, which will have local and regional effects on agricultural systems. Precipitation is critical to agriculture, and regional differences in the changes in precipitation patterns are likely to occur. Changes in $CO_2$ have occurred during the past 100 years, and continued increases in $CO_2$ concentrations are expected. For the analyses below, we used the expected values reported by IPCC (2001).

## 2.2 Key Points from the Literature

Crop species differ in their cardinal temperatures (critical temperature range) for life cycle development. There is a base temperature for vegetative development at which growth commences, and an optimum temperature at which the plant progresses as fast as possible. Temperatures above the optimum cause the growth rate to slow and finally

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cease at the maximum temperature. Progression of a crop through its life cycle (phenological) phases is accelerated by increasing temperature up to the species-dependent optimum temperature beyond which development rate slows. Faster development of non-perennial crops is not necessarily ideal because a shorter life cycle results in smaller plants, shorter reproductive phase duration, and lower yield potential. Because of this, the optimum temperature for yield is nearly always lower than the optimum temperature for leaf appearance rate, vegetative growth, or reproductive progression. Temperature affects crop life cycle duration and the fit of given cultivars to production zones. Higher temperatures during the reproductive stage of development affect pollen viability, fertilization, and grain or fruit formation. Chronic exposures to high temperatures during the pollination stage of initial grain or fruit set will reduce yield potential. Exposure to extremely high temperatures during these phases can impact growth and yield; however, acute exposure from extreme events may be most detrimental during the reproductive stages of development.

For most perennial temperate fruit and nut crops, winter temperatures play a significant role in productivity. There is considerable genotypic variation among fruit and nut crops in their winter hardiness (ability to survive specific low temperature extremes), and variation in their "winter chilling" requirement for optimum flowering and fruit set in the spring and summer. Marketable yield of horticultural crops is highly sensitive to minor environmental stresses, related to temperatures outside of the optimal range, which negatively affect visual and flavor quality.

Reviews of the early enclosure $CO_2$ studies indicate that the average yield increase over many C3 crops with doubling of $CO_2$ was reported to be 33 percent (Kimball, 1983), at a time when doubling meant increase from 330 to 660 ppm $CO_2$. The general phenomenon was expressed as increased number of tillers-branches, panicles-pods, and numbers of seeds, with minimal effect on seed size. The C4 species response to doubling of $CO_2$ was reported to be 10 percent (Kimball, 1983). High temperature stress during reproductive development can negate $CO_2$ beneficial effects on yield even though total biomass accumulation maintains a $CO_2$ benefit (e.g., for *Phaseolus* bean, Jifon and Wolfe 2000). Unrestricted root growth, optimum fertility, and excellent control of weeds, insects, and disease are also required to maximize $CO_2$ benefits (Wolfe, 1994). Most C3 weeds benefit more than C3 crop species from elevated $CO_2$ (Ziska, 2003). The literature suggests that increasing temperatures are likely to increase ET; at the same time, increasing $CO_2$ will decrease stomatal conductance so as to decrease ET by about same amount that temperature would raise it, resulting in little net effect.

The response of pasture species to climate change variables including atmospheric $CO_2$ concentration, temperature, and precipitation is uncertain and will likely be complex. In in addition to the main climatic drivers, other plant and management factors will influence future pasture-yield response (e.g., plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions). Elevated $CO_2$ will likely result in a positive growth response in many but not all pasture species, to an extent consistent with the general response of C3 and C4 vegetation to elevated $CO_2$. C3 pasture species such as Italian ryegrass, orchardgrass, rhizoma peanut, tall fescue, and timothy almost certainly

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will exhibit increased photosynthetic rates under elevated $CO_2$. The C3 grasses Kentucky bluegrass and perennial ryegrass and the C4 species bahiagrass are unlikely to respond strongly to elevated atmospheric $CO_2$.

Water availability exerts primary control on productivity and plant species composition of rangelands. $CO_2$ enrichment, altered precipitation regimes, and higher temperatures, influence water balance, and thus likely will affect plant productivity and species composition. Plant productivity of most U.S. rangelands has likely increased (perhaps by >20 percent) as a result of the 285 to 380 ppm increase in $CO_2$ over the past 200 years. Productivity will likely continue to increase in many rangelands during the next 30 years if, as predicted, atmospheric $CO_2$ climbs to ~440 ppm and average temperatures increase ~ 1 ºC during this time. Global change, particularly rising atmospheric $CO_2$, has already caused important shifts in species composition of rangelands. Such species changes likely will have as much or more impact on the ecology and utility of rangeland ecosystems than changes in net primary productivity (NPP). Warmer temperatures likely will lengthen growing seasons and affect development rates of individual species, but effects of warming will vary among species.

Animal response to climate varies according to the type of thermal challenge: short-term adaptive changes in behavioral, physiological, and immunological functions (survival-oriented) are the initial responses to acute events, while longer-term challenges impact performance-oriented responses (e.g., altered feed intake and heat balance, which affect growth, reproduction, and efficiency). Within limits, domestic livestock can likely cope with many acute thermal challenges through short-term acclimation and possibly subsequent compensatory mechanisms. Chronic challenges may require more fundamental responses, such as genetic adaptation and/or alteration. Combined temperature-humidity and other thermally-based indices are beneficial in assessing the impact of environmental stressors on domestic livestock. These indices serve as guides for strategic management decisions by characterizing past events, and provide guidance for tactical actions based on the intensity and duration of current adverse events.

## 2.3 Summary of Findings and Conclusions

Based on climate model predictions, temperature increases in the central United States are projected to create summer-time losses by 2040 of $12.4 million, $43.9 million, and $37 million dollars annually for confined swine, beef and dairy animals, respectively. These losses are a result of reductions in performance associated with lower feed intake and increases in maintenance energy requirements. Notably, these losses do not account for increased livestock mortality associated with major adverse weather events, which can exceed $25 million per event. Across the entire United States, the percent increase in days to market for swine and beef, and the percent decrease in dairy milk production for the 2040 climate scenario averaged 1.2 percent, 2.0 percent, and 2.2 percent, respectively, using a Canadian climate model, and 0.9 percent, 0.7 percent, and 2.1 percent, respectively, using a U.K. climate model. Pregnancy rates of *Bos taurus* cattle may be reduced by up to 3.2 percent for each increase in the average breeding season

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temperature-humidity index above 70, and decrease by 3.5 percent for each increase in average temperature above 23.4°C.

An analysis of crop responses to temperatures suggests that a 0.8ºC rise in temperature over the next 30 years will decrease corn, wheat, sorghum, dry bean, rice, cotton, and peanut yields by 2.5, 4.4, 6.2, 6.8, 8.0, 3.5, and 3.3 percent, respectively, in their regions of production. It is estimated that a 0.8ºC temperature rise will increase soybean yield 1.7 percent in the Midwest, but decrease yield by 2.4 percent in the South where mean air temperature during reproductive growth is 4ºC higher.

Increases in $CO_2$ from 380 to 440 ppm will increase corn and sorghum yield 1 percent, whereas the yield of the other C3 crops will increase 6.1 to 7.4 percent. Cotton is more responsive to increased $CO_2$ than other major C3 crops. Most C3 weeds are also highly responsive to $CO_2$ and may be more resistant to control by herbicides as $CO_2$ levels continue to rise. Benefits of $CO_2$ rise will offset decreases from rising temperature, giving a net yield increase for most C3 crops (average 3.5 percent, range -1.6 to +9.1 percent), but negative responses for corn (-1.5 percent) and sorghum (-5.2 percent).

As temperature rises and weather variability and drought periods increase, crops will be more frequently exposed to daily maximum temperatures above 33ºC, a point at which pollination and grain-set processes in most crops began to fail, and quality of horticultural crops can be negatively affected. Grain yield is reduced as a result of decreased grain-set, and shortened duration of grain fill. Regional climate variability will augment variation in crop production between regions during the growing season.

Causes for yield decline with rising temperature include decreased grain-set and shorter duration of grain fill, or reduced marketable yield of horticultural crops because of reduced quality. Pollination, grain-set processes, and fruit quality of horticultural crops are affected as daily maximum temperature rises above 33ºC, a situation that will occur more frequently during episodes of drought stress and increased weather variability. Crop water use (requirement) will increase 1.2 percent from a 0.8ºC temperature rise, and reduced 1.4 to 2.1 percent by the rise in $CO_2$ from 380 to 440 ppm, giving a net 0.2 to 0.9 percent reduction in water requirement for irrigated crops. For rainfed crops, this increment of water conservation would enhance yields an additional 0.2 to 0.9 percent, depending on rainfall variability and rainfall amount.

Warmer winters could negatively affect the yields of some temperate fruit crops that require an extended “winter chill” period for maximum flowering. Also, more variable winter temperatures can lead to premature leaf-out or bloom and subsequent frost damage in perennial crops.

Increased winter temperatures will allow increased winter survival and earlier seasonal onset of insect pests in northern regions. Pathogens will likely tend to increase in regions where warmer, wetter summer conditions prevail, and will likely decline in regions that become drier. As climate zones shift, the potential habitable zone of weed, insect, and disease could shift northward.

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The IPCC forecasts that ozone levels will continue to rise in the rural Midwest by about 0.5 ppb per year. This suggests that yields of soybean and other sensitive C3 crops (wheat, oats, French and snap bean, pepper, canola, and various cucurbits) may continue to decline by 1 percent every two to four years. However, this may be partially offset by rising $CO_2$. C4 crops are, in general, much less sensitive to ozone.

In general, pasture species have been less studied than cropland species in terms of their response to climate change variables, including atmospheric $CO_2$ concentration, temperature, and precipitation. The response of pasturelands to climate change might be complex because, in addition to the main climatic drivers, other plant and management factors might also influence the response (e.g., plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions). C3 pasture species such as Italian ryegrass, orchardgrass, rhizoma peanut, tall fescue, and timothy have exhibited increased photosynthetic rates under elevated $CO_2$. Other studies suggest that Kentucky bluegrass might be at the lower end of the range in the responsiveness of C3 grasses to elevated $CO_2$, especially under low nutrient conditions. Perennial ryegrass has shown a positive response in terms of photosynthetic rate but a low or even negative response in terms of plant yield. The C4 pasture species bahiagrass, an important pasture species in Florida, appears marginal in its response to elevated $CO_2$.

Shifts in optimal temperatures for photosynthesis appear very likely under elevated $CO_2$. Species like perennial ryegrass and tall fescue very likely will show a downward shift in their optimal temperatures for photosynthesis. The literature is sparse on the prediction of yield change of pastureland species under a future temperature increase of 0.8 °C. Increases in increases in temperature and the lengthening of the growing season very likely will extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season.

Water availability very likely will play a major role in the response of pasturelands to climate change. Dallisgrass appears to withstand conditions of moisture stress under elevated $CO_2$ more readily than under ambient conditions. Simulation modeling of the response of alfalfa yields to climate change suggests that future alterations in precipitation will be very important in determining yields. Roughly, for every 4 mm increase in annual precipitation, the models predict a 1 percent increase in dryland alfalfa yields.

Water availability exerts primary control on productivity and plant species composition of rangelands, each of the global changes, $CO_2$ enrichment, altered precipitation regimes, and higher temperatures affect plant productivity and species composition by altering the water balance. Plant productivity in most U.S. rangelands has likely increased at least 20 percent due to increases in $CO_2$ from 285 to 380 ppm over the past 200 years, and will continue to increase in the next 30 years when atmospheric $CO_2$ is predicted to reach 440 ppm and average temperatures increase approximately 1 ºC. Climate change, particularly rising atmospheric $CO_2$, has already caused important shifts in species composition of rangelands and may impact forage quality. Warmer temperatures are certain to lengthen growing seasons and affect development rates of individual species, with variable and mostly unpredictable outcomes in regards to the future importance of all species,

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depending in large part on changes in the synchronization of resource acquisition and reproductive events among species.

## 2.4 Observed Changes and Responses

### 2.4.1 Scope of the Agricultural Systems

Agriculture is a diverse system that covers a wide range of species and production systems across the United States. The scope of this report covers those species in which information is available from the literature to evaluate observed responses. In the crops section, the focus is on maize (corn), soybean (*Glycine max* (L.) Merr.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* (L.) Moench.), cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogea* L.), red kidney bean (*Phaseolus vulgaris* var. *vulgaris*), cowpea (*Vigna unguiculata* (L.) Walp.), and tomato (*Lycopersicon esculentum* Mill.). In the pastureland section, 13 species were considered in the analysis. For rangeland, species covered include a complex mixture of grasses and forbs, depending upon the location.

Animal production systems cover beef, dairy, swine, and poultry as the primary classes of animals. While climate changes affects all of these animals, the literature available predominantly addresses beef, dairy, and swine. Poultry is primarily grown under confined operations, so the effect of climate change more directly affects the energy requirements for building operations compared to a direct effect on the animal. Similar statements can be made for swine production since the vast majority of the production is under confinement. There is an effect of temperature on animals being moved from confinement buildings to processing plants; however, the short-term effects of stress on these animals has not been studied and is not considered a major problem because these animals are being moved quickly from production to processing.

### 2.4.2 Plant Response to Temperature

#### *1.1.1.1 General response*

Crop species differ in their cardinal temperatures (critical temperature range) for life cycle development. There is a base temperature for vegetative development at which growth commences and an optimum temperature at which the plant progresses as fast as possible. Temperatures above the optimum cause the growth rate to slow and finally cease at the maximum temperature. Vegetative development (node and leaf appearance rate) is hastened by increasing temperature up to a species optimum temperature. Vegetative development usually has a higher optimum temperature than does reproductive development (Table 2.3). Progression of a crop through its life cycle (phenological) phases is generally accelerated by increasing temperature up to the species-dependent optimum temperature beyond which development rate slows. Cardinal temperature values for selected annual (non-perennial) crops are presented in Tables 2.3 and 2.4 for conditions in which temperature is the only limiting variable.

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**Table 2.3. Cardinal base and optimum temperatures**

| Crop | Base Temp Veg | Opt Temp Veg | Base Temp Repro | Opt Temp Repro | Opt Temp Range Veg Prod | Opt Temp Range Reprod Yield | Failure Temp Reprod Yield |
|---|---|---|---|---|---|---|---|
| Maize | 8[1] | 34[1] | 8[1] | 34[1] | | 18-22[2] | 35[3] |
| Soybean | 7[4] | 30[4] | 6[5] | 26[5] | 25-37[6] | 22-24[6] | 39[7] |
| Wheat | 0[8] | 26[8] | 1[8] | 26[8] | 20-30[9] | 15[10] | 34[11] |
| Rice | 8[12] | 36[13] | 8[12] | 33[12] | 33[14] | 23-26[13,15] | 35-36[13] |
| Sorghum | 8[16] | 34[16] | 8[16] | 31[17] | 26-34[18] | 25[17,19] | 35[17] |
| Cotton | 14[20] | 37[20] | 14[20] | 28-30[20] | 34[21] | 25-26[22] | 35[23] |
| Peanut | 10[24] | >30[24] | 11[24] | 29-33[25] | 31-35[26] | 20-26[26,27] | 39[26] |
| Bean | | | | | 23[28] | 23-24[28,29] | 32[28] |
| Tomato | 7[30] | 22[30] | 7[30] | 22[30] | | 22-25[30] | 30[31] |

**Table 2.3.** Cardinal base and optimum temperatures (ºC) for vegetative development and reproductive development, optimum temperature for vegetative biomass, optimum temperature for maximum grain yield, and failure (ceiling) temperature at which grain yield fails to zero yield, for economically important crops. The optimum temperatures for vegetative production, reproductive (grain) yield, and failure point temperatures represent means from studies where diurnal temperature range was up to 10ºC.

[1]Kiniry and Bonhomme (1991), Badu-Apraku et al., 1983; [2]Muchow et al. (1990); [3]Herrero and Johnson (1980); [4]Hesketh et al. (1973); [5]Boote et al. (1998); [6]Boote et al. (1997); [7]Boote et al. (2005); [8]Hodges and Ritchie (1991); [9]Kobza and Edwards (1987); [10]Chowdury and Wardlaw (1978); [11]Tashiro and Wardlaw (1990); [12]Alocilja and Ritchie (1991); [13]Baker et al. (1995); [14]Matsushima et al. (1964); [15]Horie et al. (2000); [16]Alagarswamy and Ritchie 1991); [17]Prasad et al. (2006a); [18]Maiti (1996); [19]Downs (1972); [20]K. R. Reddy et al. (1999, 2005); [21]V. R. Reddy et al. (1995); [22]K. R. Reddy et al. (2005); [23]K. R. Reddy et al. (1992a, 1992b); [24]Ong (1986); [25]Bolhuis and deGroot (1959); [26]Prasad et al. (2003); [27]Williams et al. (1975); [28]Prasad et al. (2002); [29]Laing et al. (1984); [30]Adams et al. (2001); [31]Peat et al. (1998).

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**Table 2.4. Temperature thresholds for selected vegetable crops**

| Climatic Classification | Crop | Acceptable Temp (C) For Germination | Opt Temp (C) For Yield | Acceptable Temp(C) Growth Range | Frost Sensitivity |
|---|---|---|---|---|---|
| Hot | Watermelon | 21-35 | 25-27 | 18-35 | + |
| | Okra | 21-35 | 25-27 | 18-35 | + |
| | Melon | 21-32 | 25-27 | 18-35 | + |
| | Sweet Potato | 21-32 | 25-27 | 18-35 | + |
| Warm | Cucumber | 16-35 | 20-25 | 12-30(35) | + |
| | Pepper | 16-35 | 20-25 | 12-30(35) | + |
| | Sweet corn | 16-35 | 20-25 | 12-30(35) | + |
| | Snap bean | 16-30 | 20-25 | 12-30(35) | + |
| | Tomato | 16-30 | 20-25 | 12-30(35) | + |
| Cool-Warm | Onion | 10-30 | 20-25 | 7-30 | - |
| | Garlic | | 20-25 | 7-30 | - |
| | Turnip | 10-35 | 18-25 | 5-25 | - |
| | Pea | 10-30 | 18-25 | 5-25 | (-) |
| Cool | Potato | 7-26 | 16-25 | 5-25(30) | + |
| | Lettuce | 5-26 | 16-25 | 5-25(30) | (+) |
| | Cabbage | 10-30 | 16-18(25) | 5-25 | - |
| | Broccoli | 10-30 | 16-18(25) | 5-25 | - |
| | Spinach | 4-16 | 16-18(25) | 5-25 | - |

**Table 2.4.** Temperature thresholds for selected vegetable crops. Values are approximate and for relative comparisons among groups only. For frost sensitivity: “+” = sensitive to weak frost; “-“ = relatively insensitive; “( )” = uncertain or dependent on variety or growth stage. Adapted from Krug (1997) and Rubatzky and Yamaguchi (1997).

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**Table 2.5. Winter chill requirement, winter hardiness (minimum winter temperature), and minimum frost-free period**

| Crop | Winter Chill Requirement (hours )[1] | | Minimum Winter Temp (C) | Minimum Frost-Free Period (days) |
|---|---|---|---|---|
| | Common Varieties | Other | | |
| Almond | 100-500 | | -10 | >180 |
| Apple | 1000-1600 | 400-1800 | -46 to -4 | <100 (+) |
| Blueberry | 400-1200 (northern highbush) | 0-200 | -35 to -12 | <100 (+) |
| Cherry | 900-1200 | 600-1400 | -29 to -1 | <100 (+) |
| Citrus | 0 | | -7 to 4 | >280 |
| Grape (European) | 100-500 | | -25 to 4 | >120 |
| Grape (American) | 400-2000 (+) | | -46 to -12 | <100 (+) |
| Peach | 400-800 | 200-1200 | -29 to 4 | >120 |
| Pear | 500-1500 | | -35 to -1 | >100 |
| Pecan | 600-1400 | | -10 | >180 |
| Pistachio | 600-1500 | 400-600 (Asian) | -10 | >180 |
| Plum | 800-1200 | 500-600 (Japanese) | -29 to 4 | >140 |
| Raspberry | 800-1700 | 100-1800 | -46 (+) | <100 (+) |
| Strawberry | 300-400 | | -12 | <100 (+) |
| Walnut | 400-1500 | | -29 | >100 |

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**Table 2.5.** Winter chill requirement, winter hardiness (minimum winter temperature), and minimum frost-free period (growing season requirements) for selected woody perennial fruit and nut crops. Not shown in this table is the fact that flowers and developing fruit of all crops are sensitive to damage from mild to moderate frosts (e.g., 0 to -5 ºC), and high temperature stress (e.g., > 35 ºC), specific damaging temperatures varying with crop and variety. Values are approximate and for relative comparisons only. Adapted from Westwood (1993).

Faster development of non-perennial crops is not necessarily ideal because a shorter life cycle results in smaller plants, shorter reproductive phase duration, and lower yield potential. Because of this, the optimum temperature for yield is nearly always lower than the optimum temperature for leaf appearance rate, vegetative growth, or reproductive progression. In addition, temperatures that fall below or above specific thresholds at critical times during development can have a significant impact on yield. Temperature affects crop life cycle duration and the fit of given cultivars to production zones. Daylength sensitivity also plays a major role in life cycle progression in many crops,

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[1] Winter chilling for most fruit and nut crops occurs within a narrow temperature range of 0 to 15 ºC, with maximum chill-hour accumulation at about 7.2 ºC. Temperatures below or above this range to not contribute to chilling requirement, and temperatures above 15 ºC may even negate previously accumulated chill.

especially for soybean. Higher temperatures during the reproductive stage of development affect pollen viability, fertilization, and grain or fruit formation. Chronic exposure to high temperatures during the pollination stage of initial grain or fruit set will reduce yield potential. This stage of development is one of the most critical stages of growth in response to temperatures extremes. Each crop has a specific temperature range for vegetative and reproductive growth to proceed at the optimal rate and exposures to extremely high temperatures during these phases can impact growth and yield; however, acute exposure from extreme events may be most detrimental during the reproductive stages of development.

For most perennial temperate fruit and nut crops, winter temperatures play a significant role in productivity (Westwood, 1993). There is considerable genotypic variation among fruit and nut crops in their winter hardiness (ability to survive specific low temperature extremes), and variation in their "winter chilling" requirement for optimum flowering and fruit set in the spring and summer (Table 2.5). Marketable yield of horticultural crops is highly sensitive to minor environmental stresses, related to temperatures outside of the optimal range, which negatively affect visual and flavor quality (Peet and Wolfe, 2000).

#### *1.1.1.2 Temperature effects on crop yield*

Yield responses to temperature vary among species based on the crop's cardinal temperature requirements. Plants that have an optimum range at cooler temperatures will exhibit significant decreases in yield as the temperature increases above this range. However, reductions in yield with increasing temperature in field conditions may not be due to temperature alone, as high temperatures are often associated with lack of rainfall in many climates. The interactions of temperature and water deficits negatively affect crop yield.

***Maize***

Increasing temperature causes maize life cycle and the reproductive phase duration to be shortened, resulting in decreased grain yield (Badu-Apraku et al., 1993; Muchow et al., 1990). In the analyses of Muchow et al. (1990), the highest observed (and simulated) grain yields occurred at locations with relatively cool temperature (growing season mean of 18.0 to 19.8ºC at Grand Junction, CO) that allowed long maize life cycle, compared to warmer sites (e.g., 21.5 to 24.0ºC in Champaign, IL), or compared to warm tropical sites (26.3 to 28.9ºC). For the IL location, simulated yield decreased 5 to 8 percent per 2ºC temperature increase. Using this relationship, a temperature rise of 0.8ºC over the next 30 years in the Midwest may decrease yield by 2 to 3 percent (2.5 percent, Table 6) under irrigated or water-sufficient management. The Muchow et al. (1990) model may underestimate yield reduction with rising temperature because it had no temperature modification on assimilation or respiration, and did not provide for any failures in grain-set with rising temperature. Lobell and Asner (2003) evaluated maize and soybean production relative to climatic variation in the United States, reporting a 17 percent reduction in yield for every 1ºC rise in temperature because of the confounding effect with other yield-limiting factors. In a recent evaluation of global maize production response to both temperature and rainfall over the period 1961-2002, Lobell and Field

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(2007) reported 8.3 percent yield reduction per 1ºC rise in temperature. Runge (1968) documented maize yield responses to the interaction of daily maximum temperature and rainfall during the period 25 days prior and 15 days after anthesis of maize. If rainfall was low (zero to 44mm per 8 days), yield was reduced by 1.2 to 3.2 percent per 1ºC rise. Alternately, if temperature was warm (Tmax of 35ºC), yield was reduced 9 percent per 25.4 mm rainfall decline.

**Table 2.6. Percent grain yield response to increased temperature**

| Crop | Temperature (0.8 ºC) | $CO_2$ (380 to 440 ppm)[2] | Temp/$CO_2$ Combined Irrigated | Temp on ET of Rainfed | $CO_2$ on ET of Rainfed |
|---|---|---|---|---|---|
| | % change | | | | |
| Corn -Midwest (22.5ºC) | -2.5 | +1.0 | -1.5 | +1.2[3] | |
| Corn - South (26.7ºC) | -2.5 | +1.0 | -1.5 | +1.2[3] | |
| Soybean – Midwest (22.5ºC) | +1.7 | +7.4 | +9.1 | +1.2[3] | -2.1 |
| Soybean – South (26.7ºC) | -2.4 | +7.4 | +5.0 | +1.2[3] | -2.1 |

**Table 2.6.** Percent grain yield response to increased temperature (0.8 ºC), increased $CO_2$ (380 to 440 ppm), net effect of temperature and increased $CO_2$ on irrigated yield assuming additivity, and change in ET of rainfed crops with temperature and $CO_2$. Current mean air temperature during reproductive growth is shown in parentheses for each crop/region to give starting reference, although yield of all the cereal crops declines with a temperature slope that originates below current mean air temperatures during grain filling.

Yield decreases caused by elevated temperatures are related to temperature effects on pollination and kernel set. Temperatures above 35ºC are lethal to pollen viability (Herrero and Johnson, 1980; Schoper et al., 1987: Dupuis and Dumas, 1990). In addition, the critical duration of pollen viability (prior to silk reception) is a function of pollen moisture content, which is strongly dependent on vapor pressure deficit (Fonseca and Westgate, 2005). There is limited data on sensitivity of kernel set in maize to elevated temperature, although *in-vitro* evidence suggests that the thermal environment during endosperm cell division phase (eight to 10 days post-anthesis) is critical (Jones et al., 1984). A temperature of 35ºC compared to 30ºC during the endosperm division phase dramatically reduced subsequent kernel growth rate (potential) and final kernel size, even if placed back in 30ºC (Jones et al. 1984). Temperatures above 30ºC increasingly damaged cell division and amyloplast replication in maize kernels and thus reduced grain sink strength and yield (Commuri and Jones, 2001). Leaf photosynthesis rate of maize has a high temperature optimum of 33ºC to 38ºC with minimal sensitivity of quantum efficiency to elevated temperature (Oberhuber and Edwards, 1993; Edwards and Baker,

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[2] Response to $CO_2$ increment, with Michaelis-Menten rectangular hyperbola interpolation.

[3] Response of ET to temperature increment 1.489 x 0.8°C from Table 6.

1993), although photosynthesis rate is reduced above 38ºC (Crafts-Brandner and Salvucci, 2002).

***Soybean***

Reproductive development (time to anthesis) in soybean has cardinal temperatures that are somewhat lower, a base of 6ºC and optimum of 26ºC are used in the CROPGRO-soybean model (Boote et al., 1998), based in part on values of 2.5ºC and 25.3ºC developed by Grimm et al. (1993). The post-anthesis phase for soybean has a surprisingly low optimum temperature of about 23ºC and life cycle is slower and longer if mean daily temperature is above 23ºC (Pan, 1996; Grimm et al. 1994). This 23ºC optimum cardinal temperature for post-anthesis period matches closely to the optimum temperature for single seed growth rate (23.5ºC) reported by Egli and Wardlaw (1980), and the 23ºC optimum temperature for seed size (Egli and Wardlaw, 1980, Baker et al. 1989; Pan, 1996; Thomas, 2001; Boote et al. 2005). As mean temperature increases above 23ºC, seed growth rate, seed size, and intensity of partitioning to grain (seed harvest index) in soybean decrease until reaching zero at 39ºC mean (Pan, 1996; Thomas, 2001). The CROPGRO-soybean model parameterized with the Egli and Wardlaw (1980) temperature effect on seed growth sink strength and the Grimm et al. (1993, 1994) temperature effect on reproductive development, predicts highest grain yield of soybean at 23-24ºC, with progressive decline in yield, seed size, and harvest index as temperature increases further until reaching zero yield at 39ºC (Boote et al. 1997, Boote et al. 1998). Soybean yield produced per day of season, when plotted against the mean air temperature at 829 sites over the United States (soybean regional trials, Piper et al. 1998) showed highest productivity at 22ºC.

Pollen viability of soybean is reduced by instantaneous temperatures above 30ºC (Topt), but with a long decline slope to failure at 47ºC (Salem et al. 2007). Averaged over many cultivars, the cardinal temperatures (base temperature (Tb), optimum temperature (Topt), maxiumu temperature (Tmax)) were 13.2ºC, 30.2ºC, and 47.2ºC, respectively, for pollen germination and 12.1ºC, 36.1ºC, and 47.0ºC, respectively, for pollen tube growth. Minor cultivar differences in cardinal temperatures and tolerance of elevated temperature were present, but differences were not very large or meaningful. Salem et al. (2007) evaluated soybean grown and assayed at 38/30ºC versus 30/22ºC (day/night) temperatures. The elevated temperature reduced pollen production 34 percent, pollen germination by 56 percent, and pollen tube elongation by 33 percent. The progressive reduction in seed size (single seed growth rate) above 23ºC, along with reduction in fertility above 30C, results in reduction in seed harvest index (HI) at temperatures above 23ºC (Baker et al.1989) or above 27ºC, reaching zero HI at 39ºC (Pan, 1996, Thomas, 2001, Boote et al. 2005).

The implication of a temperature change on soybean yield is thus strongly dependent on the prevailing mean temperature during the post-anthesis phase of soybean in different regions. For the upper Midwest, where mean soybean growing season temperatures are about 22.5ºC, soybean yield may actually increase (1.7 percent) with a 0.8ºC rise (Table 6). By contrast, for soybean production in the southern United States where mean growing season temperatures are 25ºC to 27ºC, the soybean yield would be progressively reduced, 2.4 percent for 0.8ºC increase from 26.7ºC current mean (Table 2.6). These slopes of soybean yield response to temperature were taken from Figs. 2.10-11 of Boote et al. (1997) and Figure 2.5 of Boote et al. (1996). Lobell and Field (2007) reported a 1.3 percent decline in soybean yield per 1ºC increase in temperature, taken from global production against global average temperature during July-August, weighted by production area.

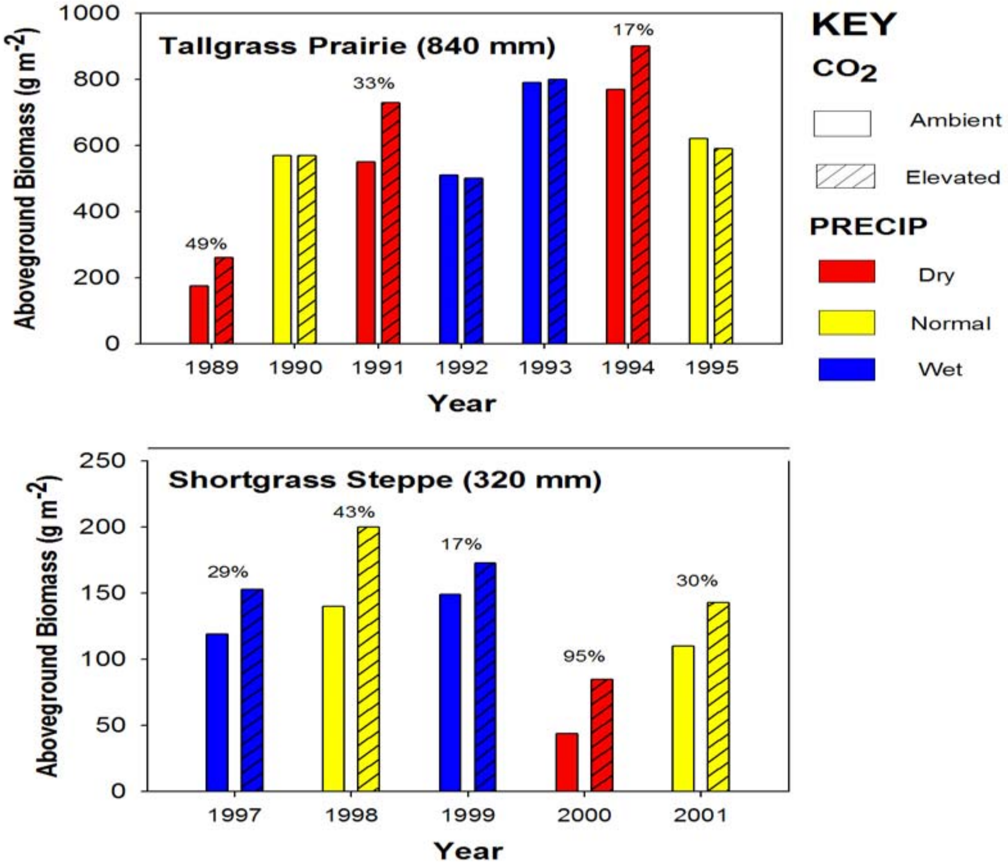

**Figure 2.10**. Aboveground plant biomass harvested during summer at the approximately time of peak seasonal aboveground plant biomass from native Kansas tallgrass prairie (Owensby et al., 1999; 1989-1995) and Colorado Shortgrass steppe (Morgan et al., 2004a; 1997-2001) grown in similarly-designed Open Top Chambers maintained at present Ambient (approximately 370 parts per million $CO_2$ in air; no cross-hatches) and Elevated (approximately 720 parts per million $CO_2$ in air; cross-hatches) atmospheric $CO_2$ concentrations. Histograms from different years are color-coded (red for dry; yellow for normal; blue for wet) according to the amount of annual precipitation receive that particular year compared to long-term averages for the two sites, 840 mm for the tallgrass prairie and 320 mm for shortgrass steppe. Where production increases due to elevated $CO_2$ were observed, the percentage increased production is given within a year above the histograms. The involvement of water in the $CO_2$ responses is seen in two ways; the relative plant biomass responses occur more commonly and in greater magnitude in the shortgrass steppe than in the tallgrass prairie, and the relative responses in both systems are greater in dry than wet years.

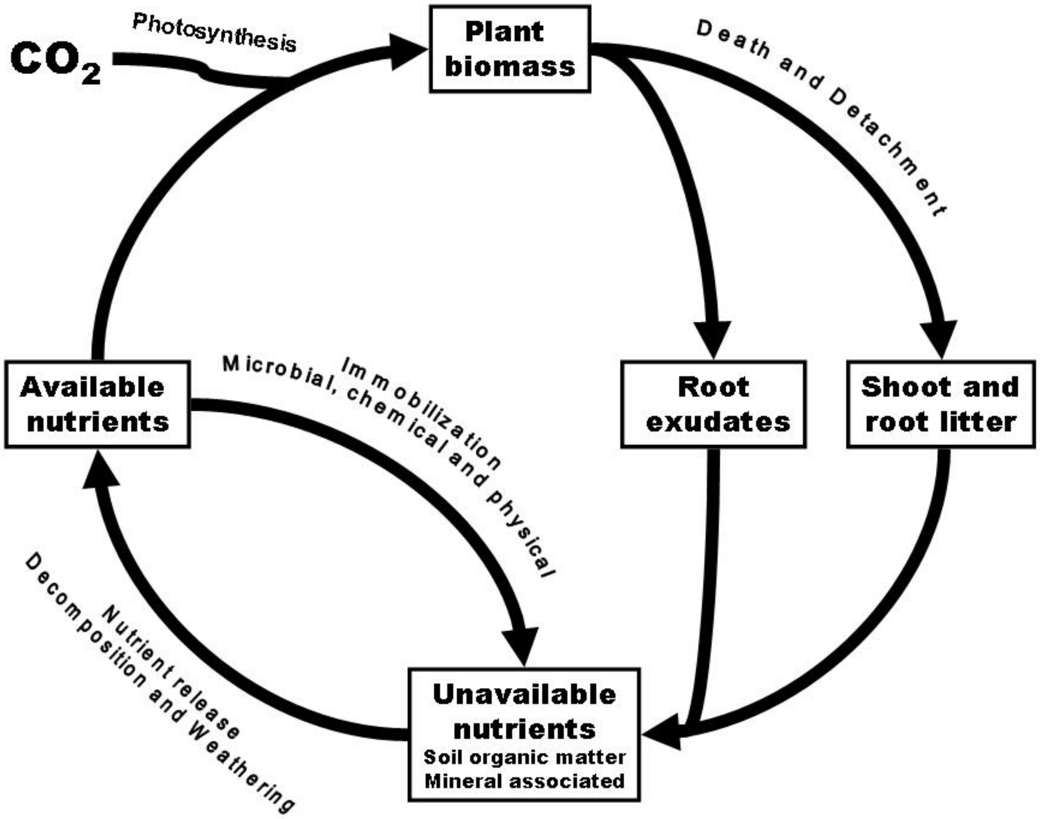

**Figure 2.11** Nutrient Cycling Feedbacks. While $CO_2$ enrichment may lead to increased photosynthesis and enhanced plant growth, the long-term response will depend on nutrient cycling feedbacks. Litter from decaying plants and root exudates enters a large soil nutrient pool that is unavailable to plants until they are broken down and released by microbial activity. Soil microbes may also fix available nutrients into new microbial biomass, thereby temporarily immobilizing them. The balance between these and other nutrient release and immobilization processes determines available nutrients and ultimate plant response.

Source: Figure reprinted with permission from *Science* (Morgan, 2002).

### *Wheat*

Grain-filling period of wheat and other small grains is dramatically shortened with rising temperature (Sofield et al., 1974, 1977; Chowdhury and Wardlaw, 1978; Goudrian and Unsworth, 1990). Sofield et al. (1974, 1977) attributed the shortened grain filling duration to factors other than assimilate limitation (documented by sink removal studies). Assuming no difference in daily photosynthesis, yield will decrease in direct proportion to the shortening of grain filling period as temperature increases. This temperature effect is already a major reason for the much higher wheat yield potential in northern Europe than in the Midwest (even with the water limitation removed).

The optimum temperature for photosynthesis in wheat is 20-30ºC (Kobza and Edwards, 1987). This is 10ºC higher than the optimum (15ºC) for grain yield and single grain growth rate (Chowdhury and Wardlaw, 1978). Any increase of temperature above 25ºC to 35ºC that are common during grain filling of wheat will reduce wheat yields because

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of shorter grain filling period. Applying the nonlinear slope of reduction in grain filling period from Chowdury and Wardlaw (1978) relative to the mean temperatures during grain fill in the wheat growing regions of the Great Plains, the reduction in yield is about 7 percent per 1ºC increase in air temperature between 18 to 21ºC and about 4 percent per 1ºC increase in air temperature above 21ºC, not considering any reduction in photosynthesis or grain-set. Similarly, Lawlor and Mitchell (2000) stated that a 1ºC rise would shorten reproductive phase by 6 percent and grain filling duration by 5 percent and reduce grain yield and HI proportionately. Bender et al. (1999) analyzed spring wheat grown at nine sites in Europe and found a 6 percent decrease in yield per 1ºC temperature rise. Lobell and Field (2007) reported a 5.4 percent decrease in global mean wheat yield per 1ºC increase in temperature. Grain size will also be reduced slightly. Effects of rising temperature on photosynthesis should be viewed as an additional reduction factor on wheat yield, primarily influenced via water deficit effects (Paulsen, 1994). Temperatures of 36/31ºC for two to three days prior to anthesis causes small unfertilized kernels with symptoms of parthenocarpy, small shrunken kernels with notching and chalking of kernels (Tashiro and Wardlaw, 1990). Increased temperature reduces starch synthesis in wheat endosperm, caused by decreased starch synthase and ADP glucose pyrophosphorylase enzyme activities (Coley et al. 1990).

### *Rice*

The response of rice to temperature has been well studied (Baker and Allen, 1993a, 1993b; Baker et al. 1995; Horie et al. 2000). Leaf-appearance rate of rice increases with temperature from a base of 8ºC, until reaching 36-40ºC (the thermal threshold of survival) (Alocilja and Ritchie, 1991; Baker et al. 1995), with biomass increasing up to 33ºC (Matsushima et al. 1964); however, the optimum temperature for grain formation and yield of rice is lower (25ºC) (Baker et al. 1995). Baker et al. (1995) summarized many of their experiments from sunlit controlled-environment chambers and concluded the optimum mean temperature for grain formation and grain yield of rice is 25ºC and grain yield is reduced about 10 percent per 1ºC temperature increase above 25ºC until reaching zero yield at 35-36ºC mean temperature, using a 7ºC day/night temperature differential (Baker and Allen, 1993a; Peng et al. 2004). Grain number, percent filled grains, and grain HI followed nearly the same optimum and failure curve points. Declining yield above 25ºC is attributed, initially, to shorter grain filling duration (Chowdhury and Wardlaw, 1978; Snyder, 2000) and then to progressive failure to produce filled grains, the latter caused by pollen viability and reduced production of pollen (Kim et al., 1996; Matsui et al., 1997; Prasad et al. 2006b). Pollen viability and production begins to decline as daytime maximum temperature (Tmax) exceeds 33ºC and reaches zero at Tmax of 40ºC (Kim et al. 1996). Because flowering occurs at mid-day in rice, the Tmax is the best indicator of heat-stress on spikelet sterility. Grain size of rice tends to hold mostly constant, declining only slowly across increasing temperature, until the pollination failure point (Baker and Allen, 1993a). Rice ecotypes, *japonica* and *indica*, mostly do not differ in the upper temperature threshold (Snyder, 2000; Prasad et al. 2006b), although the *indica* types are more sensitive to cool temperature (night temperature less than 19ºC) (Snyder, 2000). Screening of rice genotypes and ecotypes for heat tolerance (33.1/27.3ºC versus 28.3/21.3ºC mean day/night temperatures) by Prasad et al. (2006b) demonstrated significant genotypic variation in heat tolerance for percent

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filled grains, pollen production, pollen shed, and pollen viability. The most tolerant cultivar had the smallest decreases in spikelet fertility, grain yield and harvest index at elevated temperature. This increment of temperature caused, for the range of 14 cultivars, 9 to 86 percent reduction in spikelet fertility, 0 to 93 percent reduction in grain weight per panicle, and 16 to 86 percent reduction in HI. Mean air temperatures during the rice grain filling phase in summer in the southern USA and many tropical regions are about 26-27ºC which are above the 25ºC optimum, thus illustrating that elevated temperature above current will reduce rice yield in USA and tropical regions, by about 10 percent per 1ºC rise, or about 8 percent for a 0.8ºC rise.

### *Sorghum*

The base and optimum temperatures for vegetative development are 8ºC and 34ºC, respectively (Alagarswamy and Ritchie, 1991), while the optimum temperature for reproductive development is 31ºC (Prasad et al., 2006a). The optimum temperature for sorghum vegetative growth is 26ºC to 34ºC, and for reproductive growth is 25ºC to 28ºC (Maiti, 1996). Maximum dry matter production and grain yield occur at 27/22ºC, as opposed to temperatures 3ºC or 6ºC lower or 3ºC or 6ºC warmer (Downs, 1972). Grain filling duration is reduced as temperature increases over a wide range (Chowdury and Wardlaw, 1978; Prasad et al., 2006a). Nevertheless, as temperature increased above 36/26ºC to 40/30ºC (diurnal max/min), panicle emergence was delayed by 20 days, and no panicles were formed at 44/34ºC (Prasad et al., 2006a). Prasad et al. (2006a) found that grain yield, HI, pollen viability, and percent seed-set were highest at 32/22ºC and progressively reduced as temperature increased, falling to zero at 40/30ºC. Vegetative biomass was highest at 40/30ºC and photosynthesis was high up to 44/34ºC. Seed size was reduced above 36/26ºC. Rice and sorghum have exactly the same sensitivity of grain yield, seed HI, pollen viability, and success in grain formation (Prasad et al., 2006a). In addition, we suspect that maize, a related warm-season cereal, may have the same temperature sensitivity. Basing the yield response of sorghum only on shortening of filling period (Chowdury and Wardlaw, 1978), yield would decline 7.8 percnet per 1ºC temperature rise from 18.5ºC to 27.5ºC (a 6.2 percent yield reduction for 0.8ºC increase). However, if site temperature is cooler than optimum for biomass/photosynthesis (27/22ºC), then yield loss from shorter filling period would be offset by photosynthesis increase. The response from Chowdury and Wardlaw (1978) is supported by the 8.4 percent decrease in global mean sorghum yield per 1ºC increase in temperature reported for sorghum by Lobell and Field (2007).

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### *Cotton*

Cotton is an important crop in the southern United States, and is considered to have adapted to high temperature environments. Despite this perception, reproductive processes of cotton have been shown to be adversely affected by elevated temperature (Reddy et al., 2000; 2005). Being a tropical crop, cotton's rate of leaf appearance has a relatively high base temperature of 14ºC and a relatively high optimum temperature of 37ºC, thus leaf and vegetative growth appear to tolerate elevated temperature (Reddy et al., 1999, 2005). On the other hand, reproductive progression (emergence to square, square to first flower) has a temperature optimum of 28-30ºC, along with a high base temperature of about 14ºC (Reddy et al. 1997, 1999). Maximum growth rate per boll occurred at 25-26ºC, declining at higher temperatures, while boll harvest index was highest at 28ºC, declining at higher temperatures, reaching zero boll harvest index at 33-34ºC (Reddy et al. 2005). Boll size was largest at temperatures less than 20ºC, declining progressively as temperature increased. Initially there was compensation with increased boll number set as temperature increased up to 35/27ºC day/night temperature, but, above 30ºC mean temperature, percent boll set, boll number, boll filling period, rate of boll growth, boll size, and yield all decreased (Reddy et al. 2005). Instantaneous air temperature above 32ºC reduces pollen viability, and temperature above 29ºC reduces pollen tube elongation (Kakani et al. 2005), thus acting to progressively reduce successful boll formation to the point of zero boll yield at 40/32ºC day/night (35ºC mean) temperature (Reddy et al. 1992a, 1992b). These failure point temperatures are below those of soybean and peanut, but similar to those of rice and sorghum. There is not a well-defined cotton-yield response to temperature. A quadratic (parabolic) yield response to temperature from the optimum of 25ºC to the failure temperature of 35ºC was developed, where a 0.8ºC increase from 26.7 to 27.5ºC would decrease yield by 3.5 percent.

### *Peanut*

Peanut is an important crop in the southern United States. The base temperature for peanut-leaf-appearance rate and onset of anthesis are 10ºC and 11ºC, respectively (Ong, 1986). The optimum temperature for leaf appearance rate is above 30ºC, while the optimum for rate of vegetative development to anthesis is 29-33ºC (Bolhuis and deGroot, 1959). Leaf photosynthesis has a fairly high temperature optimum of about 36ºC. Cox (1979) observed that 24ºC was the optimum temperature for single pod growth rate and pod size, with slower growth rate and smaller pod size at higher temperature. Williams et al. (1975) evaluated temperature effects on peanut by varying elevation and found that peanut yield was highest at a mean temperature of 20ºC (27/15ºC max/min), a temperature that contributed to a long life cycle and long reproductive period. Prasad et al. (2003) conducted studies in sunlit, controlled-environment chambers, and reported that the optimum mean temperature for pod yield, seed yield, pod harvest index, and seed size occurred at a temperature lower than 26ºC; quadratic projections to peak and minimum suggested that the optimum temperature was 23 to 24ºC, with a failure point temperature of 40ºC for zero yield and zero HI. Pollen viability and percent seed-set in that study began to fail at about 31ºC, reaching zero at about 39 to 40ºC (44/34ºC treatment) (Prasad et al., 2003). For each individual flower, the period sensitive to elevated temperature starts six days prior to opening of a given flower and ends one day after, with greatest sensitivity on the day of flower opening (Prasad et al., 1999; Prasad et al., 2001). Percent fruit-set is first reduced at bud temperature of 33ºC, declining linearly to zero fruit-set at 43ºC bud temperature (Prasad et al., 2001). Genotypic differences in heat-tolerance of peanut (pollen viability) have been reported (Craufurd et al., 2003). As air temperature in the southern United States already averages 26.7ºC during the peanut growing season, any temperature increase will reduce seed yields (4.1 percent per 1ºC, or 3.3 percent for a 0.8ºC rise in range of 26-27ºC) using the relationship of Prasad et al. (2003). At higher temperatures, 27.5 to 31ºC, peanut yield declines more rapidly (6.9 percent per 1ºC) based on unpublished data of Boote. A recent trend in peanut production

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since the collapse of the quota system, has been the move of production from south Texas to west Texas, a cooler location with higher yield potential.

### *Dry Bean and Cowpea*

Red kidney bean is typical of many vegetable crops and is grown in relatively cool regions of the United States. Prasad et al. (2002) found that red kidney bean was quite sensitive to elevated temperature, having highest seed yield at 28/18ºC (23ºC mean) or lower (lower temperatures were not tested), with linear decline to zero yield as temperature increased to 37/27ºC (32ºC mean). In that study, pollen production per flower was reduced above 31/21ºC, pollen viability was dramatically reduced above 34/24ºC, and seed size was decreased above 31/21ºC. Laing et al. (1984) found highest bean yield at 24ºC, with a steep decline at higher temperatures. Gross and Kigel (1994) reported reduced fruit-set when flower buds were exposed to 32/27ºC during the six to 12 days prior to anthesis and at anthesis, caused by non-viable pollen, failure of anther dehiscence, and reduced pollen tube growth. Heat-induced decreases in seed and fruit set in cowpea have been associated with formation of non-viable pollen (Hall, 1992). Hall (1992) reported genetic differences in heat tolerance of cowpea lines. Screening for temperature-tolerance within bean cultivars has not been done explicitly, but the Mesoamerican lines are more tolerant of warm tropical locations than are the Andean lines, which include the red kidney bean type (Sexton et al., 1994). Taking the initial slope of decline from data of Prasad et al. (2002), bean yield is projected to decrease 7.2 percent per 1ºC temperature rise, or 5.8 percent for 0.8ºC above 23ºC.

### *Tomato*

Tomato is an important vegetable crop known to suffer heat stress in mid-summer in southern U.S. locations. The base and optimum temperature is 7º and 22ºC for rate of leaf appearance, rate of truss appearance, and rate of progress to anthesis (Adams et al., 2001). Leaf photosynthesis of tomato has a base at 6-8ºC (Duchowski and Brazaityte, 2001), while its optimum is about 30ºC (Bunce, 2000). The rate of fruit development and maturation has a base temperature of 5.7ºC and optimum of 26ºC and rate of individual fruit growth has its optimum at 22 to 25ºC (Adams et al. 2001). Largest fruit size occurs at 17-18ºC, and declines at progressively higher temperature (Adams et al. 2001, De Koning, 1996). Rate of fruit addition (fruit-set, from pollination) has an optimum at or lower than 26ºC and progressively fails as temperature reaches 32ºC (Adams et al., 2001). Peat et al. (1998) observed that number of fruits per plant (or percent fruit-set) at 32/26ºC day/night (29ºC mean) was only 10 percent of that at 28/22ºC (25ºC mean). The projected failure temperature was about 30ºC. Sato et al. (2000) found that only one of five cultivars of tomato successfully set any fruit at chronic exposures to 32/26ºC, although fruit-set recovered if the stressful temperature was relieved. Sato et al. (2000) highlighted that pollen release and pollen germination were critical factors affected by heat stress. The anticipated temperature effect on tomato production will depend on the region of production and time of sowing (in the southern United States); however, at optima of 22ºC for leaf/truss development, 22-26ºC for fruit addition, 22-25ºC for fruit growth, and fruit-set failures above 26ºC, temperatures exceeding 25ºC will reduce tomato production. Depending on region of production, tomato yield is projected to decrease 7.6 percent for 0.8ºC rise above 25ºC, assuming a parabolic yield response and

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assuming optimum temperature and failure temperatures for yield of 23.5 and 30ºC, respectively.

### *Pasturelands*

In general, grassland species have received less attention than cropland species in terms of their response to projected changes in temperature, precipitation and atmospheric $CO_2$ concentration associated with climate change (Newman et al. 2001). The response of pasturelands to climate change is complex because, in addition to the major climatic drivers ($CO_2$ concentration, temperature, and precipitation), other plant and management factors will affect this response (e.g., plant competition, perennial growth habits, seasonal productivity, etc.). Many of the studies presented below, which report on how temperate-climate pasture respond to changes in temperature, precipitation and $CO_2$ concentrations, originate from regions outside the United States.

### *Rangelands*

Although responses can be vary considerably among species, in general warming should accelerate plant metabolism and developmental processes, leading to earlier onset of spring green-up, and lengthening of the growing season in rangelands (Badeck et al. 2004). The effects of warming are also likely to be seen as changes in the timing of phenological events such as flowering and fruiting. For instance, experimental soil warming of approximately 2ºC in a tallgrass prairie (Wan et al. 2005) extended the growing season by three weeks, and shifted timing and duration of reproductive events variably among species; spring blooming species flowered earlier, late blooming species flowered later (Sherry et al. 2007). Extensions and contractions in lengths of the reproductive periods were also observed among the species tested (see also Cleland et al. 2006). Different species responses to warming suggest strong selection pressure for altering future rangeland community structure, and for the associated trophic levels that depend on the plants for important stages of their life cycles. Warming also caused both extensions and contractions of the length of the reproductive periods of the study species, which could represent a strong selection pressure on these species and for future community structure of these species and their close associates. Cleland et al. (2006) found similar results in a California grassland, where warming accelerated flowering by two to five days. Periods of drought stress may suppress warming-induced plant activity (Gielen et al. 2005), thereby effectively decreasing plant development time.

Like $CO_2$ enrichment, increasing ambient air and soil temperatures may enhance rangeland NPP, although negative effects of higher temperatures also are possible, especially in dry and hot regions. Temperature directly affects plant physiological processes, but rising ambient temperatures may indirectly affect plant production by extending the length of the growing season, increasing soil nitrogen (N) mineralization and availability, altering soil water content, and shifting plant species composition and community structure (Wan et al. 2005). Rates of biological processes for a given species typically peak at plant temperatures that are intermediate in the range over which a species is active, so direct effects of warming likely will vary within and among years and among plant species. Because of severe cold-temperature restrictions on growth rate and duration, warmer plant temperatures alone should stimulate production in high- and

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mid-latitude and high-altitude rangelands. Conversely, increasing plant temperature during summer months may reduce NPP. Increasing daily minimum air temperature and mean soil temperature (2.5 cm depth) by 2ºC increased aboveground NPP of tallgrass prairie in Oklahoma between zero percent and 19 percent during the first three years of study, largely by increasing NPP of C4 grasses (Wan et al. 2005). Warming stimulated biomass production in spring and autumn, but aboveground biomass in summer declined as soil temperature increased.

Positive effects of warming on production may be lessened by an accompanying increase in the rate of water loss. Warming reduced the annual mean of soil water content in tallgrass prairie during one year (Wan et al. 2005), but actually increased soil water content in California annual grassland by accelerating plant senescence (Zavaleta et al. 2003b).

### 2.4.3 Temperature Response of Animals

#### *1.1.1.3 Thermal stress*

The optimal zone (thermoneutral zone) for livestock production is a range of temperatures and other environmental conditions for which the animal does not need to significantly alter behavior or physiological functions to maintain a relatively constant core body temperature. As environmental conditions result in core body temperature approaching and/or moving outside normal diurnal boundaries, the animal must begin to conserve or dissipate heat to maintain homeostasis. This is accomplished through shifts in short-term and long-term behavioral, physiological, and metabolic thermoregulatory processes (Mader et al. 1997b and Davis et al. 2003). The onset of a thermal challenge often results in declines in physical activity and an associated decline in eating and grazing (for ruminants and other herbivores) activity. Hormonal changes, triggered by environmental stress, results in shifts in cardiac output, blood flow to extremities, and passage rate of digesta. Adverse environmental stress can elicit a panting or shivering response, which increases maintenance requirements of the animal and contributes to decreases in productivity. Depending on the domestic species of livestock, longer term adaptive responses include hair coat gain or loss through growth and shedding processes, respectively. In addition, heat stress is directly related to respiration and sweating rate in most domestic animals (Gaughan et al. 1999, 2000, and 2005). Production losses in domestic animals are largely attributed to increases in maintenance requirement associated with maintaining a constant body temperature, and altered feed intake (Mader et al. 2002; Davis et al. 2003; Mader and Davis, 2004). As a survival mechanism, voluntary feed intake (VFI) increases (after a one to two day decline) under cold stress and decreases almost immediately under heat stress (NRC, 1987). Depending on the intensity and duration of the environmental stress, VFI can average as much as 30 percent above normal to as much as 50 percent below normal.

Domestic livestock are remarkable in their adaptive ability. They can mobilize coping mechanisms when challenged by environmental stressors. However, not all coping capabilities are mobilized at the same time. As a general model for mammals of all species, respiration rate (RR) serves as an early warning of increasing thermal stress, and

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increases markedly above a threshold as animals try to maintain homeothermy by dissipating excess heat. At a higher threshold, body temperature (BT) begins to increase as a result of the animal's inability to adequately dissipate the excess heat load by increased respiratory vaporization (Brown-Brandl et al. 2003; Davis et al., 2003; Mader and Kreikemeier, 2006). There is a concomitant decrease in VFI as BT increases, which ultimately results in reduced performance (production, reproduction), health and well-being if adverse conditions persist (Hahn et al. 1992; Mader, 2003). Thresholds are species dependent, and affected by many factors, as noted in Figure 2.7. For shaded *Bos taurus* feeder cattle, Hahn (1999) reported RR as related to air temperature typically shows increases above a threshold of about 21°C, with the threshold for increasing BT and decreasing VFI being about 25°C. Recent studies (Brown-Brandl, et al. 2005) clearly show the influence of animal condition, genotype, respiratory pneumonia, and temperament on RR of *Bos taurus* heifers.

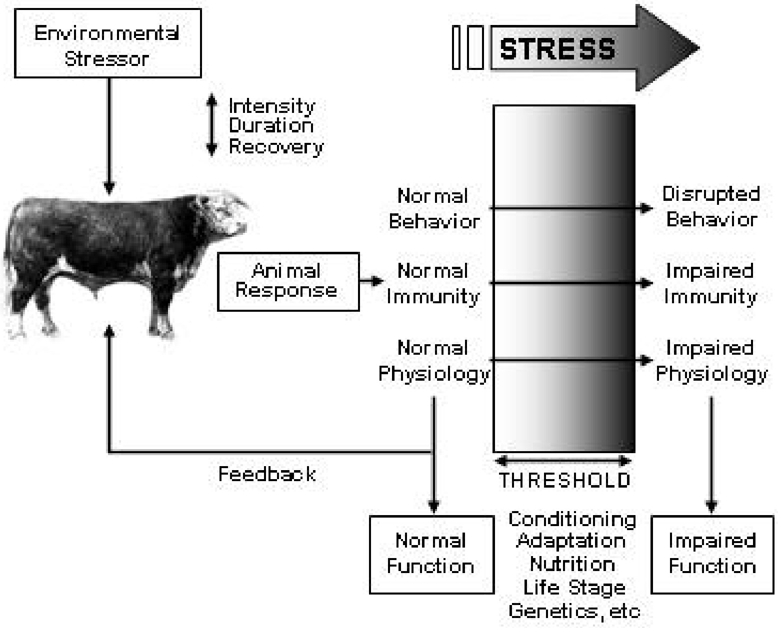

**Figure 2.7**. Response model for farm animals with thermal environmental challenges (Hahn, 1999).

There is also a time-dependency aspect of responses. For cattle, RR lags behind changes in ambient temperature, with the highest correlations obtained for a lag of two hours between RR and ambient temperature. There is also a time delay in acute BT responses (during the first three to four days of exposure) to a heat challenge, with an increasing mean and amplitude, along with a phase shift reflecting entrainment by the ambient conditions (Hahn and Mader, 1997; Hahn, 1999). Even though VFI reduction usually occurs on the first day of hot conditions, the endogenous metabolic heat load from existing rumen contents adds to the increased exogenous environmental heat load. Nighttime recovery also has been shown to be an essential element of survival when severe heat challenges occur (Hahn and Mader, 1997; Amundson et al. 2006). After three days, the animal enters the chronic response stage, with mean body temperature declining slightly and VFI reduced in line with heat dissipation capabilities. Diurnal body temperature amplitude and phase remain altered. These typical thermoregulatory responses, when left unchecked during a severe heat wave with excessive heat loads, can lead to a pathological state resulting in impaired performance or death (Hahn and Mader, 1997; Mader, 2003).

### *1.1.1.4 Methods to identify environmentally stressed animals*

Temperature provides a measure of the sensible heat content of air, and represents a major portion of the driving force for heat exchange between the environment and an animal. However, latent heat content of the air, as represented by some measure of the insensible heat content (e.g., dewpoint temperature), thermal radiation (short- and long-wave), and airflow also impact the total heat exchange. Because of the limitations of air temperature alone as a measure of the thermal environment, there have been many efforts to combine the effects of two or more thermal measures representing the influence of sensible and latent heat exchanges between the organism and its environment. It is important to recognize that all such efforts produce index values, rather than a true temperature (even when expressed on a temperature scale). As such, an index value represents the effect produced by the heat exchange process, which can alter the biological response that might be associated with changes in temperature alone. In the case of humans, the useful effect is the sensation of comfort; for animals, the useful effect is the impact on performance, health, and well-being.

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**Table 2.7 Heat wave categories**

| **Category** | **Descriptive Characteristics** | | | |
|---|---|---|---|---|
| | duration | THI*-hrs ≥79[4] | THI-hrs ≥84[4] | nighttime recovery (hrs # 72 THI[4]) |
| 1. slight | limited: 3-4 days | 10-25/day | none | good: 5-10hr/night |
| 2. mild | limited: 3-4 days | 18-40/day | #5/day | some: 3-8hr/night |
| 3. moderate | more persistent (4-6 days usual) | 25-50/day | #6/day | reduced: 1-6hr/night |
| 4. strong | increased persistence (5-7 days) | 33-65/day | #6/day | limited: 0-4hr/night |
| 5. severe | very persistent (usually 6-8 days) | 40-80/day | 3-15/day on 3 or more | very limited: 0-2hr per night |

| | | | | |
|---|---|---|---|---|
| | | | successive days | |
| 6. extreme | very persistent (usually 6-10$^{+}$ days) | 50-100/day | 15-30/day on 3 or more successive days | nil:#1 for 3 or more successive days |

**Table 2.7** Heat wave categories for *Bos taurus* feedlot cattle exposed to single heat wave events (Hahn *et al.,* 1999).[5] *Temperature Humidity Index (THI).

Contrary to the focus of human-oriented thermal indices on comfort, the primary emphasis for domestic animals has been on indices to support rational environmental management decisions related to performance, health, and well-being. Hahn and Mader (1997), Hahn et al. (1999), and Hahn et al. (2001) have used retrospective climatological analyses to evaluate the characteristics of prior heat waves causing extensive livestock losses. Although limited by lack of inclusion of wind speed and thermal radiation effects, the Temperature-Humidity Index (THI[6]) has been a particularly useful tool for profiling and classifying heat wave events (Hahn and Mader, 1997, Hahn et al. 1999). In connection with extreme conditions associated with heat waves, the THI has recently been used to evaluate spatial and temporal aspects of their development (Hubbard et al., 1999; Hahn and Mader, 1997). For cattle in feedlots, a THI-based classification scheme has also been developed to assess the potential impact of heat waves (Hahn et al. 1999). The classifications are based on a retrospective analysis of heat waves that have resulted in extensive feedlot cattle deaths, using a THI-hours approach to assess the magnitude (intensity x duration) of the heat wave events which put the animals at risk (Table 2.7). When calculated hourly from records of temperature and humidity, it can be used to compute cumulative daily THI-hrs[7] at or above the Livestock Weather Safety Index (LWSI) thresholds for the Danger and Emergency categories. The THI-hrs provide a measure of the magnitude of daytime heat load (intensity and duration), while the number of hours below THI thresholds of 74 and 72 indicate the opportunity for nighttime recovery from daytime heat.

As applied to *Bos taurus* feedlot cattle during the 1995 Nebraska-Iowa (USA), single heat wave event, evaluation of records for several weather stations in the region using the THI-hrs approach reinforced the LWSI thresholds for the Danger and Emergency categories of risk and possible death (Hahn and Mader, 1997). Based on that event, analysis indicated that 15-20 or more THI-hrs per day above a THI base level of 84 for three or more successive days were lethal for vulnerable animals (especially those recently placed in the feedlot, nearing market weight, or sick). The extreme daytime heat in 1995 was exacerbated by limited nighttime relief (only a few hrs with THI ≤ 74), high solar radiation loads (clear to mostly clear skies), and low to moderate wind speeds in the area of highest risk. For cattle in other locations with 20 or more daily THI-hrs in the Emergency category (THI ≥ 84) for only one or two days, the heat load was apparently dissipated with minimal or no mortality, although these environmental conditions can markedly depress voluntary feed intake (Hahn, 1999; NRC, 1981) with resultant reduced performance. A similar analysis of an August 1992 single heat wave event further confirmed that 15 or more THI-hrs above a base level of 84 can cause death of vulnerable animals (Hahn et al. 1999). A contributing factor to losses during that event was lack of

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acclimation to hot weather, as the summer had been relatively cool; in this area, only four years from 1887-1998 had fewer days during the summer when air temperature was ≥ 32.2°C (High Plains Regional Climate Center, 2000; www.hprcc.unl.edu).

Modifications to the THI have been proposed to overcome shortcomings related to airflow and radiation heat loads. Based on recent research, Mader et al. (2006) and Eigenberg et al. (2005) have proposed corrections to the THI for use with feedlot cattle, based on measures of windspeed (WS) and solar radiation (SRAD). For a range of conditions from 25-40°C and 30-50 percent relative humidity (RH), the THI adjustments as evaluated by Mader et al. (2006) were +0.7 for an increase in SRAD of 100 W/m2, and -2.0 for a WS increase of 1m/s, based on panting scores of observed animals. Comparatively, the equivalent THI adjustments for the same increases in SRAD and WS, as determined by Eigenberg et al. (2002) from observations of respiration rate (RR), were +0.53 and -0.14, respectively, for the same range of conditions. While the proposed adjustment factor differences are substantial, there were marked differences in the types and number of animals used in the two studies. Nevertheless, the approach appears to merit further research to establish acceptable THI corrections, perhaps for a variety of animal parameters.

By using body temperatures, a similar approach was developed to derive an Apparent Equivalent Temperature (AET) from air temperature and vapor pressure to develop "thermal comfort zones" for transport of broiler chickens (Mitchell et al. 2001). Experimental studies to link the AET with increased body temperature during exposure to hot conditions indicated potential for improved transport practices.

Gaughan et al. (2002) developed a Heat Load Index (HLI) as a guide to management of unshaded *Bos taurus* feedlot cattle during hot weather (>28°C). The HLI was developed following observation of behavioral responses (respiration rate and panting score) and changes in dry-matter intake during prevailing thermal conditions. The HLI is based on humidity, windspeed, and predicted black globe temperature.

As a result of its demonstrated broad success, the THI is currently the most widely-accepted thermal index used for guidance of strategic and tactical decisions in animal management during moderate to hot conditions. Biologic response functions, when combined with likelihood of occurrence of the THI for specific locations, provide the basis for economic evaluation to make cost-benefit comparisons for rational strategic decisions among alternatives (Hahn, 1981). Developing climatology of summer weather extremes (in particular, heat waves) for specific locations also provides the livestock manager with information about how often those extremes (with possible associated death losses) might occur (Hahn et al. 2001). The THI has also served well for making tactical decisions about when to apply available practices and techniques (e.g., sprinkling) during either normal weather variability or weather extremes, such as heat waves. Other approaches, such as the Apparent Equivalent Temperature proposed by Mitchell et al. (2001) for use in poultry transport, also may be appropriate. An enthalpy-based alternative thermal index has been suggested by Moura et al. (1997) for swine and poultry.

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**Table 2.8 Panting scores**

| Score | Description |
|---|---|
| **0** | **Normal respiration** |
| **1** | **Elevated respiration** |
| **2** | **Moderate panting and/or presence of drool or a small amount of saliva** |
| **3** | **Heavy open-mouthed panting, saliva usually present** |
| **4** | **Severe open-mouthed panting accompanied by protruding tongue and excess salivation; usually with neck extended forward** |

**Table 2.8** Panting scores assigned to steers (Mader et al., 2006).

Panting score is one observation method used to monitor heat stress in cattle (Table 2.8). As the temperature increases, cattle pant more to increase evaporative cooling. Respiration dynamics change as ambient conditions change, and surroundings surfaces warm. This is a relatively easy method for assessing genotype differences and determining breed acclimatization rates to higher temperatures. In addition, shivering score or indices also have potential for use as thermal indicators of cold stress. However, recent data were not found regarding cold stress indicators for domestic livestock.

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## 2.4.4 Crop Responses to $CO_2$

### *1.1.1.5 Crop Responses*

Reviews of the early enclosure $CO_2$ studies indicate that average yield increase over many C3 crops with doubling of $CO_2$ is 33 percent (Kimball, 1983), at a time when doubling meant increase from 330 to 660 vpm $CO_2$. The general phenomenon was expressed as increased number of tillers-branches, panicles-pods, and numbers of seeds, with minimal effect on seed size. The C4 species response to doubling of $CO_2$ was reported by Kimball (1983) to be 10 percent. High temperature stress during reproductive development can negate $CO_2$ beneficial effects on yield even though total biomass accumulation maintains a $CO_2$ benefit (e.g., for *Phaseolus* bean, Jifon and Wolfe 2000). Unrestricted root growth, optimum fertility, and excellent control of weeds, insects, and disease are also required to maximize $CO_2$ benefits (Wolfe 1994). Most C3 weeds benefit more than C3 crop species from elevated $CO_2$ (Ziska 2003).

| Crop | Leaf Photosynthesis | Total Biomass | Grain Yield | Stomatal conductance | Canopy T, ET |
|---|---|---|---|---|---|
| | | | % change | | |
| Corn | 3[1*] | 4[1, 2, 3,4] | 4[1, 2] | -34[5] | |
| Soybean | 39[6] | 37[6] | 38[6], 34[7] | -40[6] | -9[8],-12[9,10*] |
| Wheat | 35[11] | 15-27[12] | 31[13] | -33 to -43[14*] | -8[15,16*] |
| Rice | 36[17] | 30[17] | 30[17,18] | | -10[19] |
| Sorghum | 9[20, 21*] | 3[22*] | 8[20], 0[22*] | -37[21*] | -13[23*] |
| Cotton | 33[24] | 36[24] | 44[24] | -36[24] | -8[25] |
| Peanut | 27[26] | 36[26] | 30[26] | | |
| Bean | 50[26] | 30[26] | 27[26] | | |

**Table 2.9** Percent response of leaf photosynthesis, total biomass, grain yield, stomatal conductance, and canopy T or ET, to a doubling in $CO_2$ concentration (usually 350 to 700 ppm, but sometimes 330 to 660 ppm). *Responses to increase from ambient to 550 or 570 ppm (FACE) are separately noted.[8]

In recent years, new field "free-air $CO_2$ enrichment" (FACE) technology has allowed the evaluation of a few selected crops for their response under field conditions without enclosure-confounding effects. In some cases the results corroborate previous enclosure studies, while results in other cases suggest yield responses are less than previously reported. Although the continuously increasing "ambient" reference concentration is a cause for lesser response, the smaller increment of $CO_2$ enrichment requires even better replication and sampling in FACE to evaluate the response. Enclosures are not the only concern; single spaced plants or unbordered plants may respond too much, and potted plants that are root bound may not respond well. Additional research, data analysis, and

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evaluation of a broader range of crops using FACE techniques will be required to sort discrepancies where they exist.

Effects of doubling of $CO_2$ on leaf photosynthesis, total biomass, grain or fruit yield, conductance, and canopy T or ET of important non-water-stressed crops are shown in Table 2.9. The $CO_2$ responses of many species are given in the review paper by Kimball et al. (2002), in addition to specific references cited below.

Maize, being a C4 species, is less responsive to increased atmospheric $CO_2$. Single leaf photosynthesis of maize shows no effect of $CO_2$ on quantum efficiency, but there is a minor increase in leaf rate at light-saturation (3percent for 376 to 542 ppm, Leakey et al., 2006). There is a paucity of data for maize grown to maturity under elevated $CO_2$ conditions. Until 2006, there was only one data set for maize grown to maturity under $CO_2$ treatments conducted: King and Greer (1986) observed 6.2 percent and 2.6 percent responses to increasing $CO_2$ from 355 to 625 and 875 vpm, respectively, in a 111-day study. The mean of the two levels gives about 4.4 percent increase to doubling or more of $CO_2$. Recently, Leakey et al. (2006) conducted a full season study of maize grown to maturity in Free Air $CO_2$ Enrichment (FACE) and reported no significant response of maize to a 50 percent increase in $CO_2$ (376 to 542 ppm [target: 370 to 550] ppm. The small biomass sample size used in that FACE study (4 random plant samples per replicate) and the small increment of $CO_2$ causes concern about whether these experimental measurements were sufficient to detect a statistically significant response, considering the small plot sample size and that a 2-3 percent increase is all that is expected for increase in $CO_2$ from 370 to 550 ppm. The grain yield response was a non-significant (1 percent). Also, Ziska and Bunce (1997) reported 2.9 percent biomass increase to $CO_2$ increase from 371 to 674 ppm for a 33-day study in glasshouse and Maroco et al. (1999) reported a 19.4 percent biomass increase to $CO_2$ increase from 350 to 1100 ppm during a 30-day growth period at very high light (supplemented above outdoor ambient) for a short duration study on young plants. Thus, we conclude that maize biomass increase should be about 4 percent (mean of 2 x 0.0, 6.2, 2.6, 2.9, and half of 19.4) and grain yield increase should also be about 4 percent (mean of 2 x 1.0, 6.2, and 2.6) to increasing $CO_2$ from 350 to 700 ppm. This is less than the simulated 10 percent increase for C4 species to $CO_2$ increment from 330 to 660 ppm as parameterized in the CERES-Maize or EPIC models based on sparse data (Tubiello et al., 2007). In summary, the evidence for maize response to $CO_2$ is sparse and questionable. The expected increment of $CO_2$ increase over the next 30 years is anticipated to have a negligible effect (1.0 percent, Table 2.10) on maize production, unless there is a water-savings effect in drought years.

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**Table 2.10 Percent grain yield response to increased temperature**

| Crop | Temperature (0.8 ºC) | $CO_2$ (380 to 440 ppm)[9] | Temp/$CO_2$ Combined Irrigated | Temp on ET of Rainfed | $CO_2$ on ET of Rainfed |
|---|---|---|---|---|---|
| | - - - - - - - - - - | - - - - - - - - - - | % change - - - - - - | - - - - - - - - - - | - - - - - - - - - - |
| Corn -Midwest | -2.5 | +1.0 | -1.5 | +1.2[11][10] | |

| | | | | | |
|---|---|---|---|---|---|
| (22.5ºC) | | | | | |
| Corn - South (26.7ºC) | -2.5 | +1.0 | -1.5 | +1.2[10] | |
| Soybean – Midwest (22.5ºC) | +1.7 | +7.4 | +9.1 | +1.2[10] | -2.1 |
| Soybean – South (26.7ºC) | -2.4 | +7.4 | +5.0 | +1.2[10] | -2.1 |
| Wheat – Plains (19.5ºC) | -4.4 | +6.8 | +2.4 | +1.2[10] | -1.4 |
| Rice – South (26.7ºC) | -8.0 | +6.4 | -1.6 | +1.2 | -1.7 |
| Sorghum (full range) | -6.2 | +1.0 | -5.2 | +1.2[2] | -3.9 |
| Cotton – South (26.7ºC) | -3.5 | +9.2 | +5.7 | +1.2[2] | -1.4 |
| Peanut – South (26.7ºC) | -3.3 | +6.7 | +3.4 | +1.2[2] | |
| Bean – relative to 23ºC | -5.8 | +6.1 | +0.3 | +1.2[2] | |

**Table 2.10** Percent grain yield response to increased temperature (0.8 ºC), increased $CO_2$ (380 to 440 ppm), net effect of temperature and increased $CO_2$ on irrigated yield assuming additivity, and change in ET of rainfed crops with temperature and $CO_2$. Current mean air temperature during reproductive growth is shown in parentheses for each crop/region to give starting reference, although yield of all the cereal crops declines with a temperature slope that originates below current mean air temperatures during grain filling.

What are the responses of other important C4 field crop species to doubled $CO_2$? Sorghum gave a 9, 34, and 8 percent increases in leaf photosynthesis, biomass, and grain yield with doubling of $CO_2$ when grown in 1 by 2 m land area sunlit controlled-environment chambers (Prasad et al. 2005a). A $CO_2$ increase from 368 to 561 ppm for full season on sorghum in FACE studies in Arizona gave 3 and 15 percent increases in biomass and (-4 percent) and +20 percent change in grain yield, under irrigated versus water-limited conditions, respectively (Ottman et al. 2001).

Soybean is a C3 legume that is quite responsive to $CO_2$. Based on the metadata summarized by Ainsworth et al. (2002), soybean response to a doubling of $CO_2$ from 330 to 660 ppm (or 350 to 700 ppm, the authors did not specify range for the doubling) is about 39 percent for light-saturated leaf photosynthesis, 37 percent for biomass accumulation, and 38 percent for grain yield (taking values only for soybean grown in large $\geq 1m^2$ land area crop stands in soil, because yield response to $CO_2$ potted plants was shown to be affected by pot size). Allen and Boote (2000) reported a response of 34 percent in sunlit, controlled-environment chambers to increase in $CO_2$ from 330 to 660 ppm. Ainsworth et al. (2002) summarized that leaf conductance was reduced 40 percent (consistent with other C3 and C4 species, Morison, 1987), and seed harvest index was reduced by nine percent. The C3 photosynthetic response to $CO_2$ enrichment is well-documented and is generally easy to predict using either the Farquhar and von Cammerer (1982) equations or simplifications based on those equations. The leaf photosynthesis equations in the CROPGRO-soybean model (Boote et al. 1998) are based on Farquhar

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kinetics equations (Boote and Pickering, 1994), and were found by Alagarswamy et al. (2006) to predict single-leaf response to $CO_2$ with as good of accuracy as the Farquhar equations.

The CROPGRO-soybean model predicts 29 to 41 percent increase in biomass and 29 to 34 percent increase in grain yield with increase in $CO_2$ from 350 to 700 ppm (Boote et al. 1997), values that are comparable to metadata summarized by Ainsworth et al. (2002) and by Allen and Boote (2000). Future projections of response to incremental $CO_2$ increase must consider present day levels as a starting point because the response is asymptotically saturating. In fact, some of the increased yield of crops like soybean currently attributed to technological innovation over the past four to five decades is in fact attributable to the rise in $CO_2$. Simulations by Boote et al. (2003) suggested that soybean yield in Iowa would have increased 9.1 percent over the period 1958 to 2000, during which time the $CO_2$ increased from 315 to 370 ppm. Concurrently, the crop ET was predicted to decrease 1.5 percent and water use efficiency (WUE) (on grain basis) increased 10.7 percent, using a version of the model that lacked direct stomatal coupling. Using a model with direct stomatal feedback may have given greater increase in WUE. Using a Michaelis-Menten rectangular hyperbola projection, a $CO_2$ increase from 380 to 440 ppm, is projected to increase in yield by 7.4 percent (Table 2.10) for the dominant soybean growing regions of the Midwestern United States. For the same regions, the expected temperatures are so close to the optimum for soybean yield, and the temperature increment so small (0.8ºC) that the net effect of climate change on soybean yield is dominated by the $CO_2$ increment. To the extent that water-use efficiency increases with $CO_2$ enrichment and conserves soil water, yield response for rainfed regions will be enhanced by the “net” effect on ET (+1.2 – 2.1 = 0.9 percent increase)

Other C3 field crop species exhibit similar responses to increasing $CO_2$. For wheat, a cool-season cereal, doubling of $CO_2$ (350 to 700 ppm) increased light-saturated leaf photosynthesis by 30-40 percent (Long, 1991) and grain yield by about 31 percent, averaged over many data sets (Amthor, 2001). For rice, doubling $CO_2$ (330 to 660 ppm) increased canopy assimilation, biomass, and grain yield by about 36, 30, and 30 percent, respectively (Horie et al. 2000). Baker and Allen (1993a) reported 31 percent increase in grain yield, averaged over five experiments, with increase of $CO_2$ from 330 to 660 ppm. Rice shows photosynthetic acclimation associated with decline in leaf N concentration and a six to 22 percent reduction in leaf rubisco content per unit leaf area (Vu et al. 1998). For peanut, a warm-season grain legume, doubling $CO_2$ increased light-saturated leaf photosynthesis, total biomass and pod yield of peanut by 27, 36 and 30 percent, respectively (Prasad et al. 2003). Doubling $CO_2$ (350 to 700 ppm) increased light-saturated leaf photosynthesis, biomass, and seed yield of dry bean by 50, 30, and 27 percent (Prasad et al., 2002). For cotton, a warm-season non-legume, doubling $CO_2$ (350 to 700 ppm) increased light-saturated leaf photosynthesis, total biomass, and boll yield by 33 percent, 36 percent, and 44 percent (K. R. Reddy et al. 1995, 1997), and decreased stomatal conductance by 36 percent (V. R. Reddy et al. 1995). Under well-watered conditions, leaf and canopy photosynthesis of cotton increased about 27 percent with $CO_2$ enrichment, to 550 ppm $CO_2$ in a FACE experiment in Arizona (Hileman et al. 1994). Mauney et al. (1994) reported 37 percent and 40 percent increases in biomass and boll

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yield of cotton with $CO_2$ enrichment to 550 ppm. Even larger increases in yield and biomass of cotton were obtained under the same enrichment for cotton under water-deficit situations (Kimball and Mauney, 1993). An important consideration relative to cotton responses in Arizona is that the large VPD may have given more benefit to elevated $CO_2$ via water conservation effects. So, the degree of responsiveness in arid region studies may differ from that in humid regions. There were no reported effects of doubled $CO_2$ on vegetative or reproductive growth stage progression in cotton (Reddy et al. 2005), soybean (Allen and Boote, 2000; Pan, 1996), dry bean (Prasad et al. 2002), and peanut (Prasad et al. 2003).

#### *1.1.1.6 Interactions of $CO_2$ increase with temperature increase*

There could be beneficial interaction of $CO_2$ enrichment and temperature on dry matter production (greater response to $CO_2$ as temperature rises) for the vegetative phase of non-competitive plants as highlighted by Idso et al. (1987). This effect may be beneficial to production of radish (*Raphanus sativus* L.), lettuce (*Lactuca sativa* L.), or spinach (*Spinacea olervicea* L.), mainly because any factor that speeds leaf area growth (whether $CO_2$ or temperature) speeds the exponential phase of early growth. However, this “beta” factor effect does not appear to apply to closed canopies or to reproductive grain yield processes.

There are no reported beneficial interactions on grain yield caused by $CO_2$ increase with temperature increase. Main effects of $CO_2$ are present, and main effects of temperature are present, but no beneficial interactions have been reported for rice (Baker and Allen, 1993a, 1993b; Baker et al. 1995; Snyder, 2000), wheat (Mitchell et al. 1993), soybean (Baker et al. 1989; Pan, 1994), dry bean (Prasad et al. 2002), peanut (Prasad et al. 2003), and sorghum (Prasad et al. 2005a). By contrast, there are three reported negative interactions of elevated $CO_2$ with temperature on fertility (percent seed-set), where elevated $CO_2$ causes greater sensitivity of fertility (seed-set) to temperature in rice (Kim et al. 1996; Matsui et al. 1997), sorghum (Prasad et al. 2006a), and dry bean (Prasad et al. 2002). For rice, the relative enhancement in grain yield with doubled $CO_2$ decreases and actually goes negative as Tmax increases in the range 32 to 40ºC (Kim et al. 1996). Likewise, while the interaction was not significant, the relative $CO_2$ enhancement of grain yield of soybean (Baker et al. 1989) became less as temperature increased from optimum to super-optimum. In the rice, sorghum, and dry bean cases, failure point temperature for complete reproductive failure is about 1-2ºC lower at elevated $CO_2$ than at ambient. The cause is likely the degree to which the elevated $CO_2$ causes warming of the foliage, which is typically this order of magnitude (doubled $CO_2$ canopies of dry bean were 1.5ºC warmer, Prasad et al. 2002; doubled $CO_2$ canopies of soybean were 1-2ºC warmer, Allen et al. 2003; doubled $CO_2$ canopies of sorghum averaged 2ºC warmer during daytime period, Prasad et al. 2006a). The higher canopy temperature of rice, sorghum, and dry bean adversely affected fertility and grain-set. Increases in canopy temperature for wheat, rice, sorghum, cotton, poplar, potato, and soybean have been reported in FACE experiments (see figure in Kimball and Bernacchi, 2006).

In cotton, there was progressively greater photosynthesis and vegetative growth response to $CO_2$ as temperature increased up to 34ºC (V. R. Reddy, 1995), but this response did

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not carry over to reproductive growth (K. R. Reddy et al. 1995). The reproductive enhancement from doubled $CO_2$ was largest (45 percent) at the 27ºC optimum temperature for boll yield, and there was no beneficial interaction of increased $CO_2$ on reproductive growth at elevated temperature, reaching zero boll yield at 35ºC (K. R. Reddy et al. 1995).

Mitchell et al. (1993) conducted field studies of wheat grown at ambient and +4ºC temperature differential and at elevated versus ambient $CO_2$ in England. While there were no interactions of $CO_2$ and temperature on yield, high temperature reduced grain yield at both $CO_2$ levels such that yields were significantly greater at ambient $CO_2$ and ambient temperature compared to elevated $CO_2$ and high temperature. Batts et al. (1997) similarly reported no beneficial interactions of $CO_2$ and temperature on wheat yield.

In studies with bean (Jifon and Wolfe, 2005) and potato (Peet and Wolfe, 2000), there was no significant beneficial effect of $CO_2$ on yield in high temperature treatments that negatively affected reproductive development, although the beneficial effect on vegetative biomass was maintained. These results suggest that in those regions and for those crops where climate change impairs crop reproductive development because of an increase in the frequency of high temperature stress events, the potential beneficial effects of elevated $CO_2$ on yield may not be fully realized.

For peanut, there was no interaction of elevated temperature with $CO_2$ increase, as the extent of temperature-induced decrease in pollination, seed-set, pod yield, seed yield, and seed HI was the same at ambient and elevated $CO_2$ levels (Prasad et al. 2003). For red kidney bean, Prasad et al. (2002) found no beneficial interaction of elevated temperature with $CO_2$ increase, as the temperature-induced decrease in pollination, seed-set, pod yield, seed yield, and seed HI was the same or even greater at elevated than at ambient $CO_2$ levels. The temperature-sensitivity of fertility (grain-set) and yield for sorghum was significantly greater at elevated $CO_2$ than at ambient $CO_2$ (Prasad et al., 2006a), thus showing a negative interaction with temperature, associated with fertility and grain-set, but not on photosynthesis.

#### *1.1.1.7 Interactions of $CO_2$ increase with N fertility*

For non-legumes like rice, there is clear evidence of an interaction of $CO_2$ enrichment with N fertility regime. For *japonica* rice, Nakagawa et al. (1994) reported 17, 26, and 30 percent responses of biomass to $CO_2$ enrichment, at N applications of 40, 120, and 200 kg N $ha^{-1}$, respectively. For *indica* rice, 0, 29, and 39 percent responses of biomass to $CO_2$ enrichment were reported at N applications of 0, 90, and 200 kg N $ha^{-1}$, respectively (Ziska et al. 1996). For C4 bahiagrass (*Paspalum notatum* L.), Newman et al. (2006) observed no biomass response to doubled $CO_2$ at low N fertilization rate, but observed seven to 17 percent increases with doubled $CO_2$ when fertilized with 320 kg N $ha^{-1}$. Biomass production in that study was determined over four harvests in each of two years (the seven percent response in year one was non-significant, but 17 percent response in year two was significant).

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### 2.4.5 Effects of $CO_2$ Increase on Water Use and Water Use Efficiency

#### *1.1.1.8 Changes in crop water use due to increasing temperature, $CO_2$, and $O_3$*

Crop water use (i.e. ET) of crop plants is a physical process but mediated by crop physiological and morphological characteristics (e.g., Kimball, 2007). It can be described by the Penman-Monteith equation, whose form was recently standardized (Allen et al., 2005). The equation reveals several mechanisms by which the climate change parameters – temperature, $CO_2$, and $O_3$ – can affect water use. These include: (1) direct effects on crop growth and leaf area, (2) alterations in leaf stomatal aperture and consequently their conductance for water vapor loss, and (3) physical changes in the vapor pressure inside leaves.

When plants are young and widely spaced, increases in leaf area are approximately proportional to the increases in growth, and transpiration increases accordingly. However, as plants shift from vegetative to reproductive growth during their life cycle, proportionately more of the accumulating biomass is partitioned to other organs, such as developing grain. At this point, leaf area and biomass accumulation are no longer proportional. Also, as plants grow, the mutual shading and interference among the leaves within a plant canopy also causes changes in plant transpiration to asymptotically plateau with leaf area index and less coupled to changes in leaf area index (Ritchie, 1972; Villalobos and Fereres, 1990; Sau et al. 2004). Further, considering that a doubling of $CO_2$ from present-day levels is likely to increase average C3 species growth on the order of 30 percent (e.g. Kimball, 1983, 2007; Kimball et al. 2002, refer back to particular previous section), so projecting out to 2030 with a $CO_2$ concentration of about 440 ppm suggests increases in C3 plant growth only on the order of 10 percent. Therefore, because changes in growth affect ET mostly only while plants are small after planting and progressively less after canopy closure, the changes in ET rates by 2030 due to leaf area index effects are likely to be minor.

More importantly, duration of leaf area will affect total seasonal crop water requirements. Thus, the lengthening of growing seasons due to global warming likely will increase crop water requirements. On the other hand, for some determinate cereal crops, increasing temperature can hasten plant maturity, thereby shortening the leaf area duration with the possibility of reducing the total season water requirement for such crops.

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Elevated $CO_2$ causes partial stomatal closure, which decreases their conductance for the loss of water vapor from leaves to the atmosphere. Reviews of the effects of elevated $CO_2$ on stomatal conductance from chamber-based studies have reported that, on average, a doubling of $CO_2$ reduces stomatal conductance about 34 percent (e.g., Kimball and Idso, 1983). Morison (1987) calculated an average reduction of about 40 percent with no difference between C3 and C4 species. More recently, Wand et al. (1999) performed a meta-analysis on observations reported for wild C3 and C4 grass species, and found that with no stresses, elevated $CO_2$ reduced stomatal conductance by 39 and 29 percent for C3 and C4 species, respectively. Ainsworth et al. (2002) found an average reduction of about 40 percent in conductance of soybean for a wide range of $CO_2$ concentrations, with the reduction for a doubling being about 30 percent. A meta-analysis by Ainsworth and Long (2005) of data generated by free-air $CO_2$ enrichment experiments for which the daytime concentrations were 550-600 ppm produced an average reduction in stomatal conductance of 20 percent. They did not detect any significant difference between C3 and C4 species. Projecting out 30 years, the atmospheric $CO_2$ concentration likely will be about 440 ppm (IPCC, 2001). Interpolating from these reviews, it appears likely that an increase in $CO_2$ concentration from 380 to 440 ppm will cause reductions on the order 10 percent in stomatal conductance compared to today's values.

**Table 2.11 Sensitivity of evapotranspiration**

| **Weather or Plant Variable** | **ET Sensitivity (%/EC or %/%)** | |
|---|---|---|
| | **Summer day** | **Whole year** |
| $T_{ah}$, air temperature with absolute humidity constant, EC | 2.394 | 3.435 |
| $T_{rh}$, air temperature with relative humidity constant, EC | 1.489 | 2.052 |
| $R_s$, solar radiation, % | 0.585 | 0.399 |
| $e_a$, absolute vapor pressure, % | -0.160 | -0.223 |
| u, wind speed, % | 0.293 | 0.381 |
| $g_s$, surface or canopy conductance, % | 0.085 | 0.160 |
| LAI, leaf area index, % | 0.085 | 0.160 |
| $CO_2$ | | |

**Table 2.11** Sensitivity of evapotranspiration (ET; percent change in ET per EC change in temperature or percent change in ET per percent change in variable other than temperature) to changes in weather and plant variables as calculated by Kimball (2007) from the proposed ASCE standardized hourly reference equation for alfalfa (Allen *et al.,* 2005). The weather data were from the AZMET network (Brown, 1987) for Maricopa, AZ, for a clear summer day (21 June 2000) or for the whole 2000 year. Calculations were done hourly and then summed for the clear summer day or whole year.

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The water conserving response to high $CO_2$ at the leaf scale (i.e., conductance change) is modulated by processes at the whole-plant and/or ecosystem scales (e.g., high $CO_2$ can cause an increase in total leaf (transpirational surface) area). As a result, ET and soil water use are generally less affected by high $CO_2$ than is conductance at the leaf scale (Field et al. 1995). An increase in ET at elevated compared to current ambient $CO_2$, although not commonly observed, sometimes occurs (e.g., Hui et al. 2001).

Less research has been done on the effects of elevated $O_3$ on stomatal conductance compared to elevated $CO_2$, but some pertinent work has been published. Barnes et al. (1995) and Balaguer et al. (1995) measured stomatal conductance of wheat exposed to 700 $\mu$mol mol$^{-1}$ $CO_2$, about 75 nmol mol$^{-1}$ $O_3$, and $CO_2$+$O_3$ in controlled-environment chambers. The ozone treatment reduced conductance by about 20 percent, while both $CO_2$ and $CO_2$+$O_3$ reduced it by 40 percent. Wheat was exposed by Donnelly et al. (2000) to 680 $\mu$mol mol$^{-1}$ $CO_2$, 50 or 90 nmol mol$^{-1}$ $O_3$, and $CO_2$+$O_3$ in open-top chambers, and they found all three treatments produced reductions in stomatal conductance of about 50 percent with relative order changing with days after sowing and year. Using open-top chambers with potato, both Lawson et al. (2002) and Finnan et al. (2002) report stomatal conductance is reduced about 50 percent by 680 $\mu$mol mol$^{-1}$ $CO_2$ and a similar amount in combination with elevated $O_3$, but their results are variable and mutually inconsistent among treatments. In a FACE project with both $CO_2$ and $O_3$ treatments, Noormets et al. (2001) measured stomatal conductance of aspen leaves. Their results varied with leaf age and aspen clone, but generally it appears that the conductance had the following treatment rank: Control>$O_3$>$CO_2$+$O_3$>$CO_2$. Morgan et al. (2003) performed a meta-analysis of 53 prior chamber studies in which $O_3$ was elevated by 70 ppm above clean air, and they found that stomatal conductance was reduced by 17 percent on average. However, in a recent FACE experiment on soybean in which $O_3$ was elevated by 50 percent above ambient conditions, Bernacchi et al. (2007) detected no significant effect of $O_3$ on stomatal conductance. Thus, while chamber studies comparing the effects of $O_3$ on stomatal conductance showed that reductions can occur, in the case of field-grown plants exposed to present-day ambient levels of $O_3$ that are considerably above zero, the effects on conductance of the additional increases in $O_3$ levels that are likely to occur by 2030 will probably be rather small.

The water vapor pressure (e; kPa) inside leaves is tightly coupled to leaf temperature (T; ˚C) and can be calculated from the exponential Teten's equation, $e = 0.61078*\exp(17.269*T/(T+237.3))$. Therefore, anything that affects the energy balance and temperature of a crop's leaf canopy will affect the water vapor pressure inside the leaves and ultimately its water consumption. Consequently, increases in air temperature, will thereby likely also increase crop canopy temperature, leaf water vapor pressure, and ET.

Allen et al. (2005) published a standard version of the Penmen-Monteith equation for calculating ET based on short grass or 50-cm-tall alfalfa as reference crops. Focusing on alfalfa for the reference crop, the sensitivity of the equation to individual weather and plant parameters was tested using hourly weather data for the year 2000 from the AZMET station (Brown, 1987) at Maricopa, AZ (33.05 EN latitude, 112.00 EW

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longitude, 358 m elevation) (Kimball, 2007). The sensitivity results are presented in Table 2.11 adapted from Kimball (2007). Annual reference ET changes about 3.4 percent per EC change in temperature assuming all the other variables, including absolute humidity remain constant. However, with global warming, precipitation is also predicted to increase on average worldwide (IPCC, 2001), although with much uncertainty especially with regard to individual localities. Therefore, it is more likely that relative humidity will remain more constant than will absolute humidity (e.g., Amthor, 1999). When temperature increases but relative humidity is constant, annual ET increases less, about 2.1 percent/EC. If absolute vapor pressure were to change alone, such as with a changing precipitation pattern, then ET would be expected to change -0.2 percent per percent increase in absolute humidity. Although there is no specific mention of projected changes in solar radiation in the IPCC report (IPCC, 2001), projected increases in average global rainfall would seem to imply some increases in cloudiness and consequent decreases in the amount of solar radiation impinging on future crops. If such changes in radiation were to occur, the sensitivity of reference ET is 0.6 and 0.4 percent per percent change in radiation for a clear day and for a whole year, respectively, at Maricopa, AZ. Likewise for wind speed, although projected changes are not mentioned (IPCC, 2001), if they were to occur, ET likely would change about 0.3 and 0.4 percent per percent change in wind speed for a clear day and for a whole year, respectively, at Maricopa, AZ. Stomatal conductance and leaf area have the same relative effect on ET, increasing ET by 0.09 and 0.16 percent for a clear summer day and whole year, respectively.

Reiterating the projections for the next 30 years, average global temperature is likely to have increased by about 0.8 ˚C (at constant relative humidity) and atmospheric $CO_2$ concentration to about 440 ppm, the latter of which will cause stomatal conductance to decrease about 10 percent. Using the sensitivities in Table 5, ET for an alfalfa reference crop at Maricopa, AZ, can be expected to increase about 1.9 percent and 2.7 percent for a clear summer day and a whole year, respectively. At the same time, a decrease in stomatal conductance of about 10 percent due to elevated $CO_2$ concentrations of about 440 ppm will likely decrease ET by about 0.9 and 1.6 percent respectively. The two effects are about the same size and in opposite directions, so the net changes in ET are likely to be minimal.

Elevated $CO_2$ concentrations at about 550 ppm in FACE experiments have reduced water use in FACE experimental plots by about two to 13 percent depending on species (Figure 2.8). Interpolating linearly to 440 ppm of $CO_2$, the corresponding reductions likely would be about one-third of those observed in the FACE experiments (i.e., one to four percent). Because there are fetch considerations in extrapolating FACE plot data to larger areas (see discussion in Triggs et al., 2004), the reductions in crop water requirements due to elevated $CO_2$ likely will be significant but smaller yet.

Another aspect to consider is the dynamics of crop water use and the timing of rain/irrigation events. The latent energy associated with ET from soybean is 10 to 60 W/m2 less in the FACE plots compared to the control plots at ambient CO2 when the crop had ample water (Figure 2.9 adapted from Bernacchi et al. 2007).

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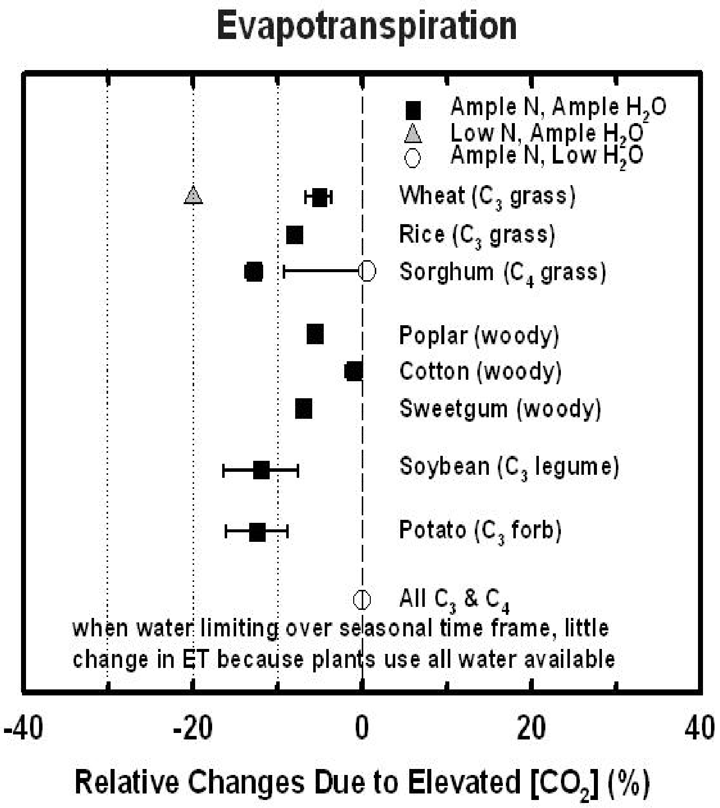

**Figure 2.8.** Relative changes in evapotranspiration due to elevated $CO_2$ concentrations in FACE experiments at about 550 ppm. [Wheat and cotton data from Table 2 of Kimball et al. (2002); rice datum from Yoshimoto et al. (2005); sorghum datum from Triggs et al. (2004); poplar datum from Tommasi et al. (2002); sweetgum from Wullschleger and Norby (2001); soybean datum from Bernacchi *et al. (*2007); and potato datum from Magliulo et al. (2003)].

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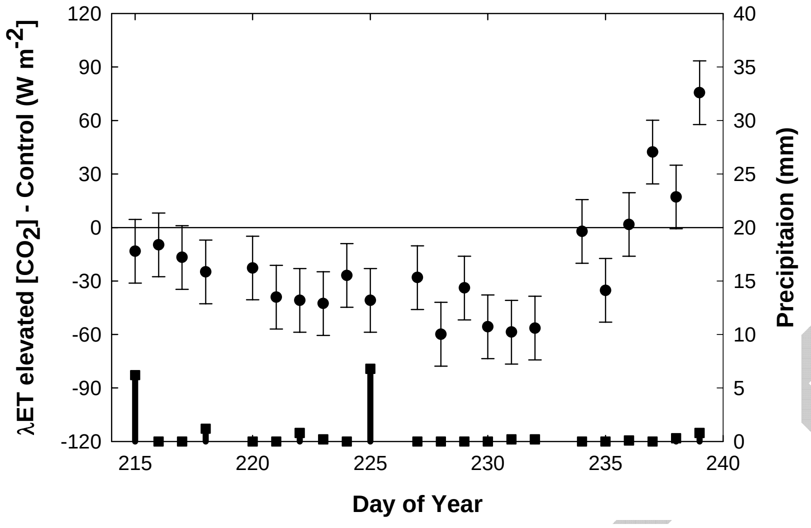

**Figure 2.9** Differences in evapotranspiration rate (latent energy, W m$^{-2}$) between soybean plots enriched to 550 ppm from free-air $CO_2$ enrichment (FACE) and plots at today's ambient $CO_2$ levels at Urbana, IL, versus day of year (circles, left axis). Corresponding precipitation is also shown (squares, right axis). Adapted from Figure 2.7 of Bernacchi et al.,

However, on about Day-of-Year (DOY) 233, the control plots had exhausted their water supply, and their water use declined. In contrast, the water conservation in the elevated-$CO_2$ plots enabled them to keep their stomata open and transpiring, and for DOYs 237-239, the FACE plots transpired more water than the controls. During this latter period, when the FACE had their stomata open while those of the control plots were closed, the FACE plots were able to continue photosynthesizing and growing while the controls were not. In other words, under-rain-fed agriculture, which often experiences periods of drought, elevated concentrations of $CO_2$ can enable some conservation of soil water, which will sustain crop productivity more days than if it were at today's $CO_2$ levels.

The net irrigation requirement is the difference between seasonal ET for a well-watered crop and the amounts of precipitation and soil water storage available during a growing season. A few researchers have attempted to estimate future changes in irrigation water requirements based on projected climate changes from general circulation models (GCMs) and estimates of decreased stomatal conductance due to elevated $CO_2$ (e.g., Allen et al. 1991; Izaurralde et al. 2003). The estimate by Izaurralde et al. (2003) is a comprehensive assessment of climate change impacts on agricultural production and water resources of the conterminous United States. They used a crop growth model (EPIC) to calculate growth and yield, as well as future irrigation requirements of corn and alfalfa. Following Stockle et al. (1992a, b), EPIC was modified to allow stomatal conductance to be reduced with increased $CO_2$ concentration (28 percent reduction corresponding to 560 μmol $CO_2$ mol$^{-1}$), as well as increasing photosynthesis via improved radiation use efficiency. For climate change projections, they used scenarios generated for 2030 (and 2095, but these are not presented here) by the Hadley Centre (HadCM2J) GCM, which was selected because its climate sensitivity is in the midrange of most of the GCMs and radiatively active gas emission scenarios. For corn, Izaurralde

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et al. (2003) calculated that by 2030 irrigation requirements will change from -1 (Lower Colorado Basin) to +451 percent (Lower Mississippi Basin). Given the variation in the sizes and baseline irrigation requirements of the basins, a representative figure for the overall U.S. increase is 64 percent if stomatal effects are ignored, or 35 percent if they are included. They made similar calculations for alfalfa whose overall irrigation requirements are predicted to increase 50 and 29 percent in the next 30 years for the cases of ignoring and including stomatal effects, respectively.

The prior sections have suggested that increasing temperatures are likely to increase ET. At the same time, increasing $CO_2$ will decrease stomatal conductance, which will decrease ET by about same amount that temperature would increase it, resulting in little net effect. In contrast to this expectation, continental river runoff records around the globe have increased through the 20th century (Gedney et al. 2006). Gedney et al. (2006) examined several climatic forcing factors, and they concluded that the increase in streamflow is mostly likely due to elevated $CO_2$, causing partial stomatal closure and consequent reductions in ET.

Pan evaporation rates have declined in the United States and elsewhere, which some thought must imply that actual ET rates must be increasing (e.g., Hobbins et al. 2004), in contrast to the continental streamflow data. To explain the mechanisms causing the observed trend in pan evaporation, Hobbins et al. (2004) plotted trends in mean annual solar radiation, illustrating declines across almost all of the United States. They also plotted trends in vapor pressure deficit, finding declines in the Eastern United States, but heterogeneity in the West. They also estimated ET from several river basins across the country as precipitation minus streamflow. These data indicated that about half these U.S. basins had increasing ET rates, and the other half had declining ET rates. However, the combined solar, vapor pressure deficit, and actual ET estimates confirmed that declines in pan evaporation were a manifestation of the complementarity between potential and actual ET.

While the main foci are on the increasing $CO_2$ concentration and increasing temperatures associated with global warming, at the same time other variables that affect ET and consequently plant water relations are also changing and will impact crop production and quality.

#### *1.1.1.9 Implications for irrigation and water deficit*

Stomatal conductance is reduced about 40 percent for doubling of $CO_2$ for both C3 and C4 species (Morison, 1987), thus causing water conservation effects and potentially less water deficit. However, the actual reduction in crop transpiration and ET will not be as much as the reduction in stomatal conductance because warming of the foliage to solve the energy balance will increase both latent heat loss (transpiration) and sensible heat loss. Allen et al. (2003) concluded that both increased foliage temperature (solving the energy balance) and increased LAI associated with $CO_2$ enrichment, were responsible for the compensatory effects on ET (small to non-existent reductions). Jones et al. (1985) reported 12 percent reduction in season-long transpiration and 51 percent increase in

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WUE measured for canopies of soybean crops grown in ambient and doubled $CO_2$ in sunlit, controlled-environment chambers. In experimental studies in the same chambers, foliage temperatures measured by infrared sensors have typically been increased 1 to 2ºC (soybean) 1.5ºC (dry bean) and 2ºC (sorghum) in response to doubled $CO_2$ (Pan, 1996; Prasad et al., 2002; Prasad et al., 2006a). Allen et al. (2003) reported that soybean foliage at doubled $CO_2$ averaged 1.3ºC warmer at mid-day. Andre and du Cloux (1993) reported 8 percent decrease in transpiration of wheat in response to doubled $CO_2$, which compares well to a 5 percent reduction in ET of wheat for a 200 ppm $CO_2$ increase in FACE studies (Hunsaker et al., 1997). Reddy et al. (2000, Figure 2.?), using similar chambers, found an 8 percent reduction in transpiration of cotton canopies at doubled $CO_2$ averaged over five temperature treatments, while Kimball et al. (1983) found a 4 percent reduction in seasonal water use of cotton at ambient versus 650 vpm $CO_2$ in lysimeter experiments in Arizona. Soybean canopies grown at 550 compared to 375 ppm in FACE experiments in Illinois, had 9 to 16 percent decreases in ET depending on season (Bernacchi et al. 2007). The slope in Bernacchi Figure 2.4 (p. 4?) shows a 12 percent reduction over three years. Allen et al. (2003) observed 9 percent reduction in ET of soybean with doubling of $CO_2$ in the sunlit, controlled-environment chambers for a 28/18ºC treatment (about the same mean temperature as the Illinois site), but they observed no reduction in ET for a high temperature treatment 40/30ºC. The extent of $CO_2$-related reduction in ET appears to be dependent on temperature. In their review, Horie et al. (2000) reported the same phenomenon in rice, where doubling $CO_2$ caused 15 percent reduction in ET at 26ºC, but resulted in increased ET at higher temperature (29.5ºC). At 24-26ºC, WUE of rice was increased by 50 percent with doubled $CO_2$, but the $CO_2$ enrichment effect declined as temperature increased. At higher temperature, the $CO_2$–induced reduction in conductance was less.

Using observed sensitivity of soybean stomatal conductance to $CO_2$ in a crop climate model, Allen (1990) showed that $CO_2$ enrichment from 330 to 800 ppm should cause an increase in foliage temperature of about 1ºC when air VPD is low, but an increase of about 2.5 and 4ºC with air VPD of 1.5 and 3 kPa, respectively. At the higher VPD values, the foliage temperatures simulated with this crop climate model (Allen, 1990) exceeded the differential observed under larger VPD in the sunlit controlled-environment chambers (Prasad et al. 2002; Allen et al., 2003; Prasad et al., 2006a). Allen et al. (2003) found that soybean canopies increased their conductance (lower resistance) at progressively larger VPD (associated with higher temperature), such that foliage temperature did not increase as much as supposed by the crop-climate-model. Concurrently, the anticipated degree of reduction in ET with doubling of $CO_2$, while being 9 percent less at cool temperature (28/18ºC), became progressively less and was non-existent (no difference) at very high temperatures (40/30ºC and 44/34ºC). In other words, the $CO_2$-induced reduction in conductance became less as temperature increased.

Boote et al. (1997, see Table 2.10-11) used a version of the CROPGRO-Soybean model with hourly energy balance and feedback of stomatal conductance on transpiration and leaf temperature (Pickering et al., 1995), to study simulated effects of 350 versus 700 ppm $CO_2$ for field weather from Ohio and Florida. The simulated transpiration was reduced 11 to 16 percent for irrigated sites and 7 percent for a rainfed site in Florida,

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while the ET was reduced 6 to 8 percent for irrigated sites and 4 percent for the rainfed site. Simulated water use efficiency was increased 53 to 61 percent, which matches the 50 to 60 percent increase in soybean WUE reported by Allen et al. (2003) for doubling of $CO_2$. The smaller reduction in transpiration and ET for the rainfed site was associated with more effective prolonged use of the soil water, also giving a larger yield response (44 percent) for rainfed crop than for irrigated (32 percent). The model simulated reductions in transpiration were close (11 to 16 percent) to those measured (12 percent) by Jones et al. (1985), and the reduction was much less than the reduction in leaf conductance. The model simulations also produced a 1ºC higher foliage temperature at mid-day under doubled $CO_2$.

Interactions of $CO_2$ enrichment with climatic factors of water supply and evaporative demand will be especially evident under water deficit conditions. The reduction in stomatal conductance with elevated $CO_2$ will cause soil water conservation and potentially less water stress, especially for crops grown with periodic soil water deficit or under high evaporative demand. This reduction in water stress effects on photosynthesis, growth, and yield has been documented for both C3 wheat (Wall et al. 2006) and C4 sorghum (Ottman et al. 2001; Wall et al. 2001; Triggs et al. 2004). Sorghum grown in the Arizona FACE site showed significant $CO_2$-induced enhancement of biomass and grain yield for water deficit treatments but no significant enhancement for sorghum grown with full-irrigation (Ottman et al. 2001). In the sorghum FACE studies, the stomatal conductance was reduced 32-37 percent (Wall et al. 2001), while ET was reduced 13 percent (Triggs et al. 2004).

### 2.4.6 Crop Response to Tropospheric Ozone

Ozone at the land surface has risen in rural areas of the United States, particularly over the past 50 years, and is forecast to continue increasing over the next 50 years. The Midwest and Eastern United States have some of the highest rural ozone levels on the globe. Average ozone concentrations rise toward the east and south, such that average levels in Illinois are higher than in Nebraska, Minnesota, and Iowa. Only Western Europe and Eastern China have similarly high levels. Argentina and Brazil, like most areas of the Southern Hemisphere, have much lower levels of ozone, and are forecast to see little increase over the next 50 years. Increasing ozone tolerance will therefore be important to the competitiveness of U.S. growers. Numerous models for future changes in global ozone concentrations have emerged that are linked to IPCC scenarios, so the impacts of ozone can be considered in the context of wider global change. For example, a modeled prediction that incorporates expected economic development and planned emission controls in individual countries predict increases in annual mean surface ozone concentrations in all major agricultural areas of the northern hemisphere (Dentener et al. 2005).

Ozone is a secondary pollutant resulting from the interaction of nitrogen oxides with sunlight and hydrocarbons. Nitrogen oxides are produced in the high temperature combustion of any fuel. They are stable and can be transported thousands of miles in the

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atmosphere. In the presence of sunlight, ozone is formed from these nitrogen oxides, and, in contrast to most pollutants, higher levels are observed in rural than urban areas. This occurs because rural areas have more hours of sunshine and less haze, and city air includes short-lived pollutants that react with and remove ozone. These short-lived pollutants are largely absent from rural areas allowing formation of high ozone concentrations. Levels of ozone during the day in much of the Midwest now reach an average of 60 parts of ozone per billion parts of air (ppb), compared to less than 10 ppb 100 years ago. While control measures on emissions of NOx and volatile organic carbons (VOCs) in North America and western Europe are reducing peak ozone levels, global background tropospheric ozone concentrations are on the rise (Ashmore, 2005). Ozone is toxic to many plants, but studies in greenhouses and small chambers have shown soybean, wheat, peanut, and cotton are the most sensitive of our major crops (Ashmore, 2002; http://www.ars.usda.gov/Main/docs.htm?docid=8453&page=1).

Ozone effects have been most extensively studied and best analyzed in soybean. Soybean is the most widely planted dicotyledonous crop and is our best model of C3 annual crops. The response of soybean to ozone can be influenced by the ozone profile and dynamics, nutrient and moisture conditions, atmospheric $CO_2$ concentration, even the cultivar investigated, which has created a very complex literature to interpret. Meta-analytic methods are useful to quantitatively summarize treatment effects across multiple studies and thereby identify commonalities. A meta-analysis of more than fifty studies of soybean, grown in controlled environment chambers at chronic levels of ozone, show convincingly that ozone exposure results in decreased photosynthesis, dry matter, and yield (Morgan et al. 2003). Even mild chronic exposure (40-60 ppb) produces such losses and these losses increase linearly with ozone concentration (Morgan et al. 2003) as anticipated from the exposure/response relationship shown by Mills et al. (2000). The meta-analytic summary further reveals that chronic ozone lowers the capacity of carbon uptake in soybean by reducing photosynthetic capacity and leaf area. Soybean plants exposed to chronic ozone levels were shorter with less dry mass and set fewer pods containing fewer smaller seeds. Averaged across all studies, biomass was decreased 34 percent, seed yield was 24 percent lower, but photosynthesis was depressed by only 20 percent. Ozone damage increased with the age of the soybean consistent with the suggestion that ozone effects accumulate over time (Adams et al. 1996, Miller et al. 1998) and may additionally reflect greater sensitivity of reproductive developmental stages particularly seed filling (Tingey et al., 2002). The meta-analysis did not reveal any interactions with other stresses, even stresses expected to lower stomatal conductance and therefore ozone entry into the leaf (Medlyn et al. 2001). However, all of the ozone effects on soybean mentioned above were less under elevated $CO_2$ a response generally attributed to lower stomatal conductance (Heagle et al. 1989).

Plant growth in chambers can be different compared to the open field (Long et al. 2006), and therefore the outcomes of the chamber experiments have been questioned as a sole basis for projecting yield losses due to ozone (Elagoz & Manning, 2005). FACE experiments in which soybean was exposed to a 20 percent elevation above ambient ozone levels indicate that ozone-induced yield losses were at least as large under open air treatment. In 2003, the background ozone level in central Illinois was unusually low over

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the growing season, averaging 45 ppb. Elevation of ozone by 20 percent in this year raised the ozone concentration to the average of the previous 10 years. In the plots with elevated ozone in 2003, yields were reduced approximately 25 percent (Morgan et al. 2006). This suggests that under open-air field conditions the yield loss, in a typical year due to ozone is even greater than predictions from greenhouse experiments (Ashmore, 2002). Analysis in the soybean FACE results showed a significant decrease in leaf area (Dermody et al. 2006), a loss of photosynthetic capacity during grain filling, and earlier senescence of leaves (Morgan et al. 2004). This may explain why the yield loss is largely due to decreased seed size rather than decreased seed number (Morgan et al. 2006). On average, yield losses in Illinois soybean FACE experiments between 2002 and 2005 were 0.5 percent per ppb increase over the 30 ppb threshold, which is twice the ozone sensitivity as determined in growth chamber studies (Ashmore, 2002). These results suggest that during an average year, ozone is currently causing soybean yield losses of 10 to 25 percent in the Midwest, with even greater losses in some years. The IPCC forecasts that ozone levels will continue to rise in the rural Midwest by about 0.5 ppb per year suggesting that soybean yields may continue to decline by one percent every two to four years. IPCC also forecasts that ozone, which is low in South America, will remain low in that region over the next 50 years.

Meta-analysis has not been conducted for the effects of ozone on any crops other than soybean or across different crops. Nevertheless, there is little doubt that current tropospheric ozone levels are limiting yield in many crops (e.g., Heagle, 1989) and further increases in ozone will reduce yield in sensitive species further. The effect of exposure to ozone on yield and yield parameters from studies conducted prior to 2000 are compiled in Table 4 of Black et al. (2000), which reveals that, in addition to soybean, the yield of the C3 crops wheat, oats, French and snap bean, pepper, rape, and various cucurbits are highly sensitive to chronic ozone exposure. Yield of woody perennial cotton is also highly sensitive to ozone (e.g., Temple, 1990; Heagle et al. 1996). While there are isolated reports that maize yield is reduced by ozone (e.g., Rudorff et al. 1996), C4 crops are generally much less sensitive to ozone. A recent study by Booker et al., (2007) and Burkey et al. (2007) on peanuts evaluated the effect of ozone under $CO_2$ levels from 375 to 730 ppm, and ozone levels of 22 to 75 ppb showed that $CO_2$ increases offset the effects of ozone. Increasing $CO_2$ levels overcame the effect of ozone on peanut yield; however, in none of the treatments was there a change in seed quality, or protein or oil content of the seed (Burkey et al. 2007).

### 2.4.7 Pastureland

An early comprehensive greenhouse study examined the photosynthetic response of 13 pasture species (Table 2.12) to elevated $CO_2$ (350 and 700 ppm) and temperature (12/7, 18/13, and 28/23 °C for daytime / nighttime temperatures, respectively) (Greer et al. 1995). On average, photosynthetic rates increased by 40 percent under elevated $CO_2$ in C3 species while those for C4 species remained largely unaffected. The response of C3 species to elevated $CO_2$ decreased as temperatures increased from 12 to 28°C. However, the temperatures at which the maximum rates of photosynthesis occurred varied with species and level of $CO_2$ exposure. At 350 ppm, four species (*L. multiflorum*, *A. capillaris*, *C. intybus*, and *P. dilatatum*) showed maximum rates of photosynthesis at

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18°C while, for the rest, the maximum occurred at 28 °C. At 700 ppm, rates shifted upwards from 18 to 28°C in *A. capillaries,* and downwards from 28 to 18 °C in *L. perenne*, *F. arundinacea*, *B. wildenowii*, and *T. subterraneum*. However, little if any correlation existed between the temperature response of photosynthesis and climatic adaptations of the pasture species.

**Table 2.12 Names, photosynthetic pathway, and growth characteristics**

| Species | Common name | Photosynthetic pathway | Growth characteristics |
|---|---|---|---|
| *Lolium multiflorum* | Italian ryegrass | C3 | Cool season annual grass |
| *Bromus wildenowii* | | C3 | Cool season perennial grass |
| *Lolium perenne* | Ryegrass | C3 | Cool season perennial grass |
| *Phalaris aquatica* | | C3 | Cool season perennial grass |
| *Trifolium dubium* | | C3 | Cool season annual broadleaf |
| *Trifolium subterraneum* | Subterraneum clover | C3 | Cool season annual broadleaf |
| *Agrostis capillaris* | | C3 | Warm season perennial grass |
| *Dactylis glomerata* | Orchardgrass | C3 | Warm season perennial grass |
| *Festuca arundinacea* | Tall fescue | C3 | Warm season perennial grass |
| *Cichorium intybus* | | C3 | Warm season perennial broadleaf |
| *Trifolium repens* | White clover | C3 | Warm season perennial broadleaf |
| *Digitaria sanguinalis* | Crabgrass | C4 | Warm season annual grass |
| *Paspalum dilatatum* | Dallisgrass | C4 | Warm season perennial grass |

**Table 2.12** Names, photosynthetic pathway, and growth characteristics of 13 pasture species. Adapted from Greer et al. (1995).

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In Florida, a 3-yr study examined the effects of elevated atmospheric $CO_2$ (360 and 700 ppm) and temperature (ambient temperature or baseline [B], B+1.5, B+3.0, and B+4.5 °C) on dry matter yield of rhizoma peanut (a C3 legume) and bahiagrass (a C4 grass) (Newman et al. 2001). On average, yields increased by 25 percent in rhizoma peanut plots exposed to elevated $CO_2$ but exhibited only a positive trend in bahiagrass plots under the same conditions. These results are consistent with C3- and C4-type plant responses to elevated $CO_2$ obtained in many other studies, where C4 plants show a reduced response to $CO_2$ because bundle sheath cells allow them to maintain a higher $CO_2$, thereby reducing the external-internal $CO_2$ gradient.

The response of forage species to elevated $CO_2$ may be affected by grazing and aboveground/belowground interactions (Wilsey, 2001). In a phytothron study, Kentucky bluegrass and timothy (*Phleum pratense* L.) – one plant of each species – were grown together in pots during 12 weeks under ambient (360 ppm) and elevated $CO_2$ (650 ppm), with and without aboveground defoliation, and with and without the presence of *Pratylenchus penetrans*, a root-feeding nematode commonly found in old fields and pastures. Timothy was the only species that responded to elevated $CO_2$ with an increase in shoot biomass leading to its predominance in the pots. This suggests that Kentucky bluegrass might be at the lower end of the range in the responsiveness of C3 grasses to elevated $CO_2$, especially under low nutrient conditions. Defoliation increased productivity only under ambient $CO_2$; thus, the largest response to elevated $CO_2$ was observed in non-defoliated plants. Timothy was the only species that showed an increase in root biomass under elevated $CO_2$. Defoliation reduced root biomass. Elevated $CO_2$ interacted with the presence of nematodes in reducing root biomass. In contrast, defoliation alleviated the effect of root biomass reduction caused by the presence of nematodes. This study demonstrates the importance of using aboveground/belowground approaches when investigating the environmental impacts of climate change (Wardle et al. 2004).

Kentucky bluegrass might not be the only species showing low response to elevated $CO_2$. Perennial ryegrass (*Lolium perenne* L.) has been reported to have low or even negative yield response to elevated $CO_2$ under field conditions but, contradictorily, often shows a strong response in photosynthetic rates (Suter et al. 2001). An experiment at the Swiss FACE examined the effects of ambient (360 ppm) and elevated (600 ppm) $CO_2$ on regrowth characteristics of perennial ryegrass (Suter et al., 2001). Elevated $CO_2$ increased root mass by 68 percent, pseudostems by 38 percent, and shoot necromass below cutting height by 45 percent during the entire regrowth period. Many of the variables measured (e.g., yield, dry matter, and leaf area index) showed a strong response to elevated $CO_2$ during the first regrowth period but not during the second suggesting a lack of a strong sink for the extra C fixed during the latter period.

The rising of $CO_2$ together with the projected changes in temperature and precipitation may significantly change the growth and chemical composition of plant species. However, it is not clear how the various forage species that harbor mutualistic relationships with other organisms would respond to elevated $CO_2$. Newman et al. (2003) studied the effects of endophyte infection, N fertilization, and elevated $CO_2$ on growth parameters and chemical composition of tall fescue. Fescue plants, with and without endophyte infection (*Neotyphodium coenophialum*), were transplanted to open chambers and exposed to ambient (350 ppm) and elevated (700 ppm) levels of $CO_2$. All chambers were fertilized with uniform rates of P and K. Nitrogen fertilizer was applied at rates of 6.7 and 67.3 g N $m^{-2}$. The results revealed complex interactions of the effects of elevated $CO_2$ on the mutualistic relationship between a fungus and its host, tall fescue. After 12 weeks of growth, plants grown under elevated $CO_2$ exhibited apparent photosynthetic

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rates 15 percent higher than under ambient conditions. The presence of the endophyte fungus in combination with N fertilization enhanced the $CO_2$ fertilization effect. Elevated $CO_2$ accelerated the rate of tiller appearance and increased dry matter production by at least 53 percent (under the low N treatment). Contrary to previous findings, Newman et al. (2003) found that elevated $CO_2$ decreased lignin concentrations by 14 percent. Reduced lignin concentration would favor the diet of grazing animals but hinder the stabilization of carbon in soil organic matter (Six et al. 2002).

Climate change may cause reduction in precipitation and, in turn, induce soil moisture limitations in pasturelands. An experiment in New Zealand examined the interaction of elevated $CO_2$ and soil moisture limitations on the growth of temperate pastures (Newton et al. 1996). Intact turves (plural of turf) composed primarily of perennial ryegrass and dallisgrass (*Paspalum dilatatum* Poir.) were grown for 324 days under two levels of $CO_2$ (350 and 700 ppm) with air temperatures and photoperiod designed to emulate the monthly climate of the region. After this equilibration period, half the turves in each $CO_2$ treatment underwent soil moisture deficit for 42 days. Turves under elevated $CO_2$ continued to exchange $CO_2$ with the atmosphere while turves under ambient $CO_2$ did not. Root density measurements indicated that roots acted as sinks for the carbon (C) fixed during the soil moisture deficit period. Upon rewatering, turves under ambient $CO_2$ had a vigorous rebound in growth while those under elevated $CO_2$ did not exhibit additional growth suggesting that plants may exhibit a different strategy in response to soil moisture deficit depending on the $CO_2$ concentration.

### 2.4.8 Rangeland

Most forage species on rangelands have either the C3 or the C4 photosynthetic pathway. Photosynthesis of C3 plants, including most woody species and herbaceous broad-leaf species (forbs), is not $CO_2$-saturated at the present atmospheric concentration, so carbon gain and productivity usually are very sensitive to $CO_2$ in these species (Drake et al., 1997). Conversely, photosynthesis of C4 plants, including many of the perennial grass species of rangelands, is nearly $CO_2$-saturated at the current atmospheric $CO_2$ concentration of ~380 ppm when soil water is plentiful, although the C4 metabolism does not preclude photosynthetic and growth responses to $CO_2$ (Polley et al. 2003). In addition, $CO_2$ effects on rates of water loss (transpiration) and plant WUE (i.e. biomass produced per unit of transpiration) are at least as important as photosynthetic response to $CO_2$ for rangeland productivity. Stomata of most herbaceous plants partially close as $CO_2$ concentration increases, thus reducing plant transpiration. Reduced water loss improves plant and soil water relations, increases plant production under water limitation, and may lengthen the growing season for water-limited vegetation (Morgan et al. 2004b).

$CO_2$ enrichment will stimulate NPP on most rangelands, with the amount of increase dependent on precipitation and soil water availability. Indeed, there is evidence that the historical increase in $CO_2$ of about 35 percent already has enhanced rangeland NPP. Increasing $CO_2$ from pre-industrial levels to today's elevated concentrations (from 250 to 550 ppm) increased aboveground NPP of mesic grassland in central Texas by between 42 percent and 69 percent (Polley et al. 2003). Biomass increased by similar amounts at pre-

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industrial to current, and current to elevated concentrations. Comparisons between $CO_2$-induced production responses of semi-arid Colorado shortgrass steppe with the sub-humid Kansas tall grass prairie suggest that Great Plains rangelands respond more to $CO_2$ enrichment during dry than wet years, and that the potential for $CO_2$-induced production enhancements are greater in drier rangelands (Figure 2.12). However, in the still-drier Mojave Desert, $CO_2$ enrichment enhanced shrub growth most consistently during relatively wet years (Smith et al. 2000). $CO_2$ enrichment stimulated total biomass (aboveground + belowground) production in one study on annual grassland in California (Field et al. 1997), but elicited no production response in a second experiment (Shaw et al. 2002).

## 2.5 Episodes of Extreme Events

### 2.5.1 Elevated temperature or rainfall deficit

Episodic increases in temperature would have their greatest effect if they occur just prior to or during critical crop pollination phases. Crop sensitivity and ability to compensate during later, improved weather will depend on the synchrony of anthesis in each crop; maize for example has a highly compressed phase of anthesis, while spikelets on rice and sorghum may achieve anthesis over a period of a week or more. Soybean, peanut, and cotton will have several weeks over which to spread the success of reproductive structures. For peanut (and presumably other legumes) the sensitivity to elevated temperature for a given flower, extends from six days prior to opening (pollen cell division and formation) up through the day of anthesis (Prasad et al. 2001). Therefore, several days of elevated temperature may affect fertility of many flowers, whether still in their formative 6-day phase or just achieving anthesis today. In addition, the first six hours of the day were more critical during pollen dehiscence, pollen tube growth and fertilization occur.

For rice, the reproductive processes that occur within one to three hours after anthesis (dehiscence of the anther, shedding of pollen, germination of pollen grains on stigma, and elongation of pollen tubes) are disrupted by daytime air temperatures above 33ºC (Satake and Yoshida, 1978). Since anthesis occurs between about 9 to 11am in rice (Prasad et al. 2006), exceeding such air temperature may be already be common and may become more prevalent in the future. Pollination processes in other cereals, maize, and sorghum may have a similar sensitivity to elevated daytime temperature as rice. Rice and sorghum have the same sensitivity of grain yield, seed HI, pollen viability, and success in grain formation in which pollen viability and percent fertility is first reduced at instantaneous hourly air temperature above 33ºC and reaches zero at 40ºC (Kim et al. 1996; Prasad et al., 2006a, 2006b). Diurnal max/min day/night temperatures of 40/30ºC (35ºC mean) cause zero yield for those two species. We believe the same would apply to maize.

### 2.5.2 Intense rainfall events

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Historical data for many parts of the United States indicate an increase in the frequency of high-precipitation events (e.g. > 5 cm in 48 hours), and this trend is projected to continue for many regions. One economic consequence of excessive rainfall is delayed spring planting, which jeopardizes profits for farmers paid a premium for early season production of high value horticultural crops such as melon, sweet corn, and tomatoes. Field flooding during the growing season causes crop losses associated with anoxia, increases susceptibility to root diseases, increases soil compaction (due to use of heavy farm equipment on wet soils), and causes more runoff and leaching of nutrients and agricultural chemicals into ground- and surface-waters. More rainfall concentrated into high precipitation events will increase the likelihood of water deficiencies at other times because of the changes in rainfall frequency (Hatfield and Prueger, 2004). Heavy rainfall is often accompanied by wind gusts in storm events, which increases the potential for lodging of crops. Wetter conditions at harvest time could increase the potential for decreasing quality of many crops.

## *2.6 Possible Future Changes and Impacts*

### 2.6.1 Projections Based on Increment of Temperature and $CO_2$ for crops

What is the expected effect of a further rise in $CO_2$ of 380 to 440 ppm along with a 0.8ºC rise in temperature over the next 30 years for representative crops? The crop responsiveness of grain yield to temperature comes from Table 2.13 with linear interpolation, but dependent on current mean temperatures during the reproductive phase in different regions (crops like soybean and maize are dominant in both Midwest and Southern regions, while some like cotton, sorghum, and peanut are only in Southern regions). The crop responsiveness of grain yield to $CO_2$ is taken from Table 10, with Michaelis-Menten rectangular hyperbola interpolation with value of 1.0 set at 350 ppm, the published enhancement ratio set at 700ppm and with a compensation $CO_2$ concentration at the x-axis consistent with C3 or C4 species at 30C. With this generalized shape, the response for 380 to 440 ppm $CO_2$ was 1.0 percent for C4 and 6.1 to 7.4 percent for C3 species, except for cotton, which had 9.2 percent response (Table 2.10). For maize, under water sufficiency conditions in the Midwest, the net yield response is -1.5 percent, assuming additivity of the -2.5 percent from 0.8ºC rise and +1.0 percent from $CO_2$ of 380 to 440 ppm (Table 2.10). The response of maize in the South could be more negative. For soybean under water sufficiency in the Midwest, net yield response is +9.1 percent, assuming additivity of the +1.7 percent from 0.8ºC rise above current 22.5ºC mean and +7.4 percent from $CO_2$ increase. For soybean under water sufficiency in the South, the temperature effect will be detrimental, -2.4 percent, with 0.8ºC temperature increment above 26.7ºC, with the same $CO_2$ effect, giving a net yield response of +5.0 percent. For wheat (with no change in water availability), the net yield response would be +2.4 percent coming from -4.4 percent with 0.8ºC rise, and +6.8 percent increase from $CO_2$ increase. For rice in the South, net yield response is -1.6 percent, assuming additivity of the -8.0 percent from 0.8ºC rise and +6.4 percent from $CO_2$ increase. For peanut in the South, the net yield response is +3.4 percent, assuming additivity of the -3.3 percent from 0.8ºC rise and +6.7 percent from $CO_2$ increase. For cotton in the South, the net yield

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response is +5.7 percent, assuming additivity of the -3.5 percent from 0.8ºC rise and +9.2 percent from $CO_2$ increase. The sorghum response is less certain, although yield reduction caused by shortening filling period is dominant, giving a net yield decrease of 5.2 percent. Bean yield response is less certain, with net effect of +0.3 percent, coming from -5.8 percent response to 0.8ºC rise and +6.1 percent from $CO_2$ increase.

Projections of crop yield under water deficit should start with the responses to temperature and $CO_2$ for the water-sufficient cases (Table 2.10). However, yield will likely be further increased to the same extent (percentage) that increased $CO_2$ causes reduction in ET. Model simulations with CROPGRO-Soybean with energy balance option and stomatal feedback from $CO_2$ enrichment (350 to 700 ppm, without temperature increase) resulted in a 44 percent yield increase for water-stressed crops compared to fully-irrigated crops (32 percent). The yield increment was nearly proportional to the decrease in simulated transpiration (11 to 16 percent). Based on this assumption, the 380 to 440 ppm $CO_2$ increment would further increase yield of C3 crops (soybean, rice, wheat, and cotton) by an additional 1.4 to 2.1 percent (incremental reduction in ET from $CO_2$ in Table 2.10). However, the projected 0.8ºC would increase ET by 1.2 percent, thereby partially negating this water-savings effect of $CO_2$.

### 2.6.2 Projections for weeds

Many weeds respond more positively to increasing $CO_2$ than most cash crops, particularly C3 "invasive" weeds that reproduce by vegetative means (roots, stolons, etc.) (Ziska and George 2004; Ziska 2003). Recent research also suggests that glyphosate, the most widely used herbicide in the United States, loses its efficacy on weeds grown at $CO_2$ levels we anticipate will occur in the coming decades (Ziska et al. 1999). While many weed species have the C4 photosynthetic pathway, and therefore show a smaller response to atmospheric $CO_2$ relative to C3 crops, in most agronomic situations crops are in competition with a mix of both C3 and C4 weeds. In addition, the worst weeds for a given crop are often similar in growth habit or photosynthetic pathway. To date, for all weed/crop competition studies where the photosynthetic pathway is the same, weed growth is favored as $CO_2$ is increased (Ziska and Runion, 2006).

The habitable zone of many weed species is largely determined by temperature, and weed scientists have long recognized the potential for northward expansion of weed species' ranges as the climate changes (Patterson et al. 1999). More than 15 years ago, Sasek and Strain (1990) utilized climate model projections of the -20ºC minimum winter temperature zone to forecast the northward expansion of kudzu *(Pueraria lobata, var. montana*), an aggressive invasive weed that currently infests more than one million hectares in the southeastern U.S. While temperature is not the only factor that could constrain spread of kudzu and other invasive weeds, a more comprehensive assessment of potential weed species migration based on the latest climate projections for the United States seems warranted.

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### 2.6.3 Projections for insects and pathogens

Plants do not grow in isolation in agroecosystems. Beneficial and harmful insects, microbes, and other organisms in the environment will also be responding to changes in $CO_2$ and climate. Studies conducted in Western Europe and other regions have already documented changes in spring arrival and/or geographic range of many insect and animal species due to climate change (Montaigne 2004; Goho 2004, Walther et al. 2002). Temperature is the single most important factor affecting insect ecology, epidemiology, and distribution, while plant pathogens will be highly responsive to humidity and rainfall, as well as temperature (Coakley et al. 1999).

There is currently a clear trend for increased insecticide use in warmer, more southern regions of the United States, compared to cooler, higher latitude regions. For example, the frequency of pesticide sprays for control of lepidopteran insect pests in sweet corn currently ranges from 15 to 32 applications per year in Florida (Aerts et al. 1999), to four to eight applications in Delaware (Whitney et al. 2000), and zero to five applications per year in New York (Stivers 1999). Warmer winters will likely increase the populations of insect species that currently are marginally over-wintering in high latitude regions, such as flea beetles (*Chaetocnema pulicaria*), which act as a vector for bacterial Stewart's Wilt (*Erwinia sterwartii*), an economically important corn pathogen (Harrington et al. 2001).

An overall increase in humidity and frequency of heavy rainfall events projected for many parts of the United States will tend to favor some leaf and root pathogens (Coakley et al. 1999). However, an increase in short- to medium-term drought will tend to decrease the duration of leaf wetness and reduce some forms of pathogen attack on leaves.

The increasing atmospheric concentration of $CO_2$ alone may affect plant-insect interactions. The frequently observed higher C:N ratio of leaves of plants grown at high $CO_2$ (Wolfe 1994) can require increased insect feeding to meet nitrogen (protein) requirements (Coviella and Trumble 1999). However, slowed insect development on high $CO_2$-grown plants can lengthen the insect life stages vulnerable to attack by parasitoids (Coviella and Trumble 1999). In a recent FACE study, Hamilton et al. (2005) found that early season soybeans grown at elevated $CO_2$ atmosphere had 57 percent more damage from insects, presumably due in this case to measured increases in simple sugars in leaves of high $CO_2$-grown plants.

### 2.6.4 Predictions of Forage Yields and Nutrient Cycling under Climate Change

Alfalfa production was simulated with the EPIC (Environmental Policy Integrated Climate) agroecosystem model (Williams, 1995), using various climate change projections from the HadCM2 (Hadley Centre Climate Model) (Izaurralde et al. 2003), BMRC (Australia's Bureau of Meteorology Research Centre), and UIUC (University of Illinois, Urbana-Champaigne) GCMs (Thomson et al. 2005). All model runs were driven with $CO_2$ levels of 365 and 560 µmol mol$^{-1}$ and non-irrigated conditions. The results give an indication of pastureland crop response to changes in temperature, precipitation, and

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$CO_2$ for major regions of the United States (Table 2.12). Of these three factors, variation in precipitation had the greatest impact on regional alfalfa yield. Under the HadCM2 projected climate, alfalfa yields increase substantially in eastern regions, with declines through the central part of the country where temperature increases are greater and precipitation is lower. Slight alfalfa yield increases are predicted for western regions. The BMRC model projects substantially higher temperatures and consistent declines in precipitation over the next several decades, leading to a decline nationwide in alfalfa yields. In contrast, the UIUC model projects more moderate temperature increases along with higher precipitation, leading to modest increases in alfalfa yields throughout the central and western regions. While these results illustrate the uncertainty of model projections of crop yields due to the variation in global climate model projections of the future, they also underscore the primary importance of future precipitation changes on crop yield.

**Table 2.13 Change in alfalfa yields**

| Region | $CO_2$ | HadCM2 | | | BMRC | | | UIUC | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ΔT °C | ΔP mm | Yield % change | ΔT °C | ΔP mm | Yield % change | ΔT °C | ΔP mm | Yield % change |
| Great Lakes | 365 | 1.13 | 74 | 17.0 | 1.79 | -6 | -0.4 | 0.96 | 19 | -1.3 |
| | 560 | | | 20.6 | | | 0.0 | | | -1.0 |
| Ohio | 365 | 0.70 | 80 | 12.5 | 1.66 | -16 | -5.2 | 0.86 | 25 | -3.7 |
| | 560 | | | 13.9 | | | -5.0 | | | -3.8 |
| Upper Mississippi | 365 | 1.24 | 74 | 10.9 | 1.71 | -14 | -3.4 | 0.89 | 29 | -2.2 |
| | 560 | | | 14.8 | | | -2.5 | | | -2.1 |
| Souris-Red-Rainy | 365 | 1.40 | -30 | -30.7 | 1.73 | -3 | -1.9 | 0.96 | 12 | -0.4 |
| | 560 | | | -25.4 | | | 2.1 | | | 2.6 |
| Missouri | 365 | 1.42 | 34 | -9.2 | 1.50 | -18 | -9.4 | 0.92 | 41 | 3.5 |
| | 560 | | | -7.1 | | | -9.1 | | | 3.1 |
| Arkansas | 365 | 1.77 | -2 | -18.6 | 1.53 | -32 | -9.6 | 0.76 | 61 | 3.8 |
| | 560 | | | -14.2 | | | -7.3 | | | 5.1 |
| Rio Grande | 365 | 3.11 | 12 | 5.0 | 1.41 | -20 | -9.3 | 0.84 | 25 | 16.2 |
| | 560 | | | 5.3 | | | -8.7 | | | 17.8 |
| Upper Colorado | 365 | 2.21 | 76 | 5.0 | 1.48 | -18 | -15.3 | 0.97 | 40 | 16.2 |
| | 560 | | | 5.4 | | | -14.1 | | | 16.7 |
| Lower Colorado | 365 | 1.43 | 2 | 7.3 | 1.31 | -23 | -16.0 | 0.97 | 27 | 7.8 |
| | 560 | | | 11.9 | | | -19.4 | | | 4.7 |
| Great Basin | 365 | 0.62 | 21 | -4.7 | 1.36 | -15 | -6.3 | 1.07 | 45 | 24.2 |
| | 560 | | | -4.5 | | | -7.1 | | | 23.7 |
| Pacific Northwest | 365 | 0.45 | 3 | 0.4 | 1.24 | -6 | 2.0 | 1.11 | 54 | 8.4 |
| | 560 | | | 1.7 | | | 1.9 | | | 8.1 |
| California | 365 | 0.95 | 58 | 8.7 | 1.13 | -45 | -5.5 | 1.08 | 17 | 6.3 |
| | 560 | | | 9.3 | | | -3.5 | | | 4.6 |

**Table 2.13.** Change in alfalfa yields in major U.S. regions as a percentage of baseline yield with average temperature and precipitation change under the selected climate model for early century (2030) climate change projections.

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Multiple regression models built from the data in Table 2.13 revealed how alfalfa yield changes ($\Delta Y$, %) were affected by $CO_2$ concentration, temperature change ($\Delta T$, °C), and precipitation change ($\Delta P$, mm). Overall, the major explanatory variable was precipitation change:

$$\Delta y = 0.23053\Delta P - 0.15657 \qquad R^2 = 0.50^{***} \qquad (1)$$

For the BMRC model, the best equation was:

$$\Delta y = 0.21838\Delta P - 2.4412 \qquad R^2 = 0.18^{*} \qquad (2)$$

For the HadCM2 model, the best equation was:

$$\Delta y = 0.227474\Delta P - 7.73302 \qquad R^2 = 0.57^{***} \qquad (3)$$

For the UIUC model, the best equation was:

$$\Delta y = 0.21211\Delta P + 28.277\Delta T - 27.22576 \qquad R^2 = 0.24,\ p<0.056 \qquad (4)$$

All equations suggest that future changes in precipitation will be very important in determining alfalfa yields. Roughly, for every 4 mm increase in annual precipitation, the models predict a one percent increase in dryland alfalfa yields.

Thornley and Cannell (1997) argued that experiments on elevated $CO_2$ and temperature effects on photosynthesis and other ecosystem processes might be limited in their usefulness for at least two reasons. Firstly, the authors argue that laboratory or field experiments incorporating sudden changes in temperature or elevated $CO_2$ are short term in nature and thus, they rarely produce quantitative changes in NPP, ecosystem C or other ecosystem properties that are connected to the long-term responses to gradual climate change. Secondly, the difficulty of incorporating grazing in these experiments prevents a full analysis of the effects of grazing on ecosystem properties such as NPP, LAI, belowground process, and ecosystem C. Thornley and Cannell (1997) used their Hurley Pasture Model to simulate ecosystem responses of ungrazed and grazed pastures to increasing trends in $CO_2$ concentrations and temperature. The simulations revealed three important results: a) rising $CO_2$ induces a C sink, b) rising temperatures alone produce a C source, and c) a combination of the two effects is likely to generate a C sink for several decades (5-15 g C $m^{-2}$ $yr^{-1}$). Modeling the dynamics of mineral N availability in grazed pastures under elevated $CO_2$, Thornley and Cannell (2000) ascertained the role of the mineral N pool and its turnover rate in slowly increasing C content in plants and soils.

### 2.6.5 Implications of Altered Productivity, Nitrogen cycle (forage quality), Phenology, and Growing Season on Species Mixes, Fertilizer, and Stocking

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In general, the response of pasture species to elevated $CO_2$ deduced from these studies is consistent with the general response of C3 and C4 type vegetation to elevated $CO_2$, although significant exceptions exist. Pasture species with C3-type metabolism increased their photosynthetic rates by up to 40 percent but not those with a C4 pathway (Greer et al. 1995). Examples of C3 species grown in the United States exhibiting increased photosynthetic rates under elevated $CO_2$ include Italian ryegrass, orchardgrass, rhizoma peanut, tall fescue, and timothy (Greer et al. 1995; Newman et al. 2001; Wilsey 2001). Kentucky bluegrass has shown low response to elevated $CO_2$ (Wilsey 2001). Perennial ryegrass has shown a positive response in terms of photosynthetic rate (Greer et al., 1995), but a low or even negative response in terms of plant yield (Suter et al. 2001). Bahiagrass, an important pasture species in Florida, appears marginal in its response to elevated $CO_2$ (Newman et al. 2001), which, in combination with current and future reductions in their area growth due to the expansion of urban areas, may force producers to use their pastures more intensely (Stewart et al. 2007).

The study of Greer et al. (1995) suggests shifts in optimal temperatures for photosynthesis under elevated $CO_2$, with perennial ryegrass and tall fescue showing a downward shift in their optimal temperature from 28 to 18°C. Unlike croplands, the literature for pasturelands is sparse in providing quantitative information to predict the yield change of pastureland species under a temperature increase of 0.8 °C. The projected increases in temperature and the lengthening of the growing season should be, in principle, beneficial for livestock produced by increasing pasture productivity and reducing the need for forage storage during the winter period.

Naturally, changes in $CO_2$ and temperature will be accompanied by changes in precipitation, with the possibility of more extreme weather causing floods and droughts. Pasture species that grow under elevated $CO_2$ may respond differently to drought conditions in comparison to those that grow under ambient conditions. Newton et al. (1996) found that turves of perennial rygrass and dallisgrass under elevated $CO_2$ grew more than turves under ambient $CO_2$. When exposed to a prolonged period of drought, turves under elevated $CO_2$ continue to exchange $CO_2$, while those under ambient conditions did not. When the water constraint was removed, the reverse occurred; the turves under ambient $CO_2$ rebounded vigorously while those under elevated $CO_2$ failed to exhibit any additional growth suggesting different strategies of the turves for responding to soil moisture deficits depending on the $CO_2$ concentration. Precipitation changes will likely play a major role in determining NPP of pasture species as suggested by the simulated one percent change in yields of dryland alfalfa for every 4-mm change in annual precipitation (Izaurralde et al. 2003; Thomson et al. 20052003).

Another aspect that emerges from this review is the need for comprehensive studies of the impacts of climate change on the pasture ecosystem including grazing regimes, mutualistic relationships (e.g., plant roots-nematodes; N-fixing organisms), as well as C, nutrient and water balances. Despite their complexities, the studies by Newton et al. (1996) and Wilson (2001) underscore the importance, difficulties, and benefits of conducting multifactor experiments. To augment their value, these studies should include the use of simulation modeling (Thornley and Cannell, 1997) in order to test hypotheses regarding ecosystem processes.

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### *1.1.1.10 $CO_2$ Effects on Rangeland Plants*

Photosynthesis of C3 rangeland plants, including most woody species and herbaceous broad-leaf species (forbs), is not $CO_2$-saturated at the present atmospheric concentration, so carbon gain and productivity usually are very sensitive to $CO_2$ in these species (Drake et al. 1997). Conversely, photosynthesis of C4 plants, including many of the perennial grass species of rangelands, is nearly $CO_2$-saturated at the current atmospheric $CO_2$ concentration of ~380 ppm when soil water in plentiful, although the C4 metabolism does not preclude photosynthetic and growth responses to $CO_2$ (Polley et al. 2003). In addition, $CO_2$ effects on rates of water loss (transpiration) and plant WUE are at least as important as photosynthetic response to $CO_2$ for rangeland productivity. Stomata of most herbaceous plants partially close as $CO_2$ concentration increases, thus reducing plant transpiration. Reduced water loss improves plant and soil water relations, increases plant production under water limitation, and may lengthen the growing season for water-limited vegetation (Morgan et al. 2004b).

$CO_2$ enrichment will stimulate NPP on most rangelands, with the amount of increase dependent on precipitation and soil water availability. Indeed, there is evidence that the historical increase in $CO_2$ of about 35 percent already has enhanced rangeland NPP. Increasing $CO_2$ from pre-industrial to elevated concentrations (from 250 to 550 ppm) increased aboveground NPP of mesic grassland in central Texas by between 42 percent and 69 percent (Polley et al. 2003). Biomass increased by similar amounts at pre-Industrial to current and current to elevated concentrations. Comparisons between $CO_2$-induced production responses of semi-arid Colorado shortgrass steppe with the sub-humid Kansas tall grass prairie suggest that Great Plains rangelands respond more to $CO_2$ enrichment during dry than wet years, and that the potential for $CO_2$-induced production enhancements are greater in drier rangelands (Figure 2.12). However, in the still-drier Mojave Desert, however, $CO_2$ enrichment enhanced shrub growth most consistently during relatively wet years (Smith et al. 2000). $CO_2$ enrichment stimulated total biomass (aboveground + belowground) production in one study on annual grassland in California (Field et al., 1997), but elicited no production response in a second experiment (Shaw et al. 2002).

### *1.1.1.11 Increases in Temperature on Rangelands*

Like $CO_2$ enrichment, increasing ambient air and soil temperatures may enhance rangeland NPP, although negative effects of higher temperatures also are possible, especially in dry and hot regions. Temperature directly affects plant physiological processes, but rising ambient temperatures may indirectly affect plant production by extending the length of the growing season, increasing soil N mineralization and availability, altering soil water content, and shifting plant species composition and community structure (Wan et al. 2005). Rates of biological processes for a given species typically peak at plant temperatures that are intermediate in the range over which a species is active, so direct effects of warming likely will vary within and among years and among plant species. Because of severe cold-temperature restrictions on growth rate

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and duration, warmer plant temperatures alone should stimulate production in high- and mid-latitude and high-altitude rangelands.Conversely, increasing plant temperature during summer months may reduce NPP. Increasing the daily minimum air temperature and mean soil temperature (2.5 cm depth) by 2ºC increased aboveground NPP of tallgrass prairie in Oklahoma between 0 percent and 19 percent during the first three years of study, largely by increasing NPP of C4 grasses (Wan et al. 2005). Warming stimulated biomass production in spring and autumn, but aboveground biomass in summer declined as soil temperature increased.

Positive effects of warming on production may be lessened by an accompanying increase in the rate of water loss. Warming reduced the annual mean of soil water content in tallgrass prairie during one year (Wan et al. 2005), but actually increased soil water content in California annual grassland by accelerating plant senescence (Zavaleta et al. 2003b).

### *1.1.1.12 Altered Precipitation Effects on Rangeland*

Historic changes in climatic patterns have always been accompanied by changes in grassland vegetation because grasslands display an optimal combination of production potential and variability in precipitation (Knapp & Smith 2001). In contrast, aboveground net primary productivity (ANPP) variability in forest systems appears to be limited by invariant rainfall patterns, while production potential more strongly limits desert and arctic/alpine systems.

Increased rainfall variability caused by altered rainfall timing (no change in rainfall amount) led to lower and more variable soil water content (0-30 cm depth), an approximate 10 percent reduction in ANPP, which was species-specific, and increased root to shoot ratios in a native tallgrass prairie ecosystem in northeastern Kansas (Fay et al. 2003). In general, vegetation responses to rainfall timing (no change in amount) were at least equal to changes caused by rainfall quantity (30 percent reduction, no change in timing). Reduced ANPP most likely resulted from direct effects of soil moisture deficits on root activity, plant water status, and photosynthesis. Projected increases in rainfall variability may alter key carbon cycling processes as well as plant community composition, independent of changes in total precipitation (Knapp et al. 2002). Thus, altered rainfall regimes are likely to elicit important changes in several aspects of rangeland ecology, and interactions of those response with other climate change elements remains a significant challenge for predicting ecosystem responses to climate change.

On most rangelands where total annual precipitation is sufficiently low that soil water limits productivity more than other soil resources, seasonality of precipitation plays an important role in regulating NPP. For example, herbaceous plants in the Great Basin are physiologically adapted to winter/early spring precipitation patterns, where reliable soil water recharge occurs prior to the growing season. A change in climate that shifts precipitation away from a winter precipitation pattern to a spring/early summer pattern would likely reduce productivity, cover, and reproduction of native herbaceous plant

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species (Svejcar et al. 2003), and could lead to the eventual loss of species most affected. Without species replacement, increased bare ground and greater vulnerability to soil erosion would increase likelihood of invasion by noxious weeds. Wildlife, domestic livestock, and other organisms that depend on herbaceous annual and perennial vegetation would likely also be affected.

Oak savannas of the southwestern United States also experience a strongly seasonal pattern of precipitation, with a primary peak in summer and lesser peak in winter (Weltzin & McPherson 2003). The herbaceous understory species are most responsive to summer precipitation, while oak seedling growth (*Quercus emoryi*.) was not responsive. Here, herbaceous biomass was more sensitive to summer precipitation than to winter precipitation, but the growth of *Q. emoryi* seedlings was not affected by season of precipitation. If precipitation regimes shift toward wetter winters and drier summers, loss of herbaceous biomass and an increase in woody vegetation in this system would be expected. However, winter precipitation can play an important role where the recharge of soil moisture is required to offset low summer precipitation. Northern Great Plains grasslands are dominated by cool-season plant species that complete most of their growth by late spring to early summer, and ANPP primarily depends on sufficient soil moisture going into the growing season (Heitschmidt and Haferkamp 2003).

### 2.6.6 Impacts on Species Composition

#### *1.1.1.13 Environmental controls on species composition*

At regional scales, the species composition of rangelands is determined mostly by climate and soils, with fire regime, grazing, and other land uses locally important. The primary climatic control on the distribution and abundance of plants is water balance (Stephenson, 1990). On rangelands in particular, species composition is highly correlated with both the amount of water plants use and its availability in time and space.

Each of the global changes considered here, $CO_2$ enrichment, altered precipitation regimes, and higher temperatures, may change species composition by altering water balance. The importance of water balance to species composition is evident in the strong correlation between current relative abundances of different plant types (C3 grasses, C4 grasses, and shrubs) and temperature and precipitation (Paruelo and Lauenroth 1996). Epstein et al. (2002) used climate change projections from GCMs and regression equations, which related current relative abundances of plant types to climatic variables, to predict future abundances of grasses and shrubs on western rangelands. Using GCM predictions of a >4ºC increase in mean annual temperature, and 10 percent increase in precipitation within the century, Epstein et al. (2002) predicted that C4 grasses would increase substantially in the western U.S., particularly in currently cool areas like the northern U.S. and southern Canada. Shrub abundance was projected to increase at the expense of grasses in the already shrubby desert ecosystems of the Southwest.

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A warmer climate should be characterized by more rapid evaporation and transpiration, and an increase in frequency of extreme events like heavy rains and droughts. Changes in timing and intensity of rainfall may be especially important on arid rangelands where plant community dynamics are ‘event-driven’ and the seasonality of precipitation determines which plant growth strategies are successful. The timing of precipitation also affects the vertical distribution of soil water, which regulates relative abundances of plants that root at different depths (Ehleringer et al. 1991; Weltzin and McPherson 1997), and influences natural disturbance regimes, which feedback to regulate species composition. For example, grass-dominated rangelands in the eastern Great Plains were historically tree-free due to periodic fire. Fires occurred frequently because the area is subject to summer droughts, dessicating grasses, and providing abundant fuel for wildfires.

Unless stomatal closure is compensated by atmospheric or other feedbacks, $CO_2$ enrichment also should affect water balance by slowing canopy-level ET (Polley et al. 2007), and the rate or extent of soil water depletion (Morgan et al. 2001; Nelson et al. 2004). Plants that are less tolerant of water stress than current dominants may be favored (Polley et al. 2000). However, because of their sensitivity to $CO_2$ rising $CO_2$ may generally favor C3 grasses, forbs, and woody plants over C4 grasses (Morgan et al. 2005, Polley, 1997). Also, deep-rooted forbs, and shrubs will also be favored under this scenario because of their strong carbon-allocation and nitrogen-use strategies (Polley et al. 2000; Bond and Midgley 2000; Morgan et al. in press).

However, rising $CO_2$ may favor plants with greater photosynthetic sensitivity to $CO_2$, such as C3 grasses and deep-rooted forbs, as compared to C4 grasses, which have a limited direct photosynthetic response to $CO_2$ (Morgan et al. 2005, Polley, 1997). The final outcome of these competitive responses of species to combined temperature, precipitation, and rising $CO_2$ will likely vary among in different rangeland ecosystems.

Observational evidence that global changes are affecting rangelands and other ecosystems is accumulating. During the last century, juniper trees in the arid west grew more than expected because of climatic conditions, implying that the historical increase in atmospheric $CO_2$ concentration stimulated juniper growth (Knapp et al. 2001). The apparent growth response of juniper to $CO_2$ was proportionally greater during dry than wet years, consistent with the notion that access to deep soil water, which tends to accumulate under elevated $CO_2$ (Morgan et al. 2004b), gives a growth advantage to deep-rooted woody vegetation (Polley, 1997, Morgan, in press). Results from many $CO_2$ experiments (Morgan et al. 2004b) suggest that expansion of shrublands over the past couple hundred years has been driven in part by a combination of climate change and increased atmospheric $CO_2$ concentrations (Polley, 1997, Archer et al. 1995).

#### *1.1.1.14 Local and short-term changes*

Our ability to predict vegetation changes at local scales and over shorter time periods is more limited because at these scales the response of vegetation to global changes depends on a variety of local processes, including disturbance regimes, and how quickly various species can disperse seeds across sometimes-fragmented landscapes. Nevertheless, patterns of vegetation response are beginning to emerge.

1) Directional shifts in the composition of vegetation occur most consistently when global change treatments alter water availability (Polley et al. 2000, Morgan et al. 2004b).

2) Effects of $CO_2$ enrichment on species composition and the rate of species change likely will be greatest in disturbed or early-successional communities where nutrient and light availability are high and species change is influenced largely by growth-related parameters (e.g., Polley et al. 2003).

3) Weedy and invasive plant species likely will be favored by $CO_2$ enrichment (Smith et al. 2000) and perhaps by other global changes because these species possess traits (rapid growth rate, prolific seed production) that permit a large growth response to $CO_2$.

4) $CO_2$ enrichment may accelerate the rate of successional change in species composition following overgrazing or other severe disturbances (Polley et al. 2003).

5) Plants do not respond as predictably to temperature or $CO_2$ as to changes in water, N, and other soil resources (Chapin et al. 1995). Progress in predicting the response of vegetation to temperature and $CO_2$ thus may require a better understanding of indirect effects of global change factors on soil resources. At larger scales, effects of atmospheric and climatic change on fire frequency and intensity and on soil water and N availability likely will influence botanical composition to a much greater extent than global change effects on production.

6) Rangeland vegetation will be influenced more by management practices (land use) than by atmospheric and climatic change. Global change effects will be superimposed on and modify those resulting from land use patterns in ways that are as yet uncertain.

#### *1.1.1.15 Nutrient cycle feed-backs*

Plant production on rangelands often is limited by nitrogen (N). Because most terrestrial N occurs in organic forms that are not readily available to plants, rangeland responses to global changes will depend partly on how quickly N cycles between the organic and inorganic compounds in which it occurs. Plant material that falls to the soil surface or is deposited belowground as the result of root exudation or death is subject to decomposition by soil fauna and micro flora and enters the soil organic matter (SOM) pool (Figure 2.11). During decomposition of SOM, mineral and other plant-available forms of N are released.

Several of the plant and environmental variables that regulate N-release may be affected by climate change and $CO_2$ enrichment. Warmer temperatures generally increase SOM

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decomposition, especially in cold regions (Reich et al. 2006b; Rustad et al. 2001), although warming also may limit microbial activity by drying soil or enhancing plant growth (Wan et al. 2005). Warming stimulated N mineralization during the first year of treatment on Oklahoma tallgrass prairie, but in the second year, caused N immobilization by reducing plant N concentration (An et al. 2005), stimulating plant growth, and increasing allocation of C compounds belowground (Wan et al. 2005). Warming can also affect decomposition processes by extending the growing season, (Wan et al. 2005). However, as water becomes limiting, decomposition becomes more dependant on soil water content and less on temperature (Epstein, Burke and Lauenroth 2002; Wan et al. 2005), with lower soil water content leading to reduced decomposition rates. A recent global model of litter decomposition (Parton et al. 2007) indicates that litter N-concentration, along with temperature and water, are the dominant drivers behind N release and immobilization dynamics, although UV-stimulation of decomposition (Austin and Vivanco 2006) is especially important in controlling surface litter decomposition dynamics in arid systems like rangelands.

Although rising atmospheric $CO_2$ has no direct affect on soil microbial processes, it can affect soil micro flora and fauna indirectly. The Progressive Nitrogen Limitation (PNL) hypothesis holds that $CO_2$ enrichment is reducing plant-available N by increasing plant demand for N and enhancing the sequestration of N in long-lived plant biomass and SOM pools (Luo et al. 2004). The greater plant demand for N is driven by $CO_2$-enhanced plant growth. Accumulation of N in organic compounds at elevated $CO_2$ may eventually reduce soil N availability and limit plant growth response to $CO_2$ or other changes (Reich et al. 2006a,b; van Groenigen et al. 2006; Parton et al. 2007). Alternatively, greater C input may stimulate N accumulation in soil/plant systems. A number of processes may be involved, including increased biological fixation of N, greater retention of atmospheric N deposition, reduced losses of N in gaseous or liquid forms, and more complete exploration of soil by expanded root systems (Luo et al. 2006). Rangeland plants often compensate for temporary imbalances in C and N availability by maximizing the amount of C retained in the ecosystem per unit of N. Thus, N concentration of leaves or aboveground tissues declined on shortgrass steppe, tallgrass prairie, and mesic grassland at elevated $CO_2$, and on tallgrass prairie with warming, but total N content of aboveground tissues increased with plant biomass in these ecosystems and on annual grasslands (Owensby et al. 1993, Hungate et al. 1997, King et al. 2004, An et al. 2005, Gill et al. 2006). The degree to which N may respond to rising atmospheric $CO_2$ is presently unknown, but may vary among ecosystems (Luo et al. 2006), and has important consequences for forage quality and soil C storage, as both depend strongly on the available soil N.

Nutrient cycling also is sensitive to changes in plant species composition; this may result because species differ in sensitivity to global changes. Soil microorganisms require organic material with relatively fixed proportions of C and N. The ratio of C to N in plant residues thus affects the rate at which N is released during decomposition in soil. Because C:N varies among plant species, shifts in species composition can strongly affect nutrient cycling (Allard et al. 2004; Dijkstra et al. 2006; Gill et al. 2006; King et al. 2004; Schaeffer et al. 2007; Weatherly et al. 2003). $CO_2$ enrichment may reduce decomposition

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by reducing the N concentration in leaf litter (Gill et al. 2006), for example, although litter quality may not be the best predictor of tissue decomposition (Norby et al. 2001). Like $CO_2$, climatic changes may alter litter quality by causing species change (Murphy et al. 2002; Semmartin et al. 2004; Weatherly et al. 2003). Elevated atmospheric $CO_2$ and/or temperature may also alter the amounts and proportions of micro flora and fauna in the soil microfood web (e.g., Hungate et al. 2000; Sonnemann and Wolters 2005), and/or the activities of soil biota (Billings et al. 2004; Henry et al. 2005; Kandeler et al. 2006). Although changes in microbial communities are bound to have important feedbacks on soil nutrient cycling and C storage, the full impact of global changes on microbes remains unclear (Niklaus et al. 2003; Ayers et al. in review).

Computer simulation models that incorporate decomposition dynamics and can evaluate incremental global changes agree that combined effects of warming and $CO_2$ enrichment during the next 100 years will stimulate plant production, but disagree on the impact on soil C and N. The Daycent Model predicts a decrease in soil C stocks, whereas the Generic Decomposition And Yield Model (G'Day) predicts an increase in soil C (Pepper et al. 2005). Measurements of N isotopes from herbarium specimens collected over the past hundred years indicate that rising atmospheric $CO_2$ has been accompanied by increased N fixation and soil N mineralization, decreased soil N losses, and a decline in shoot N concentration (Penuelas and Estiarte, 1997). Collectively, these results indicate that soil N may constrain the responses of some terrestrial ecosystems to $CO_2$.

### 2.6.7 Forage Quality

#### *1.1.1.16 Plant-animal interface*

Animal production on rangelands, as in other grazing systems, depends on the quality as well as the quantity of forage. Key quality parameters for rangeland forage include fiber content and concentrations of crude protein, non-structural carbohydrates, minerals, and secondary toxic compounds. Ruminants require forage with at least 7 percent crude protein (as a percentage of dietary dry matter) for maintenance, 10-14 percent protein for growth, and 15 percent protein for lactation. Optimal rumen fermentation also requires a balance between ruminally-available protein and energy. The rate at which digesta passes through the rumen decreases with fiber content, which depends on the fiber content of forage. Increasing fiber content slows passage and reduces animal intake.

#### *1.1.1.17 Climate change effects on forage quality*

Based on expected vegetation changes and known environmental effects on forage protein, carbohydrate, and fiber contents, both positive and negative changes in forage quality are possible as a result of atmospheric and climatic change (Table 2.14). Although non-structural carbohydrates can increase under elevated $CO_2$ (Read and Morgan, XXXX), thereby potentially enhancing forage quality, plant N, and crude protein, these typically decline in $CO_2$-enriched atmosphere. This reduces the positive effects of $CO_2$ enrichment. For example, impacts on crude protein content of forage likely will be

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negative because plant nitrogen concentration usually declines at elevated $CO_2$ (Cotrufo et al. 1998, Milchunas et al. 2005). Limited evidence suggests that the decline is greater when soil nitrogen availability is low than high (Bowler and Press, 1996; Wilsey, 1996), implying that rising $CO_2$ could reduce the digestibility of forages that are already of poor-quality for ruminants. Experimental warming also reduces tissue N concentrations (An et al. 2005), but reduced precipitation typically has the opposite effect. Reductions in forage quality could have pronounced negative effects on animal growth, reproduction, and mortality (Milchunas et al. 2005, Owensby et al. 1996), and could render livestock production unsustainable unless animal diets are supplemented with N (e.g. urea, soybean meal). On shortgrass steppe, for example, $CO_2$ enrichment reduced the crude protein concentration of autumn forage below critical maintenance levels for livestock in three out of four years and reduced the digestibility of forage by 14 percent in mid-season and by 10 percent in autumn (Milchunas et al. 2005). Significantly, the grass most favored by $CO_2$ enrichment, also had the lowest crude protein concentration. Plant tissues that re-grow following defoliation generally

**Table 2.14 Potential changes in forage quality**

| **Change** | **Examples of positive effects on forage quality** | **Examples of negative effects on forage quality** |
|---|---|---|
| Life-form distributions | Decrease in proportion of woody shrubs and increase in grasses in areas with increased fire frequency. | Increase in the proportion of woody species because of elevated $CO_2$, increases in rainfall event sizes and longer intervals between rainfall events. |
| Species or functional group distributions | Possible increase in C3 grasses relative to C4 grasses at elevated $CO_2$. | Increase in the proportion of C4 grasses relative to C3 grasses at higher temperatures. Increase in abundance of perennial forb species or perennial grasses of low digestibility at elevated $CO_2$. Increase in poisonous or weedy plants. |
| Plant biochemical properties | Increase in non-structural carbohydrates at elevated $CO_2$. Increase in crude protein content of forage with reduced rainfall. | Decrease in crude protein content and digestibility of forage at elevated $CO_2$ or higher temperatures. No change or decrease in crude protein in regions with more summer rainfall. |

**Table 2.14** Potential changes in forage quality arising from atmospheric and climatic change.

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are of higher quality than older tissue, so defoliation could ameliorate negative effects of $CO_2$ on forage quality. This however, did not occur on shortgrass steppe (Milchunas et al. 2005). Changes in life-forms, species, or functional groups resulting from differential responses to global changes (2.5.5.1) will likely vary among rangelands depending on the present climate and species composition, with mixed consequences for domestic livestock (Table 2.14).

### 2.6.8 Climatic Influences on Livestock

Climate changes, as suggested by some GCMs, could impact the economic viability of livestock production systems world-wide. Surrounding environmental conditions directly affect mechanisms and rates of heat gain or loss by all animals (NRC, 1981). Lack of prior conditioning to weather events most often results in catastrophic losses in the domestic livestock industry. In the central U.S. in 1992, 1995, 1997, 1999, 2005, and 2006, individual feedlots (intensive cattle feeding operations) lost in excess of 100 head each during severe heat episodes. The heat waves of 1995 and 1999 were particularly severe with documented cattle losses in individual states approaching 5,000 head each year (Hahn and Mader, 1997; Hahn et al. 2001). The magnitude and/or duration of the 2005 and 2006 heat waves were just as severe as the 1995 and 1999 heat waves, although the extent of losses could not be adequately documented. The winter of 1996-97 also caused hardship for cattle producers because of greater than normal snowfall and wind velocity with some feedlots reporting losses in excess of 1,000 head. During that winter, up to 50 percent of the newborn calves were lost with over 100,000 head of cattle lost in the Northern Plains of the United States. Additional snowstorm losses were incurred with the collapse of and/or loss of power to buildings that housed confined domestic livestock. Early snowstorms in 1992 and 1997 resulted in the loss of over 30,000 head of feedlot cattle each year in the Southern Plains of the United States (Mader 2003). Economic losses from reduced cattle performance (morbidity) likely exceed those associated with cattle death losses by several-fold (Balling, 1982). In addition to losses in the 1990s, in the winter of 2000-2001, feedlot cattle efficiencies of gain and daily gain decreased approximately five and 10 percent, respectively, from previous years as a result of late autumn and early winter moisture combined with prolonged cold stress conditions (Mader 2003). In addition, the 2006 snowstorms, which occurred in the southern plains around Christmas and New Years, appear to be as devastating as the 1992 and 1997 storms. These documented examples of how climate change can impact livestock production illustrate the potential for more drastic consequences of increased variability in weather patterns and extreme events that may be associated with climate change.

### 2.6.9 Potential Impact of Climate Change on Livestock

The risk potential associated with livestock production systems due to global warming can be characterized by levels of vulnerability as influenced by animal performance and environmental parameters (Simensen, 1984; Hahn, 1995). When performance level and environmental influences combine to create a low level of vulnerability, there is little risk. As performance levels increase, the vulnerability of the animal increases and when

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coupled with an adverse environment, the animal is at greater risk. Combining an adverse environment with high performance pushes the level of vulnerability and consequent risk to even higher levels. Inherent genetic characteristics or management scenarios that limit the animal's ability to adapt to or cope with the environment also puts the animal at risk. At very high performance levels, any environment other than near-optimal may increase animal vulnerability and risk.

The potential impacts of climatic change on overall performance of domestic animals can be determined using defined relationships between climatic conditions and VFI, climatological data, and GCM output. Because ingestion of feed is directly related to heat production, any change in VFI and/or energy density of the diet will change the amount of heat produced by the animal (Mader et al. 1999b). Ambient temperature has the greatest influence on VFI. However, animals exposed to the same ambient temperature will not exhibit the same reduction in VFI. Body weight, body condition, and level of production affect the magnitude of VFI and ambient temperature at which changes in VFI begin to be observed. Intake of digestible nutrients is most often the limiting factor in animal production. Animals generally prioritize available nutrients to support maintenance needs first, followed by growth or milk production, and then reproduction.

Based on predicted climate outputs from GCM scenarios, production and response models for growing confined swine and beef cattle, and milk-producing dairy cattle have been developed (Frank et al. 2001). The goal in the development of these models was to utilize climate projections – primarily average daily temperature – to generate an estimate of direct climate-induced changes in daily VFI and subsequent performance, during summer in the central portion of the United States (the dominant livestock producing region of the country) and across the entire country. The production response models were run for one current (pre-1986 as baseline) and two future climate scenarios: a double $CO_2$ (~2040) and a triple of $CO_2$ (~2090) levels. This data base employed the output from two GCM, the Canadian Global Coupled Model, Version I, and the United Kingdom Meteorological Office/Hadley Center for Climate Prediction and Research model, for input to the livestock production/response models. Changes in production of swine and beef cattle data were represented by the number of days to reach the target weight under each climate scenario and time period. Dairy production is reported in kg milk produced per cow per season. Details of this analysis are reported by Frank (2001) and Frank et al. (2001).

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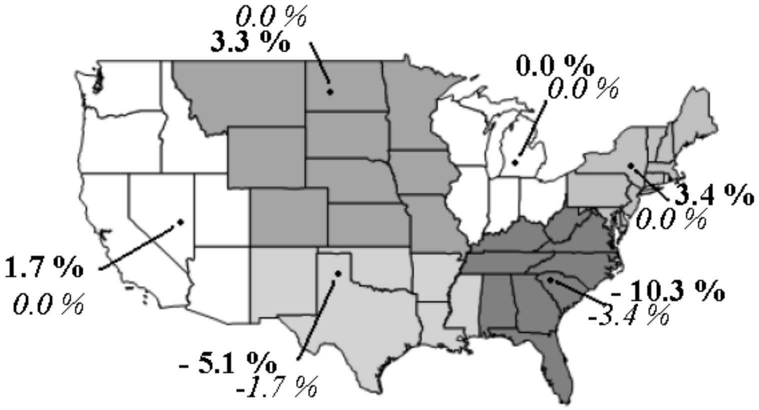

**Figure 2.12** Percent change from baseline to 2040 of days for swine to grow from 50 to 110 kg, beginning June 1 under CGC and Hadley modeled climate (Frank 2001; Frank et al. 2001).

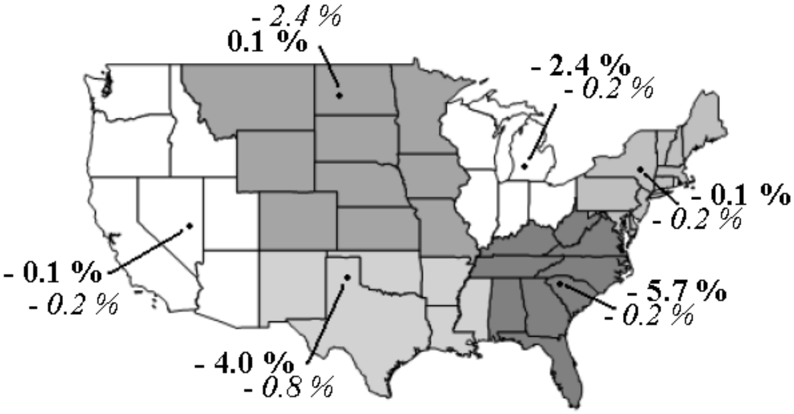

**Figure 2.13** Percent change from baseline to 2040 of days for beef cattle to grow from 350 to 550kg, beginning June 1 under CGC and Hadley modeled climate (Frank 2001; Frank et al. 2001).

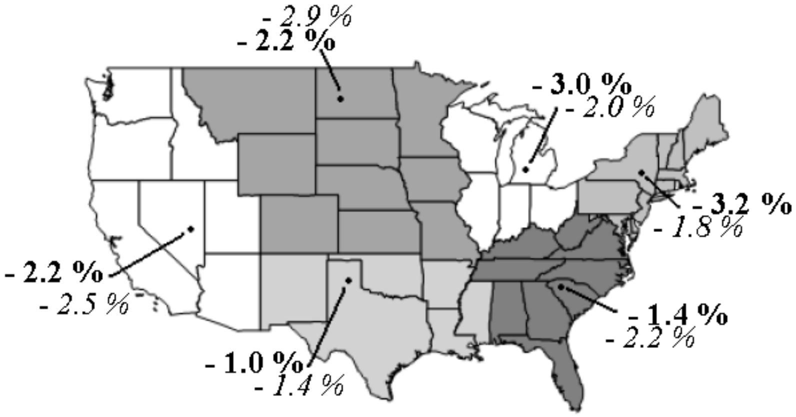

**Figure 2.14** Percent change of kg FCM/cow/season (June 1 to October 31) from baseline to 2040, under CGC and Hadley modeled climate (Frank 2001; Frank et al. 2001).

In the central U.S. (MINK region = Missouri, Iowa, Nebraska, and Kansas), days-to-slaughter weight for swine, associated with the CGC 2040 scenario, increased an average of 3.7 days from the baseline of 61.2 days (Figure 2.12). Potential losses under this scenario averaged six percent and would cost swine producers in the region $12.4 million annually. Losses associated with the Hadley scenario are less severe. Increased time-to-slaughter weight averaged 1.5 days, or 2.5 percent, and would cost producers $5 million, annually. For confined beef cattle reared in the central U.S., time-to-slaughter weight associated with the CGC 2040 scenario increased 4.8 days (above the 127-day baseline value) or 3.8 percent, costing producers $43.9 million annually (Figure 2.13). Climate changes predicted by the Hadley model resulted in a loss 2.8 days of production, or 2.2 percent. For dairy, the projected CGC 2040 climate scenario would result in a 2.2 percent (105.7 kg/cow) reduction in milk output and cost producers $28 million, annually (Figure 2.14). Production losses associated with the Hadley scenarios would average 2.9 percent and cost producers $37 million annually. Across the entire United States, percent increase in days to market for swine and beef, and the percent decrease in dairy milk production for the 2040 scenario averaged 1.2 percent, 2.0 percent, and 2.2 percent, respectively, using the CGC model, and 0.9 percent, 0.7 percent, and 2.1 percent, respectively, using the Hadley model. For the 2090 scenario, respective changes averaged 13.1 percent, 6.9 percent, and 6.0 percent using the CGC model, and 4.3 percent, 3.4 percent, and 3.9 percent using the Hadley model. Respective changes in production for various U.S. regions for the 2040 scenario are shown in Figs. 2.12, 2.13 and 2.14. In general, greater declines in productivity are found with the CGC model than with the Hadley model. Swine and beef production were affected most in the south-central and southeastern U.S. Dairy production was affected the most in the Midwest and Northeast U.S. regions.

In earlier research, Hahn et al. (1992) also derived estimates of the effects of climate change of swine growth rate and dairy milk production during summer as well as other periods during the year. In the east-central U.S., per animal milk production was found to decline 388 kg (~4 percent) for a July through April production cycle, and 219 kg (~2.2 percent) for an October through July production cycle as a result of global warming. Swine growth rate in this same region was found to decline 26 percent during the summer months, but increased nearly 12 percent during the winter months as a result of global warming. Approximately one-half of these summer domestic livestock production declines are offset by improvements in productivity during the winter. In addition, high producing animals will most likely be affected to a greater extent by global climate change than animals with lower production levels. Although percentage changes in productivity may be similar at all production levels.

A production area in which global climate change may have negative effects, which are not offset by positive winter effects, are conception rates, particularly in cattle, in which the breeding season primarily occurs in the spring and summer months. Hahn (1995) reported that conception rates in dairy cows were reduced 4.6 percent for each unit change in THI above 70. Amundson et al. (2005) reported a decrease in pregnancy rates of *Bos taurus* cattle of 3.2 percent for each increase in average THI above 70 and a decrease of 3.5 percent for each increase in average temperature above 23.4°C. These

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data were obtained from beef cows in a range or pasture management system. Amundson et al. (2006) also reported that of the environmental variables studied, minimum temperature had the greatest influence on the percent of cows getting pregnant. Clearly, increases in temperature and/or humidity have the potential to affect conception rates of domestic animals not adapted to those conditions. Summertime conception rates are considerably lower in the Gulf States compared with conception rates in the Northern Plains (Sprott et al. 2001).

In an effort to maintain optimum levels of production, climate change will likely result in livestock producers selecting breeds and breed types that have genetically adapted to conditions that are similar to those associated with the climate change. However, in warmer climates, breeds that are found to be more heat tolerant are generally breeds that have lower levels of productivity, which is likely the mechanism by which they were able to survive as a dominant breed for that region. In addition, climate change and associated variation in weather patterns will likely result in more livestock being managed in or near facilities that have capabilities for imposing microclimate modifications (Mader et al., 1997a and 1999a; Gaughan et al. 2002). Domestic livestock, in general, can cope with or adapt to gradual changes in environmental conditions; however, rapid changes in environmental conditions or extended periods of exposure to extreme conditions drastically reduce productivity and are potentially life threatening.

Estimates of livestock production efficiency suggest that negative effects of hotter weather in summer outweigh positive effects of warmer winters (Adams et al. 1999). The largest change occurred under a 5°C increase in temperature, when livestock yields fell by 10 percent in cow-calf and dairy operations in Appalachia, southeast, Delta, and southern Plains regions of the United States. The smallest change was one percent under 1.5°C warming in the same regions. Livestock production also is affected by changes in temperature and extreme events.

Another area of concern is the influence of climate change on diseases and parasites that affect domestic animals. Incidences of disease, such as bovine respiratory disease, are known to be increasing (Duff and Gaylean 2007). However, causes for this increase can be attributed to a number of non-environmentally related factors. As for parasites, similar insect migration and over-wintering scenarios observed in cropping systems may be found for some parasites that affect livestock.

Baylis and Githeko (2006) describe the potential of how climate change could affect parasites and pathogens, disease hosts, and disease vectors for domestic livestock. The potential clearly exists for increased rate of development of pathogens and parasites due to spring arriving earlier and warmer winters that allow for greater proliferation and survivability of these organisms. For example, bluetongue was recently reported in Europe for the first time in 20 years (Baylis and Githeko 2006). Warming and changes in rainfall distribution may lead to changes in spatial or temporal distributions of those diseases sensitive to moisture such as anthrax, blackleg, haemorrhagic septicaemia, and vector-borne diseases. However, these diseases, as shown by climate-driven models

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designed for Africa, may decline in some areas and spread to others (Baylis and Githeko 2006).

## 2.7 Observing/Monitoring Systems

### 2.7.1 Monitoring Relevant to Crops

#### *1.1.1.18 Environmental stress on crop production*

Stress symptoms on crop production include warmer canopies associated with increased $CO_2$ (but the increment maybe too small to detect over 30 years), smaller grain size or lower test weight from heat stress, more failures of pollination associated with heat stress, and greater variability in crop production. Heat stress could potentially be monitored by satellite image processing over the 30-year span, but causal factors for crop foliage temperature need to be properly considered (temporary water deficit from periodic low rainfall periods, effects of elevated $CO_2$ to increase foliage temperature, direct effects of elevated air temperature, offset by opposite effect from prolonged water extraction associated with $CO_2$-induced water conservation). Increased variability in crop yield and lower test weight associated with greater weather variability relative to thresholds for increased temperature can be evaluated both at the buying point, and by using annual USDA crop statistics for rainfed crops. However, elevated $CO_2$ will have a helpful effect via reduced water consumption. An assessment of irrigated crops can be done in the same way, but with less expectation of water deficit as a causal factor for yield loss. The extent of water requirement for irrigated crops could be monitored by water management district records and pumping permits, but the same issue is present for understanding the confounding effects of temperature, radiation, vapor pressure deficit, rainfall, and $CO_2$ effects.

#### *1.1.1.19 Phenological responses to climate change*

A recent analysis of over 40 years of spring bloom data from the northeastern U.S., the “lilac phenology network”, which was established by the USDA in the 1960s, provided robust evidence of a significant biological response to climate change in the region during the latter half of the 20th century (Wolfe et al. 2005).

#### *1.1.1.20 Crop pest range shifts in collaboration with Integrated Pest Management (IPM) programs*

IPM specialists, and the weather-based weed, insect, and pathogen models they currently utilize, will provide an important link between climate science and the agricultural community. The preponderance of evidence indicate an overall increase in the number of outbreaks and northward migration of a wide variety of weeds, insects, and pathogens. The existing IPM infrastructure for monitoring insect and disease populations could be particularly valuable for tracking shifts in habitable zone of potential weed, insect, and disease pests, and for forecasting outbreaks.

### 2.7.2 Monitoring Relevant to Pasturelands

Efforts geared toward monitoring the long-term response of pasturelands to climate change should be as comprehensive as possible. When possible, the monitoring efforts

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should vegetation dynamics, grazing regimes, animal behavior (e.g. indicators of animal stress to heat), mutualistic relationships (e.g. plant roots-nematodes; N-fixing organisms), and belowground processes, such as development and changes in root mass, carbon inputs and turnover, nutrient cycling, and water balance. To augment their value, these studies should include the use of simulation modeling in order to test hypotheses regarding ecosystem processes as affected by climate change. The development of protocols for monitoring the response of pasturelands to climate change should be coordinated with the development of protocols for rangelands and livestock.

### 2.7.3 Monitoring Relevant to Rangelands

Soil processes are closely linked to rangeland productivity and vegetation dynamics. As a result, future efforts to track long-term rangeland-vegetation responses to climate change and $CO_2$ should also involve monitoring efforts directed toward tracking changes in soils. While considerable progress has been made in the application of remote sensing for monitoring plant phenology and productivity, we have a long way to go in tracking critical soil attributes, which will be important in driving ecological responses of rangelands to climate change.

Nationwide, rangelands cover a broad expanse and are often in regions with limited accessibility. Consequently, ranchers and public land managers need to periodically evaluate range resources (Sustainable Rangeland Roundtable Members, 2006). Add to this the management imperative of public land agencies, monitoring of rangelands via remote sensing is already an important research activity (Afinowicz et al. 2005; Booth and Cox 2006; Clark and Hardegree 2005; Everitt et al. 2006; Weber 2006) with limited rancher acceptance (Butterfield and Malmstrom 2006). A variety of platforms are currently being evaluated, from low-flying aerial photography to satellite imagery,, for use in evaluating a variety of attributes considered as important indicators of rangeland health,like plant cover and bare ground, presence of important plant functional groups or species, to documenting changes in plant communities, including weeds invasion, primary productivity, and forage N concentration. Although not explicitly developed for global change applications, the goal of many of these methodologies to document changing range conditions suggests tools that could be employed for tracking vegetation change in rangelands, and correlated to climatic or $CO_2$ data, as done by Knapp et al. (2001). The expansion of ecological models (e.g., state-and-transition; Bestelmeyer et al. 2004; Briske et al. 2005) to incorporate knowledge of rangeland responses to global change, and integration of those models with existing monitoring efforts and plant developmental data bases like the National Phenology Network (http://www.uwm.edu/Dept/Geography/npn/) could provide a cost-effective monitoring strategy for enhancing our knowledge of how rangelands are being impacted by global change, as well as offering management options.

Fundamental soil processes related to nutrient cycling – which may ultimately determine how rangeland vegetation responds to global change are – more difficult to assess. At present, there are no easy and reliable means by which to accurately ascertain the mineral and carbon state of rangelands, particularly over large land areas. The Natrual Resources

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Conservation Service (NRCS) National Soil Characterization Data Base (http://soils.usda.gov/survey/nscd/) is an especially important baseline of soils information that can be useful for understanding the potential of soils to respond to climate change. However, it does not provide a dynamic record of responses through time. Until such information is easily accessible, or reliable methodologies are developed for monitoring rangeland soil properties, our predictions of rangeland responses to future environments will be limited. However, much can be ascertained about N cycling responses to global change from relatively easily-determined measures of leaf-N chemistry (Penuelas and Estiarte, 1997). As a result, sampling of ecologically important target species in different rangeland ecosystems would be a relatively low-cost measure to monitor biogeochemical response to global change.

## *2.8 Interactions among Systems*

### 2.8.1 Climate Change and Sustainability of Pasturelands

The current land use system in the United States requires high resource inputs, from the use of synthetic fertilizer on crops to the transport of crops to animal feeding operations. In addition to being inefficient with regard to fuel use, this system creates environmental problems from erosion to high nutrient degradation of water supplies. Recently, scientists have been examining the potential for improved profitability and improved sustainability with a conversion to integrated crop-livestock farming systems (Russelle et al. 2007). This could take many forms. One possible scenario involves grain crops grown in rotation with perennial pasture that also integrates small livestock operations into the farming system. Planting of perennial pastures decreases nitrate leaching and soil erosion, and planting of perennial legumes also reduces the need for synthetic N fertilizer. Diversifying crops also reduces incidence of pests, diseases and weeds, imparting resilience to the agro-ecosystem. This resilience will become increasingly important as a component of farm adaptation to climate change.

## *2.9 Findings and Conclusions*

### 2.9.1 Grain and Oilseed Crops

Crop yield response to temperature and $CO_2$ for maize, soybean, wheat, rice, sorghum, cotton, peanut, and dry bean in the United States were assembled from the scientific literature. Cardinal base, optimum, and upper failure-point temperatures for crop development, vegetative, and reproductive growth and slopes-of-yield decline with increase in temperature were reviewed. In general, the optimum temperature for reproductive growth and development is lower than that for vegetative growth. Consequently, life cycle will progress more rapidly, especially giving a shortened grain-filling duration and reduced yield as temperature rises. Furthermore, these crops are characterized by an upper failure-point temperature at which pollination and grain-set processes fail. Considering these aspects, the optimum mean temperature for grain yield is fairly low for the major agronomic crops: 18-22ºC for maize, 22-24ºC for soybean, 15ºC for wheat, 23-26ºC for rice, 25ºC for sorghum, 25-26ºC for cotton, 20-26ºC for peanut, 23-24ºC for dry bean, and 22-25ºC for tomato.

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The anticipated 0.8ºC rise in temperature over the next 30 years is projected to decrease maize, wheat, sorghum, and dry bean yields by 2.5, 4.4, 6.2, and 6.8 percent, respectively, in their major production regions. For soybean, the 0.8ºC temperature rise will increase yield 1.7 percent in the Midwest where temperatures during July, August, September average 22.5ºC, but will decrease yield 2.4 percent in the South, where mean temperature during July, August, September averages 26.7ºC. Likewise, in the South, that same mean temperature will result in reduced rice, cotton, and peanut yields, which will decrease 8.0, 3.5, and 3.3 percent, respectively. An anticipated $CO_2$ increase from 380 to 440 ppm will increase maize and sorghum yield by only one percent, whereas the listed C3 crops will increase yield by 6.1 to 7.4 percent, except for cotton, which shows a 9.2 percent increase. The response to $CO_2$ was developed from interpolation of extensive literature summarization of response to ambient versus doubled $CO_2$. The net effect of temperature and $CO_2$ on yield will be maize (-1.5 percent), soybean (Midwest, +9.1 percent; South, +5.0 percent), 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). The $CO_2$-induced decrease in measured ET summarized from chamber and FACE studies, from 380 to 440ppm, gives a fairly repeatable reduction in ET of 1.4 to 2.1 percent, although the 0.8ºC rise in temperature would increase ET by 1.2 percent, giving a net 0.2 to 0.9 percent reduction in ET. This effect could lead to a further small 0.2 to 0.9 percent increase in yield under rainfed production. A similar small reduction in crop water requirement will occur under irrigated production.

As temperature rises, crops will increasingly begin to experience upper failure point temperatures, especially if climate variability increases and if rainfall lessens or becomes more variable.Under this situation, yield responses to temperature and $CO_2$ would move more toward the negative side. Despite increased $CO_2$-responsiveness of photosynthesis/biomass as temperature increases, there were no published beneficial interactions of increased $CO_2$ upon grain yield as temperature increased because temperature effects on reproductive processes, especially pollination, are so dominant. On the other hand, there are cases of negative interactions on pollination associated with the rise in canopy temperature caused by lower stomatal conductance.

Maximum $CO_2$ benefits generally require unrestricted root growth, optimum fertility, and control of weeds, insects, and disease. Many C3 weeds benefit more than C3 crops from elevated $CO_2$, and some research indicates that glyphosate, the most widely used herbicide in the United States., loses effectiveness at $CO_2$ levels that are projected to occur later this century. For those regions and crops where climate change impairs reproductive development because of an increase in the frequency of high temperature stress events (e.g., > 35ºC), the potential beneficial effects of elevated $CO_2$ on yield may not be fully realized.

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### 2.9.2 Horticultural Crops

Although horticultural crops account for more than 40 percent of total crop market value in the United States (2002 Census of Agriculture), there is relatively little information on their response to $CO_2$, and few reliable crop simulation models for use in climate change assessments compared to that which is available for major grain and oilseed crops. 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.

### 2.9.3 Weeds

The potential habitable zone of many weed species is largely determined by temperature. For example, kudzu (*Pueraria lobata*, var. montana) is an aggressive species that has a northern range currently constrained by the -20ºC minimum winter temperature isocline. 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 C3 invasive weeds that reproduce by vegetative means (roots, stolons, etc.). Recent research also suggests that glyphosate loses its efficacy on weeds grown at elevated $CO_2$. While there are many weed species that have the C4 photosynthetic pathway and therefore show a smaller response to atmospheric $CO_2$ relative to C3 crops, in most agronomic situations, crops are in competition with a mix of both C3 and C4 weeds.

### 2.9.4 Insects and Disease Pests

In addition to crops and weeds, beneficial and harmful insects, microbes and other organisms present in agroecosystems will be responding to changes in $CO_2$ and climate. Numerous studies have already documented changes in spring arrival, over-wintering, and/or geographic range of several insect and animal species due to climate change. Disease pressure from leaf and root pathogens may increase in regions where increases in humidity and frequency of heavy rainfall events are projected, and decrease in regions projected to encounter more frequent drought.

### 2.9.5 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. Unlike

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cropped and intensively-managed pasture systems, the vegetation composition and overall ecology of rangelands develops in response to interactions of the environment and management. While most information on these events comes either from short-term (last five years at most) manipulative experiments, modeling exercises, or long-term observations of rangeland vegetation changes (taken during the past 100+ years), the certainty of recent climate and $CO_2$ predictions by the 2007 IPCC, along with an increasingly complete understanding of ecosystem responses to climate change provide a stable background upon which to forecast anticipated changes in U.S. rangelands for the next 30 to 50 years.

By itself, increased atmospheric $CO_2$ leads to higher rangeland plant productivity through greater photosynthesis rates and WUE. However, soil nutrient limitations may eventually constrain production response. Because of its ability to stimulate both photosynthesis and WUE, rising $CO_2$ is leading to enhanced rangeland plant productivity. Furthermore, rangeland value depends as much – or more – on plant species composition as on productivity. The sensitivity of different species to $CO_2$ will also direct shifts in plant community species composition as $CO_2$ levels continues to climb. Increasing temperature will have both positive and negative benefits on plant productivity, depending on the prevailing climate and the extent to which temperature leads to desiccation. Like $CO_2$, temperature will certainly induce species shifts depending on species sensitivity and adaptability to temperature changes. Modeling exercises suggest generally positive NPP responses of Great Plains native grasslands to combined rising $CO_2$ and temperature (Pepper et al. 2005; Parton et al. 2007). This is also supported by experimental results suggesting enhanced productivity in shortgrass steppe under warming and elevated $CO_2$ (Morgan et al. 2004a). An important exception to these findings is with California's annual grasslands, where production appears only minimally responsive to increases in $CO_2$ or temperature (Dukes et al. 2005). Alterations in precipitation patterns will interact with rising $CO_2$ and temperature, although uncertainties about the nature of precipitation shifts, especially at regional levels, and the lack of multiple global change experiments that incorporate $CO_2$, temperature, and precipitation, severely limit our ability to predict consequences for rangelands. Our lack of knowledge of how these global change factors and soil nutrient cycling will interact to affect soil N availability also reduces confidence in accurately predicting what will happen with soil carbon storage in the next 30 years.

In terms of species shifts, we expect plants with the C3 photosynthetic pathway – forbs, woody plants, and possibly legumes – to be favored by rising $CO_2$, although interactions of species responses with rising temperature and precipitation patterns may affect these functional group responses (Morgan 2005, in press). For instance, warmer temperatures and drier conditions will tend to favor C4 species, which may cancel out the $CO_2$-advantage of C3 grasses. There is already some evidence that climate change-induced species changes are underway in rangelands. 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 $CO_2$. Combined effects of climate and land management change can drive species change that can have a tremendous negative impact on the range livestock industry (Bond and Midgley 2000; Morgan et al., in press; Polley, 1997). Spread of the annual grass *Bromus tectorum* (cheatgrass) through the Intermountain

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region of western North America appears driven at least in part by species sensitivity to rising atmospheric $CO_2$ (Smith et al. 2000; Ziska et al. 2005). In turn, this has altered the frequency and timing of wildfires by reducing establishment of perennial herbaceous species by pre-empting soil water early in the growing season (Young 1991). It seems likely that plant species changes will have as much or more impact on livestock operations as alterations in plant productivity.

**Table 2.15. $CO_2$ and climate change responses**

| Factor | RESPONSES TO RISING $CO_2$ AND CLIMATE CHANGE | MANAGEMENT OPTIONS |
|---|---|---|
| Primary production | *Increase or little change with rising $CO_2$:* Applies to most systems, especially water-limited rangelands. N may limit $CO_2$ response in some systems.<br>*Increases or little change with temperature:* Applies to most temperate and wet systems.<br>*Decreases with temperature:* Applies to arid and semi-arid systems that experience significantly enhanced evapotranspiration and drought, particularly where precipitation is not expected to increase.<br>*Variable responses with precipitation:* Depends on present climate, and nature of precipitation change. Increases in production in regions where water is limiting, but increasing temperatures and more intense precipitation events will reduce this. | Adjust forage harvesting:<br>Stocking rates.<br>Grazing systems.<br>Mowing practices (productive grasslands).<br>Develop and utilize adapted forage species (e.g. legumes, C4 grasses where appropriate, more drought-resistant species and cultivars).<br>Enterprise change (e.g. movement to more or less intensive agricultural practices). |
| Plant community species composition | Global changes will drive competitive responses that alter plant communities: In some systems, legumes and C3 species may be favoured in future $CO_2$-enriched environments, but community reactions will be variable and highly site specific. Warmer environments will favour C4 metabolisms. Both productive and reproductive responses will be featured in community changes. Ultimate plant community responses will probably reflect alterations in soil nutrients and water, and involve complex interactions between changes in $CO_2$, temperature and precipitation. Weed invasions may already be underway, due to rising atmospheric $CO_2$. Proximity to urban areas will add complex interactions with ozone and N deposition. | All of the above.<br>Weed control:<br>Fire management and/or grazing practices to convert woody lands to grasslands.<br>Herbicides where appropriate to control undesirables.<br>Enterprise change or emphasis:<br>Change between intensive/extensive practices.<br>C storage strategy.<br>Tourism, hunting, wildlife.<br>Biodiversity. |
| Forage quality | Increasing $CO_2$ will alter forage quality. In productive grasslands with ample N, forage quality may increase due to more TNC. In N-limited native systems, $CO_2$-induced reduction in N and increased fibre may lower quality. | Utilize/interseed legumes where N is limiting and practice is feasible.<br>Fertilize where feasible.<br>Alter supplemental feeding practices. |
| Animal performance to altered climate | *Increased temperature, warm regions:* Reduced feed intake, feed efficiency, animal gain, milk production and reproduction. Increased disease susceptibility, and death.<br>*Increased temperature, cold regions:* Enhanced animal performance, lowered energy costs. | Animal usage:<br>Select adapted animal breeds from different world regions to match new climate.<br>Improve animal genetics.<br>Select different animal species (i.e. camels, sheep and goats for more drought-prone areas).<br>Adjust forage harvesting (above)<br>Alter management (e.g., timing of breeding, calving, weaning)<br>Enterprise change (above) |

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**Table 2.15.** $CO_2$ and climate change responses and management options for grazing land factors.

One of our biggest concerns is in the area of how grazing animals affect ecosystem response to climate change. Despite knowledge that large grazing animals have important impacts on the productivity and nutrient cycling for rangelands (Augustine and McNaughton 2004, 2006; Semmartin et al. 2004), little global change research has addressed this particular problem. Manipulative field experiments in global change research are often conducted on plots too small to incorporate grazing animals, so these findings do not reflect the effect grazing domestic livestock can have on N cycling due to diet selectivity, species changes, and nutrient cycling, all of which can interact with $CO_2$ and climate (Allard et al. 2004; Semmartin et al. 2004). 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. To date, only one experiment has examined four global changes: rising $CO_2$, temperature, precipitation, and N deposition (Dukes et al. 2005; Zavaleta et al. 2003a). Although interactions between global change treatments on plant production were rare, strong effects on relative species abundances and functional plant group responses suggest highly complex interactions of species responses to combined global changes that may ultimately impact nutrient cycling with important implications for plant community change and C 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.

Rangelands are used primarily for grazing. For most domestic herbivores, the preferred forage is grass. Other plants – including trees, shrubs, and other broadleaf species – can lessen livestock production and profitability by reducing availability of water and other resources to grasses, making desirable plants unavailable to livestock or physically complicating livestock management, or poisoning grazing animals (Dahl and Sosebee, 1991). However, in addition to livestock grazing, rangelands provide many other goods and services, including biodiversity, tourism, and hunting. They are also important as watershed catchments. Carbon stores are increasingly being considered as an economic product (Liebig et al. 2005; Meeting et al. 2001; Moore et al. 2001; Schuman, Herrick and Janzen 2001). However, there is still uncertainty about the greenhouse gas sink capacity of rangelands, how it will be altered by climate change – including rising atmospheric $CO_2$ – and, ultimately, the economics of rangeland C sequestration (Schlesinger 2006; van Kooten 2006). While we are still unable to predict accurately the consequences of all aspects of climate change for rangelands, a recent list of management options (Morgan 2005) suggests the types of choices ranchers and land managers will need to consider in the face of climate change (Table 2.15).

A challenge for rangeland scientists, public land managers, ranchers, and others interested in rangelands will be understanding how the dynamics of climate change and

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land management translate into ecological changes that impact long-term use and sustainability. Perhaps more than most occupations, ranching in the present-day United States is as much a lifestyle choice as it is an economic decision (Bartlett et al. 2002), so economics alone will not likely drive decisions that ranchers make in response to climate change. Nevertheless, ranchers are already looking to unconventional rangeland uses like tourism or C storage. In regions where vegetation changes are especially counter-productive to domestic livestock agriculture, shifts in enterprises will occur. Shifts between rangeland and more intensive agriculture may also occur, depending on the effects of climate-induced environmental changes and influence of economics that favor certain commodities. However, once a native rangeland is disturbed, whether intentionally through intensive agriculture or unintentionally through climate change, restoration can be prohibitively costly, and in some cases, impossible. Therefore, management decisions on the use of private and public rangelands will need to be made with due diligence paid towards their long-term ecological impacts.

### 2.9.6 Animal Production Systems

Increases in air temperature reduce 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. From that perspective, environmental management for ruminants exposed to global warming needs to consider 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).

In terms of environmental management needed to address global climate change, the impacts can be reduced by recognizing the adaptive ability of the animals and by proactive application of appropriate counter-measures (sunshades, evaporative cooling by direct wetting or in conjunction with mechanical ventilation, etc.). Specifically, the capabilities of livestock managers to cope with these 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 animal populations.

Climate changes affect certain parasites and pathogens, which could result in adverse effects on host animals. Interactions exist among temperature, humidity, and other environmental factors, which, in turn, influences energy exchange. Indices or measures that reflect these interactions remain ill-defined, but research to improve them is underway. Factors other than thermal (i.e., dust, pathogens, facilities, contact surfaces, technical applications) also need better definition. Duration and intensity of potential stressors are of concern with respect to the coping and/or adaptive capabilities of an animal. Further, exposure to one type of stressor may lead to altered resistance to other types. Other interactions may exist, such that 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.

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Innovations in electronic system capabilities will undoubtedly continue to be exploited for the betterment of livestock environments with improved economic utilization of environmental measures, and mitigation strategies. There is much potential for application of improved sensors, expert systems, and electronic stockmanship. Continued progress should be closely tied to animal needs based on rational criteria, and must include further recognition of health criteria for animal caretakers as well. The ability of the animal's target tissues to respond to disruptions in normal physiological circadian rhythms may be an important indicator of stress. Also, the importance of obtaining multiple measures of stress is also becoming more apparent. 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 in developing integrated stress measures. Establishing threshold limits for impaired functions that may result in reduced performance or health are essential. Modeling of physiological systems as our knowledge base expands will help the integration process.

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# 3 Land Resources

MG Ryan, SR Archer, RA Birdsey, CN Dahm, LS Heath, JA Hicke, DY Hollinger, TE Huxman, GS Okin, R Oren, JT Randerson, WH Schlesinger

## *3.1 The effects of climate change on land resources*

Forests are found in all 50 states but are most common in the humid eastern U.S., the west coast, at higher elevations in the interior west and southwest, and along riparian corridors in the plains states (Figure 3.1) (Zhu and Evans, 1994). Forested land occupies about 740 million acres, or about one-third of the United States. Forests in the eastern U.S. cover 380 million acres – 74 percent are broadleaf forests – with most of the land, 83 percent, privately owned. The 360 million acres of forest land in the western U.S. are mostly conifer forests (78 percent), and split between public (57 percent), and private ownership (nationalatlas.gov/articles/biology/a_forest.html).

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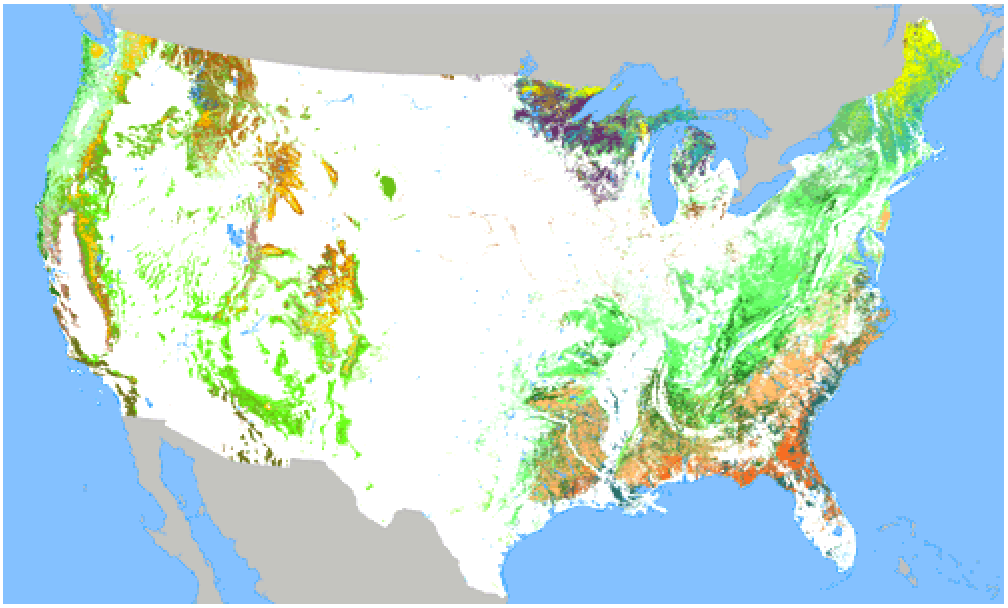

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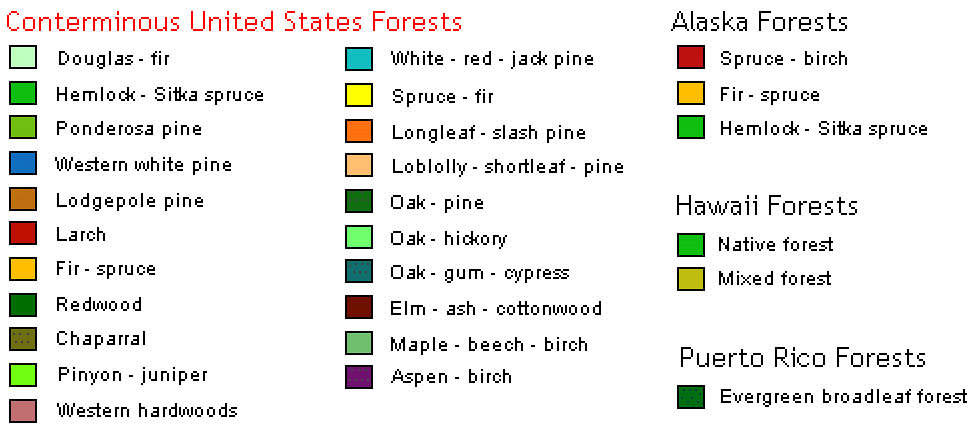

**Figure 3.1** Distribution of forest lands in the continental U.S. by forest type. This map was derived from Advanced Very High Resolution Radiometer (AVHRR) composite images recorded during the 1991 growing season. Each composite covered the United States at a resolution of one kilometer. Field data collected by the Forest Service were used to aid classification of AVHRR composites into forest-cover types. Details on development of the forest cover types dataset are in Zhu and Evans (1994).

Forests provide many ecosystem services that are important to the wellbeing of the United States: watershed protection, water quality, and flow regulation; wildlife habitat and diversity, recreational opportunities, and aesthetic and spiritual fulfillment; raw material for wood and paper products; climate regulation, carbon storage, and air quality; biodiversity conservation. While not all of these services have easily quantified market values, all services have considerable economic value (Costanza et al. 1997; Daily et al. 2000; Krieger 2001; Millennium-Ecosystem-Assessment 2005), and Americans are strongly attached to their forests. A changing climate will alter forests and the services they provide – sometimes changes will be viewed as beneficial, but often they will be viewed as detrimental.

Arid lands are defined by low, and highly variable precipitation, and are found in the United States in the subtropical hot deserts of the Southwest and the temperate cold deserts of the Intermountain West (Figure 3.2). Arid lands provide many of the same ecosystem services as forests (with the exception of raw materials for wood and paper products), and support a large ranching industry. These diverse environments are also valued for their wildlife habitat, and plant and animal diversity, their regulation of water flow and quality, their opportunities for outdoor recreation, and their open spaces for expanding urban environments. A changing climate will alter arid lands and their services. Compared with forests, arid lands face additional challenges related to changing climate: the legacy of historical land use and the sensitivity of arid lands to future land use; the widespread presence and success of exotic invasive species in changing arid ecosystems and their disturbance patterns (especially fire); and the very slow growth of many of the species that hinders recovery from disturbance.

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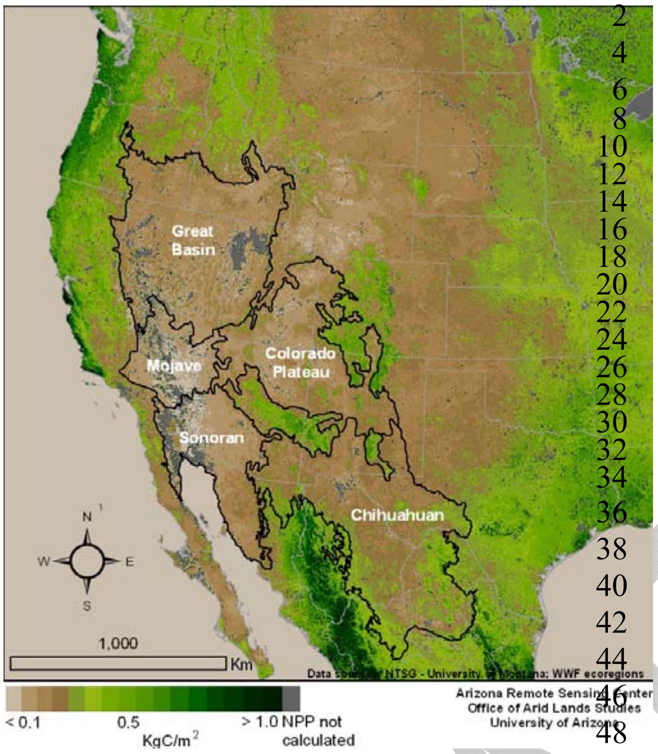

**Figure 3.2** The five major North American deserts, outlined on a 2006 map of net primary productivity (NPP). Modeled NPP was produced by the Numerical Terradynamic Simulation Group (http://www.ntsg.umt.edu/) using the fraction of absorbed photosynthetically active radiation measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and land cover-based radiation use efficiency estimates Running et al. (2000). Desert boundaries based on Olson et al. (2001).

Climate strongly influences both forests and arid lands. Climate shapes the broad patterns of ecological communities, the species within them, their productivity, and the ecosystem goods and services they provide – the interaction of vegetation and climate is a fundamental tenet of ecology. Many studies show how vegetation has changed with climate over the past several thousand years, so we know that changes in climate will change vegetation. Given a certain climate and long enough time, we can generally predict the ecological communities that will result. However, predicting the effects of a changing climate on forests and arid lands for the next few decades is challenging, especially with regard to the rates and dynamics of change. Plants in these communities can be long-lived; hence, changes in species composition may lag behind changes in climate. Furthermore, seeds and conditions for better-adapted communities are not always present.

Past studies linking climate and vegetation may also provide poor future predictions because the same physical climate may not occur in the future, and because many factors other than the physical climate may be changing as well. $CO_2$ is increasing in the atmosphere, nitrogen deposition is much larger than in the past, and appears to be increasing, ozone pollution is locally increasing, and species invasions from other ecosystems are widespread. These factors cause important changes themselves, but their interactions are difficult to predict. This is particularly so because these interactions represent novel combinations beyond our experience base.

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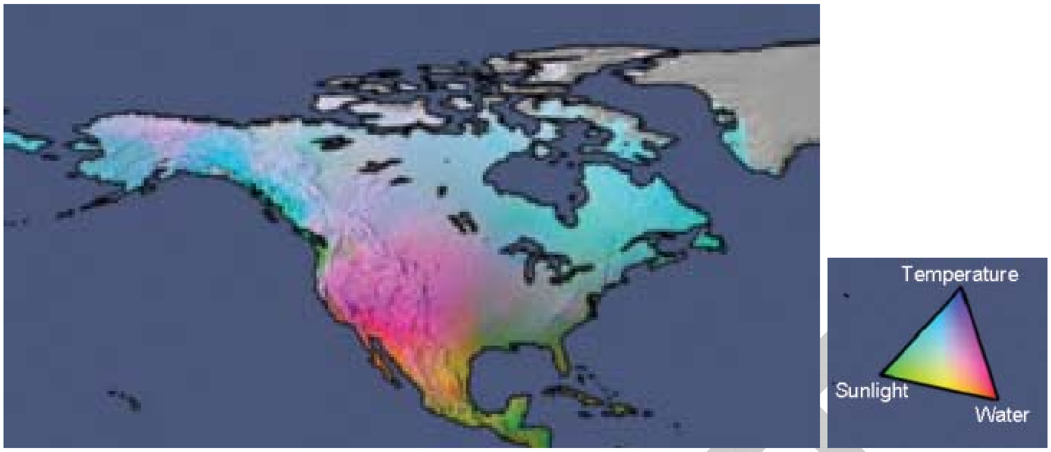

**Figure 3.3** Potential limits to vegetation net primary production based on fundamental physiological limits by sunlight, water balance, and temperature. From Boisvenue and Running (2006).

Disturbance (such as drought, storms, insect outbreaks, 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 disturbances to forests and arid lands (Dale et al. 2001). Trees and arid land vegetation can take from decades to centuries to re-establish after a disturbance. Therefore, changes in disturbance regimes caused by climate-change can affect land resources (Dale et al. 2001). Both human-induced and natural disturbances shape ecosystems by influencing species composition, structure, and function (such as productivity, water yield, erosion, carbon storage, and susceptibility to future disturbance). In forests, more than 55 million acres are currently impacted by disturbance, with the largest being insects and pathogens (Dale et al. 2001). These disturbances cause an estimated economic loss of 3.7 billion dollars (Dale et al. 2001). In the past several years, scientists have learned that the magnitude and impact of these disturbances and their response to climate rivals that expected from changes in temperature and precipitation (Dale et al. 2001).

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**Figure 3.4** Aerial view of extensive attack by mountain pine beetle in lodgepole pine forests in British Columbia. Photo by Lorraine Maclauchlan, Ministry of Forests, Southern Interior Forest Region. (http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/bbphotos.htm)

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Disturbance may reset and rejuvenate some ecosystems in some cases; and, cause enduring change in others. For example, climate may favor the spread of invasive exotic grasses into arid lands where the native vegetation is too sparse to carry a fire. When these areas burn, they typically convert to non-native monocultures and the native vegetation is lost. In another example, drought may weaken trees and make them susceptible to insect attack and death – a pattern that recently occurred in the Southwest. In these forests, drought and insects converted large areas of mixed pinyon-juniper forests into juniper forests. However, fire is an integral component of many forest ecosystems, and many forests (such as the lodgepole pine forests that burned in the Yellowstone fires of 1988) depend on fire to regenerate many species. So, climate effects on disturbance will likely shape future forests and arid lands as much as the effects of climate itself.

Disturbances and changes to the frequency or type of disturbance present challenges to resource managers. Many disturbances command quick action, public attention, and resources. Surprisingly, most resource planning in the United States does not consider disturbance, even though disturbances are common, and preliminary information exists on the frequency and areal extent of disturbances (Dale et al. 2001). Disturbances in the future may be larger and more common than those experienced historically, and planning for disturbances should be encouraged (Dale et al. 2001; Stanturf et al. 2007).

Current trends in climate that affect forests and arid lands show that the United States has warmed in Alaska, the Interior West and Southwest, and in the Northern states. The

Southeast has cooled. Over the past hundred years, precipitation has declined in the Interior West, the Southwest, and the eastern portions of the Southeast (Figs. 1.5 and 1.6). Climate models project that these trends will continue.

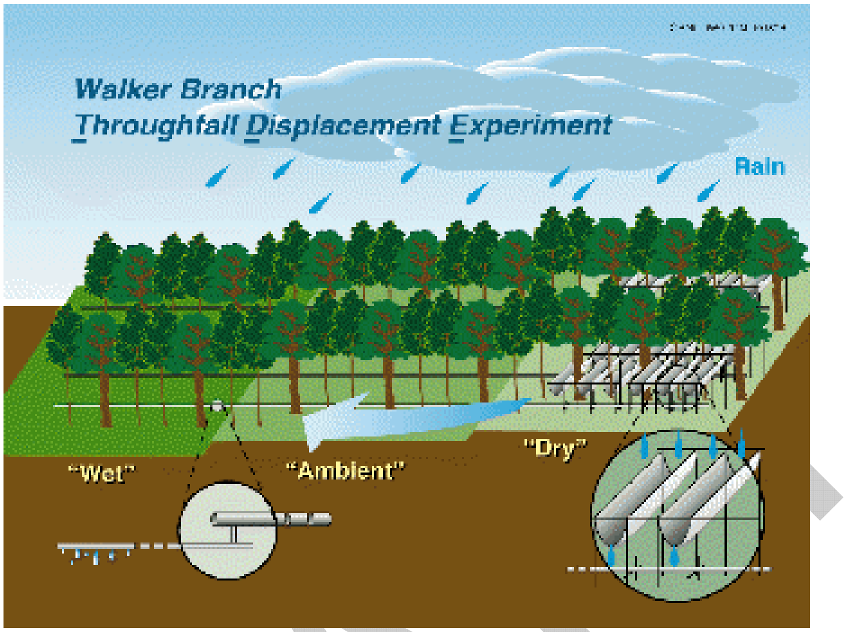

**Figure 3.5** Direct manipulation of precipitation in the Throughfall Displacement experiment at Walker Branch (Oak Ridge National Laboratory).

**Figure 3.6** FACE ring at the Rhinlander FACE facility, Rhinelander, WI.

Our goal in this chapter is to predict how forests and arid lands will respond to predicted changes in climate over the next few decades. We will discuss the effects of climate and its components on the structure and function of forest and arid land ecosystems. We will

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also highlight the effects of climate on disturbance and how these disturbances change ecosystems.

## 3.2 Brief Summary of Key Points from the Literature

### 3.2.1 Forests

Climate strongly affects forest productivity and species composition. Forest productivity in the United States has increased two to eight percent in the past two decades, but separating the role of climate from other factors causing the increase is complicated and varies by location. Some factors that act to increase forest growth are observed greater precipitation in the Midwest and Lake States, observed increases in nitrogen deposition, an observed increase in temperature in the Northern U.S. that lengthens the growing season, changing age structure of forests, and management practices. These factors interact, and identifying the specific cause of a productivity change is complicated by insufficient data. Even in the case of large forest mortality events, such as fire and insect outbreaks, attributing a specific event to climate or a change in climate may be difficult because of interactions among factors. For example, in the widespread mortality of pinyon pine in the Southwest, intense drought weakened the trees, but generally, the Ips beetle killed them.

In addition to the direct effects of climate on tree growth, climate also affects the frequency and intensity of natural disturbances such as fire, insect outbreaks, ice storms, and windstorms. These disturbances have important consequences for timber production, water yield, carbon storage, species composition, invasive species, and public perception of forest management. Disturbances also draw management attention and resources. Because of observed warmer and drier climate in the West in the past two decades, forest fires have grown larger and more frequent during that period. Several large insect outbreaks have recently occurred or are occurring in the United States. Increased temperature and drought likely influenced these outbreaks, but other factors, such as a more uniform forest age structure, which is a legacy of logging, or climate-induced fires in the late 1800s and early 1900s, or fire suppression since, may also play a role.

Atmospheric $CO_2$ elevated to 550 parts per million toward the end of this century will increase forest productivity and carbon storage in forests, with the carbon primarily being stored in live trees. Average productivity increase for a variety of experiments was 23 percent. The response of tree growth and carbon storage to elevated $CO_2$ depends on site fertility, water availability, and perhaps stand age, with fertile, younger stands responding more strongly.

Forest inventories can detect long-term changes in forest growth and species composition, but they have limited ability to attribute changes to specific factors, including climate. Combining forest inventories with experimental data, remote sensing, and models is a promising new approach. Monitoring of disturbances affecting forests is

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currently ineffective, fragmented, and generally unable to attribute disturbances to specific factors, including climate.

### 3.2.2 Arid Lands

Plants and animals in arid lands live near their physiological limits, so slight changes in temperature and precipitation will substantially alter the composition, distribution, and abundance of species, and the products and services that arid lands provide. Observed and projected decreases in the frequency of freezing temperatures, lengthening of the frost-free season, and increased minimum temperatures will alter plant species ranges and shift geographic and elevational boundaries of the Great Basin, Mojave, Sonoran, and Chihuahuan Deserts. The extent of these changes will also depend on changes in precipitation and fire. Increased drought frequency will put arid systems at risk for major changes in vegetation cover. Losses of vegetative cover coupled with increases in precipitation intensity and climate-induced reductions in soil aggregate stability will dramatically increase potential erosion rates. Transport of eroded sediment to streams coupled with changes in the timing and magnitude of minimum and maximum flows will affect water quality, riparian vegetation and aquatic fauna. Wind erosion will have continental-scale impacts on downwind ecosystems, air quality, and human populations.

The response of arid lands to climate change will be strongly influenced by interactions with non-climatic factors at local scales. Climate effects should be viewed in the context of these other factors, and simple generalizations should be viewed with caution. Climate will strongly influence the impact of land use on ecosystems and how ecosystems respond. Grazing has traditionally been the most extensive land use in arid regions. However, land use has significantly shifted to exurban development and recreation since 1950. Arid land response to climate will thus be influenced by new environmental pressures related to air pollution and N-deposition, motorized off-road vehicles, feral pets, and horticultural invasives, in addition to grazing.

Emissions of VOC gases by plants have increased because of the displacement of native grasslands by desert shrubs. However, the implications for tropospheric ozone and aerosol production are not yet known. Non-native plant invasions will likely have a major impact on future VOC emissions and how arid land ecosystems respond to climate and climate change. Exotic grasses generate large fuel loads that predispose arid lands to more frequent and intense fire than historically occurred. Such fires can radically transform diverse desert scrub, shrub-steppe, and desert grassland/savanna ecosystems into monocultures of non-native grasses. This process is well underway in the Cold Desert region, and is in its early stages in Hot Deserts. Because of their profound impact on the fire regime and hydrology, invasive plants in arid lands may trump direct climate impacts on native vegetation.

Given the concomitant changes in climate, atmospheric CO2, nitrogen deposition, and species invasions, novel wildland and managed ecosystems will likely develop. In novel ecosystems, species occur in combinations, and relative abundances that have not

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occurred previously in a given biome. In turn, novel ecosystems present novel challenges for conservation and management.

## 3.3 Summary of Findings and Conclusions

### 3.3.1 Forests

A changing climate will very likely change forest productivity. Current and projected changes in temperature and precipitation are likely to lower forest productivity in the Interior West, the Southwest, eastern portions of the Southeast, and Alaska, and increase forest productivity in the Northeastern U.S., the Lake States, and in western portions of the Southeast. However, projected increases in hurricanes and ice storms will likely act to lower productivity in the Southeast and Northeast, and exacerbate or offset changes caused by temperature and precipitation.

Temperature increases have lengthened, and will continue to lengthen, the growing season, and will very likely yield warmer winters, particularly in Alaska, the West, and northern continental United States. These temperature increases will likely lead to larger, more frequent forest fires in the western U.S., and possibly for portions of the East as well. Where increased temperatures and forests coincide, the range and frequency of large insect outbreaks will likely increase. More disturbances in the future will likely lower carbon storage in forests in the coming decades, counteracting the projected effect of increasing $CO_2$.

Elevated $CO_2$ will very likely increase forest photosynthesis, but the response to $CO_2$ will be lower for infertile forests and perhaps for older forests. Nitrogen deposition (most prominent in the eastern U.S.) will very likely increase forest productivity and the response of forest growth to the rise in atmospheric $CO_2$. The interactions of elevated $CO_2$, temperature, precipitation, ozone pollution, and nitrogen deposition are likely to be important in determining forest growth and species composition, but the net result of these interactions is poorly understood.

### 3.3.2 Arid Lands

U.S. deserts will likely expand to the north, east, and upward in elevation in response to changing temperatures. Simultaneously, arid lands may contract in their southern borders. Higher temperatures predicted to co-occur with more severe drought portend increased mortality for the dominant woody vegetation typical of North American deserts and will encourage establishment of exotic annual grasses**.** Proliferation of exotic grasses will predispose sites to more frequent and more intense fires that kill native woody plants and charismatic flora, such as Saguaro cactus. The interaction of climate, fire, and invasive grasses will likely determine the future plant distribution in U.S. arid lands.

Water strongly limits plant productivity in arid lands, and projected reductions in precipitation will very likely lower productivity and carbon storage. Even though annual carbon storage per unit area is low in arid lands, their large extent yields a considerable contribution to global carbon storage. The risk of loss of carbon from these ecosystems is

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high; greatest losses will likely be associated with desertification processes and annual plant invasions. Arid land soils are often deficient in nitrogen, so expected erosional losses of soil nitrogen will further restrict productivity. Nitrogen losses possibly will be partially offset by greater nitrogen deposition. Emissions of VOC gases by plants will be elevated by higher temperatures and greater water stress, but displacement of high-emitting shrubs by low-emitting non-native grasses may counteract this.

Floods and droughts that structure arid riverine corridors are likely to increase in number and intensity. The net result of climate warming will be greater depletion of water along riverine corridors. The balance of competition between native and non-native species in riparian zones will continue to shift in favor of non-native species as temperatures increase, as the timing and amount of precipitation shifts, and as the intensity of disturbances is magnified.

Higher temperatures and decreased soil moisture will likely reduce the stability of soil aggregates, making the surface more erodible. Climate change will likely further increase erosion by reducing vegetation cover. Increases in precipitation intensity and the proportion of precipitation delivered in high-intensity storms will likely accelerate water erosion from uplands and delivery of nutrient-rich sediment to riparian areas. Increases in wind speed and gustiness will 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.

### 3.3.3 Observing Systems

Current observing systems can detect changes in growth and species composition in forests and in some arid lands, but are inadequate to separate the effects of changes in climate from other effects. There are few observing systems for monitoring wind and water erosion, and for examining interactions among climatic and non-climatic drivers. To identify climate effects would require a broad network, with many indicators, coupled with a network of controlled experimental manipulations. A coordinated national network that monitors ecosystem disturbance and recovery would greatly contribute to attributing disturbances to a particular cause, and identifying the consequences of those disturbances. However, no such network currently exists. Time-series of satellite observations can identify disturbance, changes in productivity, and changes in land use. Lack of assured continuity for satellite observations may jeopardize these observations in the future.

## *3.4 Observed Changes or Trends - Forests*

### 3.4.1 Climate and Ecosystem Context

Anyone traveling from the lowlands to the mountains will notice that species composition changes with elevation and with it, the structure and function of these forest ecosystems. Biogeographers have mapped these different vegetation zones and linked them with their

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characteristic climates. The challenge facing scientists now is to understand how these zones and the individual species within them will move with a changing climate, at what rate, and with what effects on ecosystem function.

Temperature, water, and radiation are the primary abiotic factors that affect forest productivity (Figure 3.3). Any response to changing climate will depend on the factors that limit production at a particular site. For example, any site where productivity is currently limited by lack of water or a short growing season will increase productivity if precipitation increases and if the growing season lengthens. Temperature controls the rate of metabolic processes for photosynthesis, respiration, and growth. Generally, plant metabolism has an optimum temperature. Small departures from this optimum usually do not change metabolism and short-term productivity, although changes in growing season length may change annual productivity. Large departures and extreme events (such as frosts in orange groves) can cause damage or tree mortality. Water controls cell division and expansion (which promote growth), and stomatal opening, which regulates water loss and $CO_2$ uptake in photosynthesis. Productivity will generally increase with water availability in water-limited forests (Knapp et al. 2002). Radiation supplies the energy for photosynthesis, and both the amount of leaf area and incident radiation control the quantity of radiation absorbed by a forest. Nutrition and atmospheric $CO_2$ also strongly influence forest productivity if other factors are less limiting (Boisvenue and Running 2006), and ozone exposure can lower productivity (Hanson et al. 2005). Human activities have increased nitrogen inputs to forest ecosystems, atmospheric $CO_2$ concentration, and ozone levels. The effects of $CO_2$ are everywhere, but ozone and N deposition are common to urban areas, and forests and arid lands downwind from urban areas. The response to changes in any of these factors is likely to be complex and dependent on the other factors.

Forest trees are evolutionarily adapted to thrive in certain climates. Other factors, such as fire and competition from other plants, also regulate species presence, but if climate alone changes enough, species will move to suitable conditions or go locally extinct if suitable conditions are unavailable (Woodward, 1987). One example of such a species shift is sugar maple in the northeastern U.S. – suitable climate for it may move northward into Canada and the distribution will likely follow (Chuine and Beaubien 2001), assuming the species is able to disperse propagules rapidly enough to keep pace with the shifting climatic zone. Because trees live for decades and centuries, it is likely that forest species composition will take time to adjust to changes in climate.

Disturbances such as forest fires, insect outbreaks, ice storms and hurricanes also change forest productivity, carbon cycling, and species composition – climate influences the frequency and size of disturbances. Many features of ecosystems can be predicted by forest age, and disturbance regulates forest age. After a stand-replacing disturbance, forest productivity increases until the forest fully occupies the site or develops a closed canopy, then declines to near zero in old age (Ryan et al. 1997). Carbon storage after a disturbance generally declines while the decomposition of dead wood exceeds the productivity of the new forest, then increases as the trees grow larger and the dead wood from the disturbance disappears (Kashian et al. 2006). In many forests, species

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composition also changes with time after disturbance. Susceptibility to fire and insect outbreaks changes with forest age, but we do not know if the response of forest productivity to climate, N deposition, $CO_2$, and ozone differs for old and young forests because most studies have only considered young trees or forests. Changes in disturbance prompted by climate change are likely as important as the changes in precipitation, temperature, N deposition, $CO_2$, and ozone for affecting productivity and species composition.

### 3.4.2 Temperature

Forest productivity in the United States has generally been increasing since the middle of the 20th century (Boisvenue and Running 2006), with an estimated increase of two to eight percent between 1982 and 1998 (Hicke et al. 2002b), but the causes of this increase (increases in air and surface temperature, increasing $CO_2$, N deposition, or other factors) are difficult to isolate (Cannell et al. 1998). These affects can be potentially disentangled by experimentation, by analysis of species response to environmental gradients, planting trees from seeds grown in different climates in a common garden, anomaly analysis, and other methods. Increased temperatures will affect forest growth and ecosystem processes through several mechanisms (Hughes 2000, Saxe et al. 2001) including effects on physiological processes such as photosynthesis and respiration, and responses to longer growing seasons triggered by thermal effects on plant phenology (e.g., the timing and duration of foliage growth). Climate warming will be superimposed on interannual temperature variations that already exceed several degrees, and may differ in the future. Across geographical or local elevational gradients, forest primary productivity has long been known to increase with mean annual temperature and rainfall (Leith 1975). This result also generally holds within a species (Fries et al. 2000) and in provenance trials where trees are found to grow faster in a slightly warmer location than that of the seed source itself (Wells and Wakeley 1966, Schmidtling 1994). In Alaska, where temperatures have warmed strongly in recent times, changes in soil processes are similar to those seen in experimental warming studies (Hinzman et al. 2005). In addition, permafrost is melting, exposing organic material to decomposition and drying soils (Hinzman et al. 2005).

Along with a general trend in warming, the length of the northern hemisphere growing season has been increasing in recent decades (Menzel and Fabian 1999, Tucker et al. 2001). Forest growth correlates with growing season length (Baldocchi et al. 2001), with longer growing seasons (earlier spring) leading to enhanced net carbon uptake and storage (Black et al. 2000, Hollinger et al. 2004). The ability to complete phenological development within the growing season is a major determinant of tree species range limits (Chuine and Beaubien 2001). However, Sakai and Weiser (1973) have also related range limits to the ability to tolerate minimum winter temperatures.

### 3.4.3 Fire and Insect Outbreaks

Westerling et al. (2006) analyzed trends in wildfire and climate in the western U.S. from 1974 – 2004. They show that both the frequency of large wildfires and fire season length

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increased substantially after 1985, and that these changes were closely linked with advances in the timing of spring snowmelt, and increases in spring and summer air temperatures. Much of the increase in fire activity occurred in mid-elevation forests in the northern Rocky Mountains, and Sierra Nevada Mountains. Earlier spring snowmelt probably contributed to greater wildfire frequency in at least two ways, by extending the period during which ignitions could potentially occur, and by reducing water availability to ecosystems in mid-summer, thus enhancing drying of vegetation and surface fuels (Westerling et al. 2006). These trends in increased fire size correspond with an increased cost of fire suppression (Calkin et al. 2005).

In boreal forests across North America, fire activity also has increased in recent decades. Kasischke and Turetsky (2006) combined fire statistics from Canada and Alaska to show that burned area more than doubled between the 1960s/70s and the 1980s/90s. The increasing trend in boreal burned-area appears to be associated with a change in both the size and number of lightning-triggered fires (> 1000 km$^2$), which increased during this period. In parallel, the contribution of human-triggered fires to total burned area decreased from the 1960s to the 1990s (from 35.8 percent to 6.4 percent) (Kasischke and Turetsky 2006). As in the western U.S., a key predictor of burned area in boreal North America is air temperature, with warmer summer temperatures causing an increase in burned area on both interannual and decadal timescales (Gillett et al. 2004, Duffy et al. 2005, Flannigan et al. 2005). In Alaska, for example, June air temperatures alone explained approximately 38 percent of the variance of the natural log of annual burned area during 1950-2003 (Duffy et al. 2005).

Insects and pathogens are significant disturbances of forest ecosystems in the United States (Figure 3.4), costing $1.5 billion annually (Dale et al. 2001). Extensive reviews of the effects of climate change on insects and pathogens have reported many cases where climate change has affected and/or will affect forest insect species range and abundance (Ayres and Lombardero 2000; Malmström and Raffa 2000; Bale et al. 2002). This review focused on forest insect species within the United States that are influenced by climate and are ecologically or economically important.

Major outbreaks in recent years include:  a mountain pine beetle (*Dendroctonus ponderosae*) outbreak affected >10 million hectares (Mha) of forest in British Columbia (Taylor et al. 2006), and 267,000 ha in Colorado (Colorado State Forest Service 2007); more than 1.5 Mha was attacked by spruce beetle (*Dendroctonus rufipennis*) in southern Alaska, and western Canada (Berg et al. 2006); >1.2 Mha of pinyon pine (*Pinus edulis*) mortality occurred because of extreme drought, coupled with an Ips beetle outbreak in the Southwest (Breshears et al. 2005); and millions of ha affected by southern pine beetle (*Dendroctonus frontalis*), spruce budworm *Choristoneura fumiferana*), and western spruce budworm (*Choristoneura occidentalis*) in recent decades in southeastern, northeastern, and western forests, respectively (USDA Forest Service 2005). Ecologically important whitebark pine (*Pinus albicaulis*) is being attacked by mountain pine beetle in the Northern and Central Rockies (Logan and Powell 2001). For example, almost 70,000 ha, or 17 percent, of whitebark pine forest in the Greater Yellowstone Ecosystem is

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infested by mountain pine beetle (Gibson 2006). Evident from these epidemics is the widespread nature of insect outbreaks in forests throughout the United States.

Climate plays a major role in driving, or at least influencing, infestations of these important forest insect species in the United States (e.g., Holsten et al. 1999; Logan et al. 2003a; Carroll et al. 2004; Tran et al. in press), and these recent large outbreaks are likely influenced by observed increases in temperature. Temperature controls life cycle development rates, influences synchronization of mass attacks required to overcome tree defenses, and determines winter mortality rates (Hansen et al. 2001b; Logan and Powell 2001; Hansen and Bentz 2003; Tran et al. in press). Climate also affects insect populations indirectly through effects on hosts. Drought stress, resulting from decreased precipitation and/or warming, reduces the ability of a tree to mount a defense against insect attack (Carroll et al. 2004, Breshears et al. 2005), though this stress may also cause some host species to become more palatable to some types of insects (Koricheva et al. 1998). Both temperature and precipitation variability influence epidemics, however, the relative importance of each has yet to be determined.

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## *3.5 Possible Future Changes and Impacts - Forests*

### 3.5.1 Warming

A review of recent experimental studies found that rising temperatures would generally enhance tree photosynthesis (Saxe et al. 2001), as a result of increased time operating near optimum conditions, and because rising levels of atmospheric $CO_2$ increase the temperature optimum for photosynthesis (Long 1991). Warming experiments, especially for trees growing near their cold range limits, generally increase growth (Bruhn et al. 2000; Wilmking et al. 2004; Danby and Hik 2007). The experimental warming of soils alone has been found to stimulate nitrogen mineralization and soil respiration (Rustad et al. 2001). An important concern for all experimental manipulations is that the treatments occur long enough to determine the full suite of effects. It appears that the large initial increases in soil respiration observed at some sites decrease with time back toward pretreatment levels (Rustad et al. 2001; Melillo et al. 2002). This result may come about from changes in C pool sizes, substrate quality (Kirschbaum 2004; Fang et al. 2005), or other factors (Davidson and Janssens 2006).

A general response of leaves, roots, or whole trees to short-term increases in plant temperature is an approximate doubling of respiration with a 10ºC temperature increase (Ryan et al. 1994, Amthor 2000). Over the longer term, however, there is strong evidence for temperature acclimation (Atkin and Tjoelker 2003; Wythers et al. 2005), which is probably a consequence of the linkage of respiration to the production of photosynthate (Amthor 2000). One negative consequence of warming for trees, is that it can increase the production of isoprene and other hydrocarbons in many tree species (Sharkey and Yeh 2001) – compounds that may lead to higher levels of surface ozone and increased plant damage. Physiologically, the overall result of the few degrees of warming expected over the next few decades is likely a modest increase in photosynthesis and tree growth

(Hyvonen et al. 2007). However, where increased temperature coincides with decreased precipitation (western Alaska, Interior West, Southwest), forest growth is expected to be lower (Hicke et al. 2002b).

For the projected temperature increases over the next few decades, most studies support the conclusion that a modest warming of a few degrees Celsius will lead to greater tree growth in the United States. There are many causes for this enhancement including direct physiological effects, a longer growing season, and potentially greater mineralization of soil nutrients. Because different species may respond somewhat differently to warming, the competitive balance of species in forests may change. Trees will probably become established in formerly colder habitats (more northerly, higher altitude) than at present.

### 3.5.2 Changes in Precipitation

Relationships between forest productivity and precipitation have been assessed using continental gradients in precipitation (Webb et al. 1983; Knapp and Smith 2001), interannual variability within a site (Hanson et al. 2001), and by manipulating water availability (Hanson et al. 2001). Forest productivity varies with annual precipitation across broad gradients (Webb et al. 1983; Knapp and Smith 2001), and with interannual variability within sites (Hanson et al. 2001). Some of these approaches are more informative than others for discerning climate change effects.

Gradient studies likely poorly predict the response to changes in precipitation, because site-specific factors such as site fertility control the response to precipitation (Gower et al. 1992, Maier et al. 2004). The response of forest productivity to interannual variability also likely poorly predicts response to precipitation changes, because forests have the carbohydrate storage and deep roots to offset drought effects over that time, masking any effects which might be apparent over a longer-term trend.

The effects of precipitation on productivity will vary with air temperature and humidity. Warmer, drier air will evaporate more water and reduce water availability faster than cooler, humid air. Low humidity also promotes the closure of stomata on leaves, which reduces photosynthesis and lowers productivity even where soil water availability is abundant.

Manipulation of water availability in forests allows an assessment of the direct effects of precipitation (Figure 3.5). Two experiments where water availability was increased through irrigation showed only modest increases in forest production (Gower et al. 1992; Maier et al. 2004), but large increases with a combination of irrigation and nutrients. In contrast, forest productivity did not change when precipitation was increased or reduced 33 percent, but with the same timing as natural precipitation (Hanson et al. 2005). Tree growth in this precipitation manipulation experiment also showed strong interannual variability with differences in annual precipitation. Hanson et al. (2005) conclude that "differences in seasonal patterns of rainfall within and between years have greater impacts on growth than percentage changes in rainfall applied to all rainfall events."

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No experiments have assessed the effect of changes in precipitation on forest tree species composition. Hanson et al. (2005) showed that growth and mortality changed in response to precipitation manipulation for some smaller individuals, but we do not know if these changes will lead to composition changes. However, one of the best understood patterns in ecology is the variation of species with climate and site water balance. So, if precipitation changes substantially, it is highly likely that species composition will change (Breshears et al. 2005). However, we have limited studies with which to predict the rate of change and the relationship with precipitation amount.

Drought is a common feature of all terrestrial ecosystems (Hanson and Weltzin 2000), and generally lowers productivity in trees. Drought events can have substantial and long-lasting effects on ecosystem structure, species composition and function by differentially killing certain species or sizes of trees (Hanson and Weltzin 2000; Breshears et al. 2005), weakening trees to make them more susceptible to insect attacks (Waring 1987), or by increasing the incidence and intensity of forest fires (Westerling et al. 2006).

If existing trends in precipitation continue, forest productivity will likely decrease in the Interior West, the Southwest, eastern portions of the Southeast, and Alaska. Forest productivity will likely increase in the northeastern U.S., the Lake States, and in western portions of the Southeast. An increase in drought events will very likely reduce forest productivity wherever these events occur.

### 3.5.3 Elevated Atmospheric $CO_2$ and Carbon Sequestration

The effects of increasing atmospheric $CO_2$ on carbon cycling in forests are most realistically observed in FACE (Figure 3.6) experiments. These experiments have recently begun to provide time-series sufficiently long for assessing the effect of $CO_2$ projected for the mid-21st century on some components of the carbon cycle. The general findings from a number of recent syntheses using data from the three American and one European FACE sites (King et al. 2004; Norby et al. 2005; McCarthy et al. 2006a; Palmroth et al. 2006) show that North American forests *will* absorb more $CO_2$ and *might* retain more carbon as atmospheric $CO_2$ increases. The increase in the *rate* of carbon sequestration will be highest (mostly in wood) on nutrient-rich soils with no water limitation, and will decrease with decreasing fertility and water supply. Several yet unresolved puzzles prevent a definitive assessment of the effect of elevated $CO_2$ on other components of the carbon cycle in forest ecosystems:

- Although total carbon allocation to belowground increases with $CO_2$ (King et al. 2004; Palmroth et al. 2006), there is only equivocal evidence of $CO_2$-induced increase in soil carbon (Jastrow et al. 2005; Lichter et al. 2005).
- Older forests can be strong carbon sinks (Stoy et al. 2006), and older trees absorb more $CO_2$ in elevated $CO_2$ atmosphere, but wood production of these trees show limited or only transient response to $CO_2$ (Körner et al. 2005).
- When responding to $CO_2$, trees require and obtain more nitrogen (and other nutrients) from the soil. Yet, despite appreciable effort, the soil processes supporting such increased uptake have not been identified, leading to the

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expectation that nitrogen availability may increasingly limit the response to elevated $CO_2$ (Finzi et al. 2002; Luo et al. 2004; de Graaff et al. 2006; Finzi et al. 2006; Luo et al. 2006).

To understand the complex processes controlling ecosystem carbon cycling under elevated $CO_2$, and solve these puzzles, longer time-series are needed (Walther 2007).

### *Major findings on specific processes leading to these generalities*

Net primary production (NPP) is defined as the balance between canopy photosynthesis and plant respiration. Canopy photosynthesis increases with atmospheric $CO_2$, but less than expected based on physiological studies because of negative feedbacks in leaves (biochemical down-regulation) and canopies (reduced light, and conductance with increasing LAI; (Saxe et al. 2001; Schäfer et al. 2003; Wittig et al. 2005). On the other hand, plant respiration increases only in proportion to tree growth and amount of living biomass – that is, tissue-specific respiration does not change under elevated $CO_2$ (Gonzelez-Meller et al. 2004). The balance between these processes, NPP, increases in stands on moderately fertile and fertile soils. The short-term (<10 years), median response among the four "forest" FACE experiments was an increase of 23±2 percent (Norby et al. 2005). Although the average response was similar among these sites that differed in productivity (Norby et al. 2005), the within-site variability in the response to elevated $CO_2$ can be large (<10 percent to >100 percent). At the Duke FACE site, this within-site variability was related to nitrogen availability (Oren et al. 2001; Finzi et al. 2002; Norby et al. 2005). The absolute magnitude of the additional carbon sink varies greatly among years; at the Duke FACE, much of this variability is caused by droughts and disturbance events (McCarthy et al. 2006a).

The enhancement of NPP at low LAI is largely driven by an enhancement in LAI, whereas at high LAI, the enhancement reflects increased light-use efficiency (Norby et al. 2005, McCarthy et al. 2006a). The sustainability of the NPP response and the partitioning of carbon among plant components may depend on soil fertility (Curtis and Wang 1998; Oren et al. 2001; Finzi et al. 2002). NPP in intermediate fertility sites may undergo several phases of transient response, with $CO_2$-induced enhancement of stemwood production dominating initially followed by fine-root production after several years (Oren et al. 2001; Norby et al. 2004). In high productivity plots, the initial response so far appears sustainable (Körner 2006).

Carbon partitioning to pools with different turnover times is highly sensitive to soil resources. With increasing soil nutrient supply, LAI of stands under elevated $CO_2$ become increasingly greater than that of stands under ambient $CO_2$. This response affects carbon allocation to other pools. ANPP increases with LAI (McCarthy et al. 2006a) with no additional effects of elevated $CO_2$. The fraction of ANPP allocated to wood, a moderately slow turnover pool, increases with LAI in broadleaf FACE experiments (from ~50 percent at low LAI, to a maximum of 70 percent at mid-range LAI), with the effect of elevated $CO_2$ on allocation entirely accounted for by changes in LAI. In pines, allocation to wood decreased with increasing LAI (from ~65 percent to 55 percent), but

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was higher (averaging ~68 percent versus 58 percent) under elevated $CO_2$ (McCarthy et al. 2006a). Despite the increased canopy photosynthesis, there is no evidence of increased wood production in pines growing on very poor, sandy soils (Oren et al. 2001).

Total carbon allocation belowground (TBCA), and $CO_2$ efflux from the forest floor decrease with increasing LAI, but the enhancement under elevated $CO_2$ is approximately constant (~22 percent) over the entire range of LAI (King et al. 2004; Palmroth et al. 2006). About a third of the extra carbon allocated belowground under elevated $CO_2$ is retained in litter and soil storage at the U.S. FACE sites (Palmroth et al. 2006). At Duke FACE, a third of the incremental carbon sequestration is found in the forest floor. The $CO_2$-induced enhancement in fine root and mycorrhizal fungi turnover have not translated to a significant net incremental storage of carbon in the mineral soil (Schlesinger and Lichter 2001; Jastrow et al. 2005; Lichter et al. 2005). A recent meta-analysis (Jastrow et al. 2005), incorporating data from a variety of studies in different settings, estimated a median $CO_2$-induced increase in the rate of soil C sequestration of 5.6 percent (+19 g C $m^{-2}$ $y^{-1}$). A longer time-series is necessary to separate the treatment signal of soil C accumulation from the background noise in the C pool of real forest soil (McMurtrie et al. 2001).

In summary, canopy photosynthesis will likely increase with rising concentrations of atmospheric $CO_2$. In moderate to high fertility sites, aboveground biomass production will be the dominant sink for the extra photosynthate fixed under elevated $CO_2$. In low to moderately-low fertility sites, the extra photosynthate fixed under elevated $CO_2$ will be allocated belowground, where heterotrophic organisms will rapidly cycle most of the extra carbon back to the atmosphere.

### 3.5.4 Interactive effects including $O_3$, N deposition, and forest age

Ozone is produced from photochemical reactions of nitrogen oxides and volatile organic compounds. Ozone can damage plants (Ashmore 2002) and lower productivity, and these responses have been documented for U.S. forests (Matyssek and Sandermann 2003; Karlsson et al. 2004). In the United States, controls on emissions of nitrogen oxides and volatile organic compounds are expected to reduce the peak ozone concentrations that currently cause the most plant damage (Ashmore 2005). However, background tropospheric concentrations may be increasing as a result of increased global emissions of nitrogen oxides (Ashmore 2005). These predicted increases in background ozone concentrations may reduce or negate the effects of policies to reduce ozone concentrations (Ashmore 2005). Ozone pollution will modify the effects of elevated $CO_2$ and any changes in temperature and precipitation (Hanson et al. 2005), but these interactions are difficult to predict because they have been poorly studied.

Nitrogen deposition in the eastern U.S. and California can exceed 10 kg N $ha^{-1}$ $yr^{-1}$ and likely has increased 10 to 20 times above pre-industrial levels (Galloway et al. 2004). Forests are generally limited by nitrogen availability, and fertilization studies show that this increased deposition will enhance forest growth and carbon storage in wood (Gower et al. 1992; Albaugh et al. 1998; Adams et al. 2005). However, chronic nitrogen inputs

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over many years could lead to 'nitrogen saturation' (a point where the system can no longer use or store nitrogen), a reduction in forest growth, and increased levels of nitrate in streams (Aber et al. 1998; Magill et al. 2004). Increased nitrogen availability from nitrogen deposition will enhance the productivity increase from elevated $CO_2$ (Oren et al. 2001) and the positive effects of changes in temperature and precipitation. Overall, the effects of nitrogen deposition might exceed those of elevated $CO_2$ (Körner 2000).

Forest growth changes with forest age (Ryan et al. 1997), likely because of reductions in photosynthesis (Ryan et al. 2004). Because of the link of forest growth with photosynthesis, the response to drought, precipitation, nitrogen availability, ozone, and elevated $CO_2$ may also change with forest age. Studies of elevated $CO_2$ on trees have been done with young trees (which show a positive growth response), but the one study on mature trees showed no growth response (Körner et al. 2005). This is consistent with model results found in an independent study (Kirschbaum 2005). Tree size or age may also affect ozone response (older trees may be more resistant, Grulke and Miller 1994), and response to drought (older trees may be more resistant, Irvine et al. 2004).

### 3.5.5 Fire frequency and severity

Several lines of evidence suggest that large, stand-replacing wildfires will likely increase in frequency over the next several decades because of climate warming (Figure 3.7). Chronologies derived from fire debris in alluvial fans (Pierce et al. 2004) and fire scars in tree rings (Kitzberger et al. 2007) provide a broader temporal context for interpreting contemporary changes in the fire regime. These longer-term records unequivocally show that warmer and drier periods during the last millennium are associated with more frequent and severe wildfires in western forests. GCM projections of future climate during 2010-2029 suggest that the number of low humidity days (and high fire danger days) will increase across much of the western U.S. – allowing for more wildfire activity with the assumption that fuel densities and land management strategies remain the same (Flannigan et al. 2000; Brown et al. 2004). Flannigan et al. (2000) used two GCM simulations of future climate to calculate a seasonal severity rating, related to fire intensity and difficulty of fire control. Depending on the GCM used, forest fires in the Southeast are projected to increase from 10 to 30 percent and 10 to 20 percent in the Northeast by 2060. Other biome models used with a variety of GCM climate projections simulate a larger increase in fire activity and biomass loss in the Southeast, sufficient to convert the southernmost Southeast forests to savannas (Bachelet et al. 2001).

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**Figure 3.7** Ponderosa pine after the Hayman fire in Coloraso, June 2002.

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By combining climate-fire relationships derived from contemporary records with GCM simulations of future climate, Flannigan et al. (2005) estimated that future fire activity in Canadian boreal forests will approximately double by the end of this century for model simulations in which fossil fuel emissions were allowed to increase linearly at a rate of one percent per year. Both Hadley Center and Canadian GCM simulations projected that fuel moisture levels will decrease and air temperatures will increase within the continental interior of North America because of forcing from greenhouse gases and aerosols.

Santa Ana winds and human-triggered ignitions play an important role in shaping the fire regime of Southern California shrublands and forests (Keeley and Fotheringham 2001; Westerling et al. 2004). Santa Ana winds occur primarily during fall and winter and are driven by large scale patterns of atmospheric circulation – specifically by a high pressure system over the Great Basin and, simultaneously, a low pressure system offshore of Southern California and Mexico (Raphael 2003; Conil and Hall 2006). By correlating Santa Ana events with these larger-scale patterns of atmospheric circulation, Miller and Schlegel (2006) assessed how Santa Ana events may change in the future using output from GCMs. The total number of annual Santa Ana events was not predicted to change substantially over the next 30 years. However, for one of the GCM simulations (using the Geophysical Fluid Dynamics Laboratory version 2 model) there was a shift in the seasonal cycle in the mid to latter half of the 21st century, with fewer Santa Ana events occurring in September and more occurring in December (Miller and Schlegel 2006). The implication of a shift in the seasonal cycle of Santa Ana conditions for the Southern California fire regime remains uncertain.

Future increases in fire emissions across North America will have important consequences for climate forcing agents, air quality, and ecosystem services. More frequent fire will increase emissions of greenhouse gases and aerosols (Amiro et al. 2001) and increase deposition of black carbon aerosols on snow and sea ice (Flanner et al. 2007). Even though many forests will regrow and sequester the carbon released in the fire, forests burned in the next few decades can be sources of $CO_2$ for decades and not recover the carbon lost for centuries (Kashian et al. 2006) – an important consideration for slowing the increase in atmospheric $CO_2$. In boreal forests, the warming effects from fire-emitted greenhouse gases may be offset at regional scales by increases in surface albedo caused by a shift in the stand age distribution (Randerson et al. 2006). Future changes in boreal forest fires in Alaska and Canada will have consequences for air quality in the central and eastern U.S. because winds often transport carbon monoxide, ozone, and aerosols from boreal fires to the south (McKeen et al. 2002, Morris et al. 2006, Pfister et al. 2006). Increased burning in boreal forests and peatlands also has the potential to release large stocks of mercury currently stored in cold and wet soils (Turetsky et al. 2006). These emissions may exacerbate mercury toxicities in northern hemisphere food chains caused by coal burning.

### 3.5.6 Insect outbreaks

Rising temperature is the aspect of climate change most influential on forest insect species through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effects on host plant capacity to resist attack (Ayres and Lombardero 2000; Malmström and Raffa 2000; Bale et al. 2002). Future northward range expansion attributed to warming temperatures has been predicted for mountain pine beetle (Logan and Powell 2001) and southern pine beetle (*Dendroctonus frontalis*) (Ungerer et al. 1999). Future range expansion of mountain pine beetle has the potential of invading jack pine (*Pinus banksiana*), a suitable host that extends across the boreal forest of North America (Logan and Powell 2001). Increased probability of spruce beetle outbreak (Logan et al. 2003a) as well as increase in climate suitability for mountain pine beetle attack in high-elevation ecosystems (Hicke et al. 2006) has been projected in response to future warming. The combination of higher temperatures with reduced precipitation in the Southwest has led to enhanced tree stress, and also affected Ips beetle development rates; continued warming, as predicted by climate models, will likely maintain these factors (Breshears et al. 2005).

Indirect effects of future climate change may also influence outbreaks. Increasing atmospheric $CO_2$ concentrations may lead to increase ability of trees to recover from attack (Kruger et al. 1998). Enhanced tree productivity in response to favorable climate change, including rises in atmospheric $CO_2$, may lead to faster recovery of forests following outbreaks, and thus a reduction in time to susceptibility to subsequent attack (Fleming 2000). Although eastern spruce budworm (*Choristoneura fumiferana*) life cycles are tightly coupled to host tree phenology even in the presence of climate change,

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enemy populations that are significant in governing epidemic dynamics are not expected to respond to climate change in a synchronized way (Fleming 2000). Changing fire regimes in response to climate change (Flannigan et al. 2005) will affect landscape-scale forest structure, which influences susceptibility to attack (Shore et al. 2006).

Nonnative invasive species are also significant disturbances to forests in the United States. Although little has been reported on climate influences on these insects, a few studies have illustrated climate control. The hemlock woolly adelgid (*Adelges tsugae*) is rapidly expanding its range in the eastern United States, feeding on several species of hemlock (Box 1). The northern range limit of the insect in the United States is currently limited by low temperatures (Parker et al. 1999), suggesting range expansion in the event of future warming. In addition, the hemlock woolly adelgid has evolved greater resistance to cold conditions as it has expanded north (Butin et al. 2005). The introduced gypsy moth (*Lymantria dispar*) has defoliated millions of hectares of forest across the eastern United States, with great efforts expended to limit its introduction to other areas (USDA Forest Service 2005). Projections of future climate and gypsy moth simulation modeling reveal substantial increases in probability of establishment in the coming decades (Logan et al. 2003a).

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**BOX 1**: The Eastern Hemlock and its Woolly Adelgid.

Outbreaks in forests of insects and diseases affect forest structure and composition, leading to altered cycling of matter and energy, and changes in biodiversity and ecosystem services. The hemlock woolly adelgid (HWA, Adelges tsugae Armand), native to Asia, was first recorded in 1951 in Virginia, and has since spread, causing a severe decline in vitality and survival of eastern hemlock (Tsuga canadensis) in North American forests (Maps 1 & 2, Stadler et al. 2006). Roads, major trails, and riparian corridors provide connectivity enabling long-distance dispersal of this aphid-like insect, probably by humans or birds (Koch et al. 2006). Although HWA is consumed by some insect predators (Flowers et al. 2006), once it arrives at a site, complete hemlock mortality is just a matter of time (Orwig et al. 2002; Stadler et al. 2005). Hemlock seedlings are readily attacked and killed by the HWA, so damaged hemlock stands are replaced by stands of black birch, black oaks, and other hardwoods, depending on site conditions (Brooks 2004; Small et al. 2005; Sullivan and Ellison 2006). Plant biodiversity increases not only in the canopy; considerable understory develops, including greater herb richness and abundance and increased density of saplings of more species than found in the original forests; invasive shrubs and woody vines of several species also expand in response to the improved light conditions (Goslee et al. 2005; Small et al. 2005; Eschtruth et al. 2006). Four insectivorous bird species have high affinity for hemlock forest type, two of which, the blue-headed vireo and Blackburnian warbler, appeared to specialize on certain habitats. Unchecked expansion of HWA could negatively impact several million pairs from northeastern United States hemlock forests due to elimination of preferred habitat (Tingley et al. 2002, Ross et al. 2004). Changes in canopy attributes upon replacement of hemlock with deciduous broadleaf species alter the radiation regime, hydrology, and nutrient cycling (Cobb et al. 2006; Stadler et al. 2006), and result in greater temperature fluctuations and longer periods of times in which streams are dry (Snyder et al. 2002). These conditions reduce habitat quality for certain species of fish. Brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) were two to three times as prevalent in hemlock than hardwood streams (Ross et al. 2003). Low winter temperature is the main factor checking the spread of HWA (Skinner et al. 2003). However, the combination of increasing temperature and the capacity of HWA to evolve greater resistance to cold shock as it has expanded its range northward (Butin et al. 2005) means

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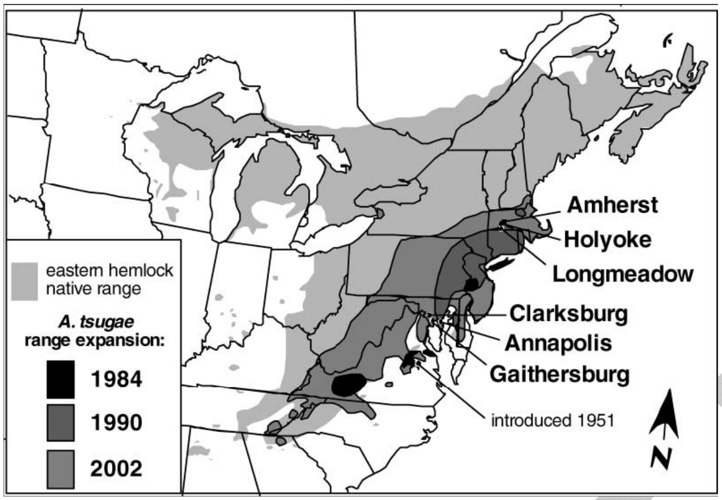
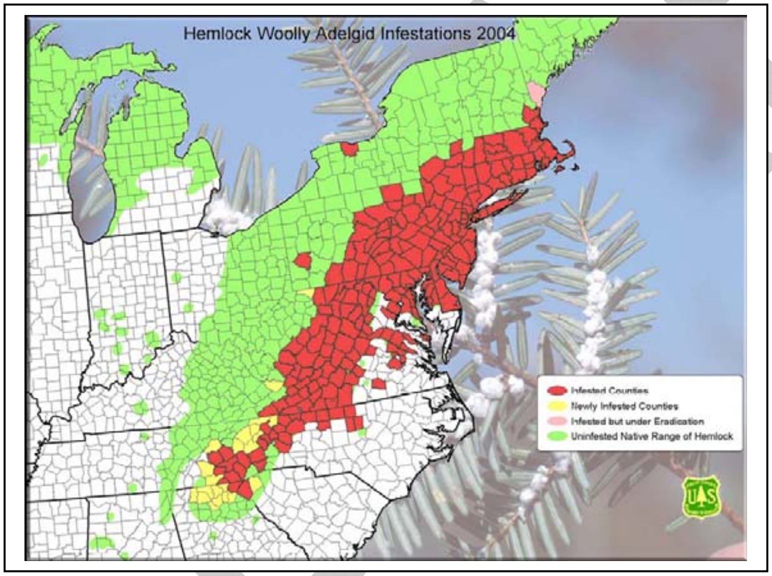
that stands that have been relatively protected by cold temperatures (Orwig et al. 2002) may fall prey to the insect in the not so distant future (Map 3).



**Map 1**. Sample sites and range expansion of *Adelges tsugae* relative to the native range of eastern hemlock in North America. Map from Butin et al. 2005 (redrawn from USDA Forest Service and Little, 1971).



**Map 2**. Onken B and Reardon R (compilers) (2005), Third Symposium on Hemlock Wooly Adelgid in the Eastern United States, Asheville, North Carolina. USDA Forest Service FHTET-2005 01http://www.na.fs.fed.us/fhp/hwa/pub/2005_proceedings/frontcover.pdf

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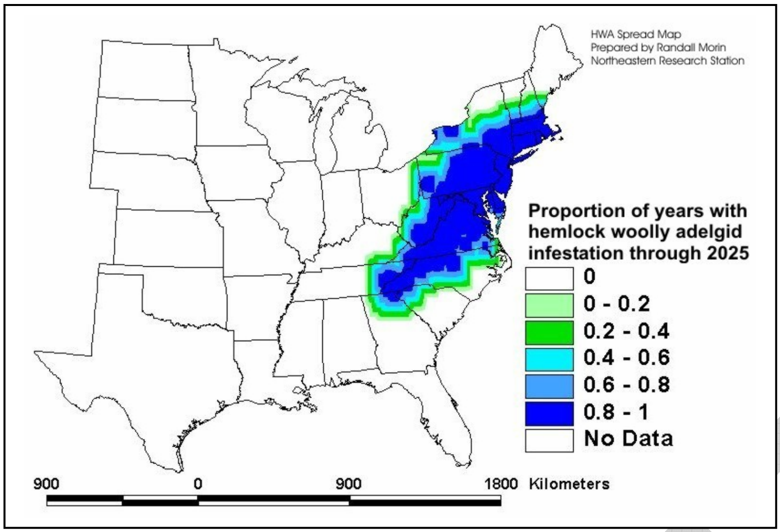

**Map 3**. Hemlock Woolly Adelgid spread map prepared by Randall Marin, Northeastern Research Station, U.S. Forest Service. Souto, D., Luther, T., Chianese, B., 1996. Past and current status of HWA in eastern and Carolina hemlock stands. In: Salom, S.M., Tignor, T.C., Reardon, R.C. (Eds.), Proceedings of the First Hemlock Woolly Adelgid Review, USDA For. Serv., Morgantown, WV, pp. 9-15. http://www.na.fs.fed.us/fhp/hwa/maps/hwaprojectedspreadmap.htm

As important disturbances, insect outbreaks affect many forest ecosystem processes. Outbreaks alter tree species composition within stands, and may result in conversion from forest to herbaceous vegetation through lack of regeneration (Holsten et al. 1995). Carbon stocks and fluxes are modified through a large decrease in living biomass and a corresponding large increase in dead biomass, reducing carbon uptake by forests as well as enhancing decomposition fluxes. In addition to effects at smaller scales, widespread outbreaks have significant effects on regional carbon cycling (Kurz and Apps 1999; Hicke et al. 2002a). Other biogeochemical cycles, such as nitrogen, are affected by beetle-caused mortality (Throop et al. 2004). Defoliation, for example as related to gypsy moth outbreaks, facilitates nitrogen movement from forest to aquatic ecosystems, elevating stream nitrogen levels (Townsend et al. 2004).

Significant changes to the hydrologic cycle occur after a widespread insect epidemic, including increases in annual water yield, advances in the annual hydrograph, and increases in low flows (Bethlahmy 1974; Potts 1984). Water quantity is enhanced through reductions in transpiration, in addition to reductions in snow interception, and subsequent redistribution and sublimation. These effects can last for many years following mortality (Bethlahmy 1974).

Interactions of outbreaks and fire likely vary with time, although observational evidence is limited to a few studies (Romme et al. 2006). In central Colorado, number of fires, fire extent, and fire severity were not enhanced following outbreaks of spruce beetle (Bebi et al. 2003; Bigler et al. 2005; Kulakowski and Veblen in press). Other studies of the 1988 Yellowstone fire that followed two mountain pine beetle epidemics found mixed fire effects, depending on outbreak severity and time since outbreak (Turner et al. 1999, Lynch et al. 2006). A quantitative modeling study of fire behavior found mixed fire

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effects following an outbreak of western spruce budworm (Hummel and Agee 2003); more modeling studies that incorporate complete effects are needed to explore other situations.

Multiple socioeconomic impacts follow severe insect outbreaks. Timber production and manufacturing and markets may not be able to take advantage of vast numbers of killed trees (Ferguson 2004), and beetle-killed timber has several disadvantages from a manufacturing perspective (Byrne et al. 2006). Water quantity may be enhanced for a period (Bethlahmy 1974). Perceived enhanced fire risk and views about montane aesthetics following beetle-cause mortality influence public views of insect outbreaks, which will drive public policy. Threats to ecologically important tree species may have ramifications for charismatic animal species (e.g., influences of whitebark pine mortality on the grizzly bear (*Ursus arctos* horribilis)) (Logan and Powell 2001). Impacts are enhanced as human population, recreation, and tourism increase in forested regions across the nation.

### 3.5.7 Storms (hurricanes, ice storms, windstorms)

Predictions of forest carbon (C) sequestration account for the effect of fires (e.g., Harden et al. 2000), yet other wide-ranging and frequent disturbances, such as hurricanes (Figure 3.8) and ice storms, are seldom explicitly considered. Both storm types are common in the southeastern United States, with an average return time of six years for ice storms (Bennett 1959), and two years for hurricanes (Smith 1999). These, therefore, have the potential for significant impact on C sequestration in this region, which accounts for ~20 percent of annual C sequestration in conterminous U.S. forests (Birdsey and Lewis 2002, Bragg et al. 2003). Recent analysis demonstrated that a single category 3 hurricane and severe ice storms could each transfer to the decomposable pool the equivalent of 10 percent of the annual U.S. C sequestration, with subsequent reductions in sequestration caused by direct stand damage (McNulty 2002, McCarthy et al. 2006b). For example, hurricanes Rita and Katrina together damaged a total of 2,200 ha and 63 million $m^3$ of timber volume (Stanturf et al. 2007).

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**Figure 3.8** Forest damage from Hurricane Hugo. Andrew J. Boone, South Carolina Forestry Commission, www.forestryimages.org.

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Common forest management practices, such as fertilization and thinning, forest type, and increasing atmospheric $CO_2$ levels can change wood and stand properties, and thus may change vulnerability to ice storm damage. A pine plantation experienced a ~250 g C $m^{-2}$ reduction in living biomass during a single ice storm, equivalent to ~30 percent of the annual net ecosystem carbon exchange of this ecosystem. In this storm at the Duke FACE, nitrogen fertilization had no effect on storm damage, conifer trees were more than twice as likely to be killed by ice storm damages as leafless deciduous-broadleaf trees, and thinning increased broken limbs or trees threefold. However, elevated $CO_2$ reduced the storm damage to a third of that of the ambient $CO_2$ stand (McCarthy et al. 2006b). Although this result suggests that forests may suffer less damage in a future ice storm when atmospheric $CO_2$ is higher, future climate may create conditions leading to greater ice storm frequency, extent and severity (da Silva et al. 2006), which may balance the decreased sensitivity to ice damage under elevated $CO_2$. All of these predictions are very uncertain (Cohen et al. 2001).

### 3.5.8 Changes in Overstory Species Composition

Several approaches can predict changes in biomes (major vegetation assemblages such as conifer forests, and savanna/woodland) and changes in species composition or overstory species communities (Hansen et al. 2001a). These approaches use either rules that define the water balance, temperature, seasonality, etc. required for a particular biome, or statistically link species distributions or community composition with climate envelopes. These efforts have mostly focused on equilibrium responses to climate changes over the next century (Hansen et al. 2001a), so predictions for the next several decades are unavailable.

Bachelet et al. (2001) used the Mapped Atmosphere-Plant-Soil System (MAPPS) model with the climate predictions generated by seven different global circulation models to predict how biome distributions would change with a doubling of $CO_2$ by 2100. Mean annual temperature of the United States increased from 3.3 to 5.8 °C for the climate predictions. Predicted forest cover in 2100 declined by an average of 11 percent (range for all climate models was +23 percent to -45 percent). The MAPPS model coupled to the projected future climates predicts that biomes will migrate northward in the East and to higher elevations in the West. For example, mixed conifer and mixed hardwood forests in the Northeast move into Canada, and decline in area by 72 percent (range: -14 to -97 percent), but are replaced by eastern hardwoods. In the Southeast, grasslands or savannas displace forests and move their southern boundaries northward, particularly for the warmer climate scenarios. In the West, forests displace alpine environments, and the wet conifer forests of the Northwest decline in area nine percent (range: 54 to + 21 percent), while the area of interior western pines changes little. Species predictions for the Eastern U.S. using a statistical approach showed that most species moved north 60-300 miles (Hansen et al. 2001a).

Authors of these studies cautioned that these equilibrium approaches do not reflect the transient and species-specific nature of the community shifts that are projected to occur. Success in moving requires suitable climate, but also dispersal that may lag behind changes in climate (Hansen et al. 2001a). Some species will be able to move quicker than others will, and some biomes and communities may persist until a disturbance allows changes to occur (Hansen et al. 2001a). The authors of these studies agreed that while climate is changing, novel ecosystems will arise – novel because some species will persist in place, some species will depart, and new species will arrive.

## 3.6 Indicators and observing systems – Forests

### 3.6.1 Characteristics of Observing Systems

Many Earth observing systems (Bechtold and Patterson 2005; Denning 2005) are designed to allow for integration of multiple kinds of observations using a hierarchical approach that takes advantage of the characteristics of each. A typical system uses remote sensing to obtain a continuous measurement over a large area, coupled with statistically-designed field surveys to obtain more detailed data at a finer resolution. Statistically, this approach (known as “multi-phase” sampling) is more efficient than sampling with just a single kind of observation or conducting a complete census (Gregoire and Valentine, in press). Combining observed data with models is also common because often the variable of interest cannot be directly observed, but observation of a closely-related variable may

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be linked to the variable of interest with a model. Model-data synthesis is often an essential component of Earth observing systems (Raupach et al. 2005).

To be useful, the system must observe a number of indicators more than once over a period, and also cover a large-enough spatial scale to detect a change. The length of time required to detect a change with a specified level of precision depends on the variability of the population being sampled, the precision of measurement, and the number of samples (Smith 2004). Non-climatic local factors, such as land use change, tend to dominate vegetation responses at small scales, masking the relationship with climate (Parmesan and Yohe 2003). A climate signal is therefore more likely to be revealed by analyses that can identify trends across large geographic regions (Walther et al. 2002). The relationship between biological observations and climate is correlational; thus, it is difficult to separate the effects of climate change from other possible causes of observed effects (Walther et al. 2002). Inference of causation can be determined with carefully controlled experiments that complement the observations. Yet, observation systems can identify some causal relationships and therefore have value in developing climate impact hypotheses. Schreuder and Thomas (1991) determined that if both the potential cause and effect variables were measured at inventory sample plots, a relationship could be established if the variables are measured accurately, estimated properly, and based on a large enough sample. But, in practice, additional information is often needed to strengthen a case, for example, a complementary controlled experiment to verify the relationship.

### 3.6.2 Indicators of Climate Change Effects

The species that comprise communities respond both physiologically and competitively to climate change. One scheme for assessing the impacts of climate change on species and communities is to assess the effects on: (1) the physiology of photosynthesis, respiration, and growth; (2) species distributions; and (3) phenology, particularly life cycle events such as timing of leaf opening. There may also be effects on functions of ecosystems such as hydrologic processes.

***Effects on physiology***

Net primary productivity is closely related to indices of “greenness” and can be detected by satellite over large regions (Hicke et al. 2002b). Net ecosystem productivity (NEP) can be measured on the ground as changes in carbon stocks in vegetation and soil (Boisvenue and Running 2006). Root respiration and turnover are sensitive to climate variability and may be good indicators of climate change if measured over long enough time periods (Atkin et al. 2000; Gill and Jackson 2000). Gradient studies show variable responses of growth to precipitation changes along elevational gradients (Fagre et al. 2003). Climate effects on growth patterns of individual trees is confounded by other factors such increasing $CO_2$ and N deposition, so response of tree growth is difficult to interpret without good knowledge of the exposure to many possible causal variables. For example, interannual variability in NPP, which can mask long-term trends, can be summarized from long-term ecosystem studies and seems to be related to interactions

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between precipitation gradients and growth potential of vegetation (Knapp and Smith 2001).

### *Effects on species distributions*

Climate change affects composition and geographical distribution, and these changes are observable over time by field inventories, remote sensing, and gradient studies. Both range expansions and retractions are important to monitor (Thomas et al. 2006), and population extinctions or extirpations are also possible. Range and vegetation density changes have been observed in Alaska by field studies and remote sensing (Hinzman et al. 2005). Detecting range and abundance shifts in wildlife populations may be complicated by changes in habitat from other factors (Warren et al. 2001).

### *Effects on phenology*

Satellite and ground systems can document onset and loss of foliage, with the key being availability of long-term data sets (Penuelas and Filella 2001). Growing season was found significantly longer in Alaska based on satellite normalized difference vegetation Index (NDVI) records (Hinzman et al. 2005). Schwartz et al. (2006) integrated weather station observations of climate variables with remote sensing and field observations of phenological changes using Spring Index phenology models. However, Fisher et al. (2007) concluded that species or community compositions must be known to use satellite observations for predicting the phenological response to climate change.

### *Effects on natural disturbances and mortality*

Climate change can affect forests by altering the frequency, intensity, duration, and timing of natural disturbances (Dale et al. 2001). The correlation of observations of changes in fire frequency and severity with changes in climate are well documented (e.g., Flannigan et al. 2000; Westerling et al. 2006), and the inference of causation in these studies is established by in situ studies of fire and vegetation response, and fire behavior models. Similar relationships hold for forest disturbance from herbivores and pathogens (Ayres and Lombardero 2000; Logan et al. 2003b). Tree mortality may be directly caused by climate variability, such as in drought (Gitlin et al. 2006).

### *Effects on hydrology*

Climate change will affect forest water budgets and these changes have been observed over time by long-term stream gauge networks and research sites. Changes in permafrost and streamflow in the Alaskan Arctic region are already apparent (Hinzman et al. 2005). There is some evidence of a global pattern (including in the United States) in response of streamflow to climate from stream-gauge observations (Milly et al. 2005). Inter-annual variation in transpiration of a forest can be observed by sap flow measurements (Phillips and Oren 2001; Wullschleger et al. 2001).

### *Causal variables*

It is important to have high-quality, spatially-referenced observations of climate, air pollution, deposition, and disturbance variables. These are often derived from observation networks using spatial statistical methods (e.g., Thornton et al. 2000).

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### 3.6.3 Current Capabilities and Needs

There are strengths and limitations to each kind of observation system: intensive monitoring sites such as Long Term Ecological Research (LTER) sites and protected areas; extensive observation systems such as Forest Inventory and Analysis (FIA) or the U.S. Geological Survey (USGS) stream-gauge network; and remote sensing. A national climate observation system may be improved by integration under an umbrella program such as the National Ecological Observatory Network (NEON), or Global Earth System of Systems (GEOSS) (see Table 3.1). Also, increased focus on "sentinel" sites, could help identify early indicators of climate effects on ecosystem processes, and provide observations of structural and species changes (NEON 2006).

**Table 3.1 Current and Planned Observation Systems for Climate Effects on Forests**

| Observation System | Characteristics | Reference |
|---|---|---|
| **Forest Inventory and Analysis (U.S. Forest Service)** | **Annual and periodic measurements of forest attributes at a large number (more than 150,000) of sampling locations. Historical data back to 1930s in some areas.** | **Bechtold and Patterson 2005** |
| **AmeriFlux (Department of Energy and other Agencies)** | **High temporal resolution (minutes) measurements of carbon, water, and energy exchange between land and atmosphere at about 50 forest sites. A decade or more of data available at some of the sites.** | **http://public.ornl.gov/ameriflux/** |
| **Long Term Ecological Research network (National Science Foundation)** | **The LTER network is a collaborative effort involving more than 1,800 scientists and students investigating ecological processes over long temporal and broad spatial scales. The 26 LTER Sites represent diverse ecosystems and research emphases** | **http://www.lternet.edu/** |
| **Experimental Forest Network (U.S. Forest Service)** | **A network of 77 protected forest areas where long-term monitoring and experiments have been conducted.** | **Lugo 2006** |
| **National Ecological Observation Network** | **The NEON observatory is specifically designed to address central scientific questions about the interactions of ecosystems, climate, and land use.** | **http://www.neoninc.org/** |
| **Global Terrestrial Observing System (GTOS)** | **GTOS is a program for observations, modelling, and analysis of terrestrial ecosystems to support sustainable development.** | **http://www.fao.org/gtos/** |

Intensive monitoring sites measure many of the indicators that are likely to be affected by climate change, but have mostly been located independently and so do not optimally represent either (1) the full range of forest condition variability, or (2) forest landscapes that are most likely to be affected by climate change (Hargrove et al. 2003). Forest inventories are able to detect long-term changes in composition and growth, but since they are limited in ability to attribute observed changes to climate, improvement in observing the potential causal variables associated with responses would help interpret

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the results (Schreuder and Thomas 1991). Some additions to the list of measured variables would also improve the inventory approach (The Heinz Center 2002; USDA 2003). Remote sensing, when coupled with models, can detect changes in vegetation-response to climate variability (Running et al. 2004; Turner et al. 2004). Interpretation of remote sensing observations is greatly improved by associating results with ground data (Pan et al. 2006).

Maintaining continuity of remote sensing observations at appropriate temporal and spatial scales must be a high priority. NASA's Earth Science division cannot support continued operations of all satellites indefinitely, so it becomes a challenge for the community using the measurements to identify long-term requirements for satellites, and provide a long-term framework for critical Earth science measurements and products (NASA Office of Earth Science 2004).

Another high-priority need is to improve ability to monitor the effects of disturbance on forest composition and structure, and to attribute changes in disturbance regimes to changes in climate. This will involve a more coordinated effort to compile maps of disturbance events from satellite or other observation systems, to follow disturbances with in situ observations of impacts, and to keep track of vegetation changes in disturbed areas over time. There are several existing programs that could be augmented to achieve this result, such as intensifying the permanent sample plot network of the FIA program for specific disturbance events, or working with forest regeneration and restoration programs to install long-term monitoring plots.

## 3.7 How Changes in One System Affect Other Systems – Forests

Disturbances in forests such as fire, insect outbreaks, and hurricanes usually kill some or all of the trees and lower leaf area. These reductions in forest cover and leaf area will likely change the hydrology of the disturbed areas. Studies of forest harvesting show that removal of the tree canopy or transpiring surface will increase water yield, with the increase proportional to the amount of tree cover removed (Stednick 1996). The response will vary with climate and species, with wetter climates showing a greater response of water yield to tree removal. For all studies, average water yield increased 2.5 mm for each one percent of the tree basal-area removed (Stednick 1996). High-severity forest fires can increase sediment production and water yield as much as 10 to 1000 times, with the largest effects occurring during high-intensity summer storms (see review in Benavides-Solorio and MacDonald 2001). An insect epidemic can increase annual water yield, advance the timing annual hydrograph, and increase base flows (Bethlahmy 1974; Potts 1984). Presumably, the same effects would occur for trees killed in windstorms and hurricanes.

Disturbances can also affect native plant species diversity, by allowing opportunities for establishment of non-native invasives, particularly if the disturbance is outside of the range of variability for the ecosystem (Hobbs and Huenneke 1992). Areas most vulnerable to invasion by non-natives are those areas that support the highest plant diversity and growth (Stohlgren et al. 1999). In the western U.S., these are generally the

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riparian areas (Stohlgren et al. 1998). We expect that disturbances that remove forest litter or expose soil (fire, trees tipped over by wind) will have the highest risk for admitting invasive non-native plants.

## 3.8 Findings and Conclusions - Forests

### 3.8.1 Introduction

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 area as fires 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.

### 3.8.2 Key Findings and Conclusions

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

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- Rising $CO_2$ will very likely increase photosynthesis for forests.
  - On high fertility sites, this increased photosynthesis will likely increase wood growth and carbon stored in wood.
  - On low to moderate fertility sites, the 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

- N deposition has very likely increased forest growth and will continue to do so. N 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 increased where they occur.

- 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 FIA Program, AmeriFlux, USA National Phenology Network, LTER network and the upcoming National Ecological Observation Network, coupled with remote sensing.
  - No coordinated system exists for monitoring forest disturbance.

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- 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 N 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 supply critical information on long-term responses of different species.

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## *3.9 Observed and Predicted Changes or Trends – Arid Lands*

### 3.9.1 Introduction

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), 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, and 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 3.9). 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.

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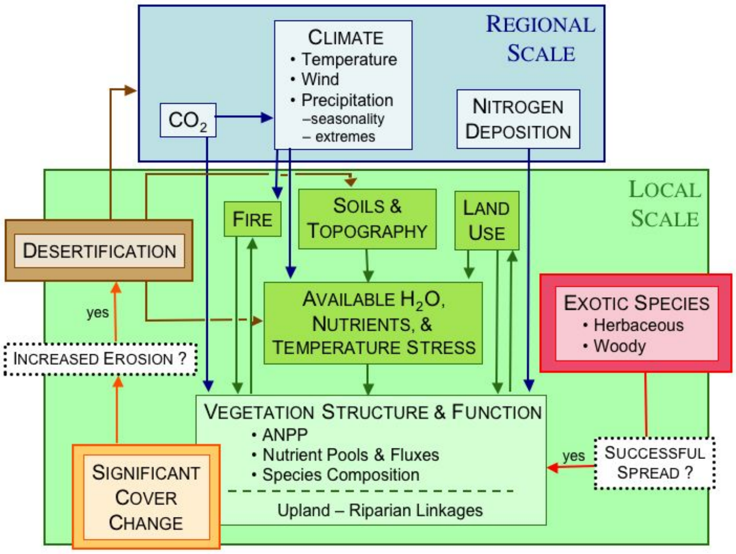

**Figure 3.9** Organizational framework for interpreting climate and climate change effects on arid land ecosystems.

## 3.9.2 Bio-Climatic Setting

Arid lands of the continental United States are represented primarily by the subtropical Hot Deserts of the Southwest, and the temperate Cold Deserts of the Intermountain West (Figure 3.2). The Hot Deserts differ primarily with respect to precipitation seasonality (Figure 3.10). The Mojave Desert is dominated by winter precipitation (thus biological activity in the cool season), whereas the Chihuahuan Desert is dominated by summer precipitation (thus biological activity during hotter conditions). The hottest of the three deserts, the Sonoran, is the intermediate, receiving both winter and summer precipitation. The Cold Deserts are also dominated by winter precipitation, much of which falls as snow, owing to the more temperate latitudes and higher elevations (West 1983). These arid land formations are characterized by unique plants and animals, and if precipitation seasonality changes, marked changes in species and functional group composition and abundance would be expected.

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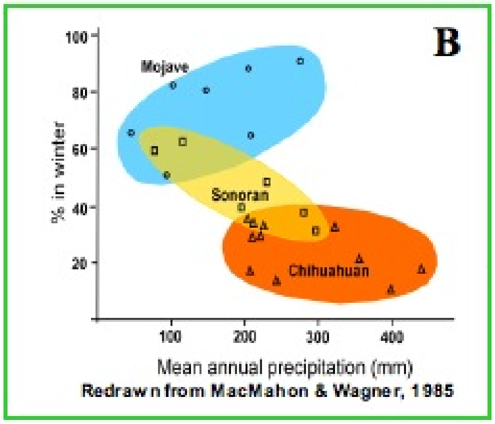
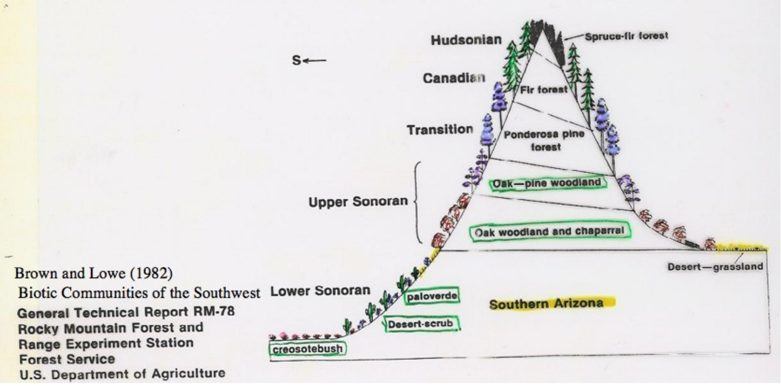


**Figure 3.10** Mean annual precipitation and its seasonality in three Hot Deserts (from MacMahon and Wagner 1985).

Such changes might first occur in the geographic regions where these formations and their major subdivisions interface. Extreme climatic events are major determinants of arid and semi-arid ecosystem structure and function (Holmgren et al. 2006). For example, while changes in temperature will affect levels of physiological stress and water requirements during the growing season, minimum temperatures during winter may be a primary determinant of species composition and distribution. In the Sonoran Desert, in addition to warm season rainfall, freezing temperatures strongly influence distributions of many plant species (Turner et al. 1995). The vegetation growing season, as defined by continuous frost-free air temperatures, has increased by on average about two days/decade since 1948 in the conterminous U.S., with the largest changes occurring in the West (Easterling 2002; Feng and Hu 2004). A recent analysis of climate trends in the Sonoran Desert (1960-2000) also shows a decrease in the frequency of freezing temperatures, lengthening of the frost-free season, and increased minimum temperatures (Weiss and Overpeck 2005). With warming expected to continue throughout the 21st Century, potential ecological responses may include contraction of the overall boundary of the Sonoran Desert in the southeast and expansion northward, eastward, and upward in elevation, and changes to plant species ranges. Realization of these changes will be co-dependent on what happens with precipitation and disturbance regimes (e.g., fire).

The biotic communities that characterize many U.S. arid lands are influenced by Basin and Range topography.Thus, within a given bioclimatic zone, communities transition from desert scrub and grassland to savanna, woodland and forest along strong elevation gradients (Figure 3.11). Changes in climate will affect the nature of this zonation, with arid land communities potentially moving up in elevation in response to warmer and drier conditions. Experimental data suggest shrub recruitment at woodland-grassland ecotones will be favored by increases in summer precipitation, but unaffected by increases in winter precipitation (Weltzin and McPherson 2000). This suggests that increases in summer precipitation would favor down-slope shifts in this ecotone. Floristic and ecosystem process changes along these elevation gradients may precede those occurring on a regional basis, and as such, may be early indicators of climate change.



Brown and Lowe (1982)
Biotic Communities of the Southwest
General Technical Report RM-78
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

**Figure 3.11** Elevation life zones along an arid land elevation gradient (from Brown, 1994).

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### 3.9.3 Climate Influences at Local Scales

Climate and atmospheric $CO_2$ influence communities at broad spatial scales, but topography, soils, and landform control local variation in ecosystem structure and function within a given elevation zone, making local vegetation very complex. Topography influences water balance (south-facing slopes are drier), air drainage and night temperatures, and routing of precipitation. Soil texture and depth affect water capture, water storage, and fertility (especially nitrogen). These factors may interact with water availability to limit plant production and control species composition. Plants that can access water in deep soil or in groundwater depend less on precipitation for growth and survival, but such plants may be sensitive to precipitation changes that affect the recharge of deep water stores. If the water table increases with increases in rainfall or decreased plant cover, soil salinity may increase and adversely affect vegetation (McAuliffe 2003). To predict vegetation response to climate change, we need to understand these complex relationships between soil, soil hydrology, and plant response.

### 3.9.4 Climate and Disturbance

Disturbances such as fire and grazing are superimposed against the backdrop of climate variability, climate change, and spatial variation in soils and topography. The frequency and intensity of a given type of disturbance will determine the relative abundance of annual, perennial, herbaceous, and woody plants on a site. Extreme climate events such as drought may act as triggers to push arid ecosystems experiencing chronic disturbances such as grazing past desertification ‘tipping points’ (CCSP 4.2 2007; Gillson and Hofffman 2007). An increase in the frequency of climate trigger events would put arid systems increasingly at risk for major changes in vegetation cover. Climate is also a key factor dictating the effectiveness of resource management plans and restoration efforts (Holmgren and Scheffer 2001). Precipitation (and its interaction with temperature) plays a major role in determining how plant communities are impacted by, and how they respond to, a given type and intensity of disturbance. It is generally accepted that effects of grazing in arid lands may be mitigated in years of good rainfall and accentuated in drought years. However, this generalization is context dependent. Landscape-scale factors such as rainfall and stocking rate affect grass cover in pre- and post-drought periods, but grass dynamics before, during, and after drought varies with species-specific responses to local patch-scale factors (e.g., soil texture, micro-topographic redistribution of water) (Yao et al. 2006). As a result, a given species may persist in the face of grazing and drought in some locales and be lost from others. Spatial context should thus be factored in to assessments of how changes in climate will affect ecosystem stability (their ability to maintain function in the face of disturbance (e.g., resistance)); and the rate and extent to which they recover from disturbance (e.g., resilience). Advances in computing power, geographic information systems, and remote sensing now make this feasible.

Disturbance will also affect rates of ecosystem change in response to climate change because it reduces vegetation resistance to slow, long-term changes in climate (Cole 1985; Overpeck et al. 1990). Plant communities dominated by long-lived perennials may exhibit considerable biological inertia and changes in community composition may lag

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behind significant changes in climate. Species established under previous climate regimes may thus persist in novel climates for long periods of time. Indeed, it has been suggested that the desert grasslands of the Southwest were established during the cooler, moister Little Ice Age but have persisted in the warmer, drier climates of the 19th and 20th Centuries (Neilson 1986). Disturbances create opportunities for species better adapted to the current conditions to establish. In the case of desert grasslands, livestock grazing subsequent to Anglo-European settlement may have been a disturbance that created opportunities for desert shrubs such as mesquite and creosote bush to increase in abundance. Rates of ecosystem compositional change in response to climate change may therefore depend on the type and intensity of disturbance, and the extent to which fundamental soil properties (especially depth and fertility) are altered by disturbance.

### 3.9.5 Desertification

Precipitation and wind are agents of erosion. Wind and water erosion are primarily controlled by plant cover. Reductions in plant cover by fire or grazing create opportunities for accelerated rates of erosion; and loss of soils feeds back to affect species composition in ways that can further reduce plant production and cover. Disturbances in arid lands can thus destabilize sites and quickly reduce their ability to capture and retain precipitation inputs. This is the fundamental basis for desertification, a long-standing concern (Van de Koppel et al. 2002). Desertification involves the expansion of deserts into semi-arid and subhumid regions, and the loss of productivity in arid zones. It typically involves loss of ground cover and soils, replacement of palatable, mesophytic grasses by unpalatable xerophytic shrubs, or both (Figure 3.12). There has been long-standing controversy in determining the relative contribution of climatic and anthropogenic factors as drivers of desertification. Local fence line contrasts argue for the importance of land use (e.g., changes in grazing, fire regimes); vegetation change in areas with no known change in land use argue for climatic drivers.

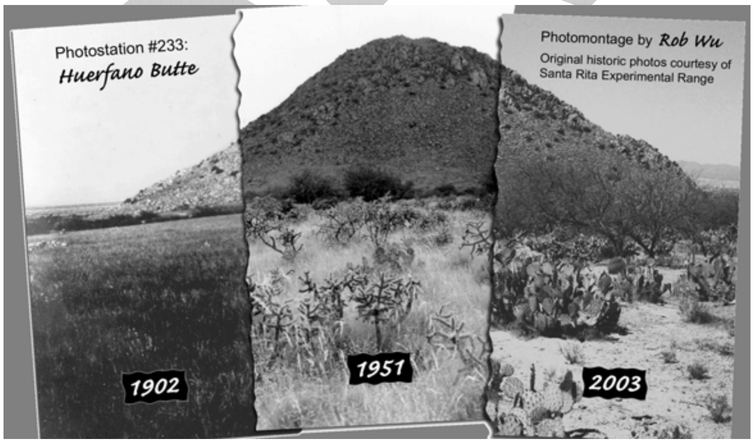

**Figure 3.12** Desertification of desert grassland (Santa Rita Experimental Range near Tucson, AZ).

Grazing has traditionally been the most pervasive and extensive climate-influenced land use in arid lands (with the exception of areas where access to ground or surface water

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allows agriculture; see Chapter 3.2). Large-scale, unregulated livestock grazing in the 1800s and early 1900s is widely regarded as contributing to widespread desertification (Fredrickson et al. 1998). Grazing peaked around 1920 on public lands in the West; and by the 1970s had been reduced by approximately 70 percent (Holechek et al. 2003). These declines reflect a combination of losses in carrying capacity (ostensibly associated with soil erosion, and reductions in the abundance of palatable species), and creation of federally funded experimental ranges in the early 1900s (e.g., the Santa Rita Experimental Range in Arizona, and the Jornada Experimental Range in New Mexico), which are charged with developing stocking rate guidelines, the advent of the science of range management, and federal legislation intended to regulate grazing (Taylor Grazing Act 1934) and combat soil erosion (Soil Erosion Act 1935), and shifting of livestock operations to higher rainfall regions. While livestock grazing remains an important land use in arid lands, there has been a significant shift to exurban development and recreation, reflecting dramatic increases in human population density since 1950 (Hansen and Brown 2005). Arid land response to future climate will thus be mediated by new suites of environmental pressures such air pollution and N-deposition, motorized off-road vehicles, feral pets, and horticultural invasives in addition to grazing.

### 3.9.6 Biotic Invasions

Arid lands of North America were historically characterized by mixtures of shrublands, grasslands, and shrub-steppe or shrub-savanna. Since Anglo-European settlement, shrubs have increased at the expense of grasses (Archer 1994). Causes for this shift in plant-life-form abundance are the topic of active debate, but center around climate change, atmospheric $CO_2$ enrichment, nitrogen deposition, and changes in grazing and fire regimes (Archer et al. 1995; Van Auken 2000). In many cases, increases in woody plant cover reflect the proliferation of native shrubs (e.g., mesquite, creosote bush); in other cases, non-native shrubs have increased in abundance (e.g., tamarix). Historically, the displacement of grasses by woody plants in arid lands was of concern due to its potential impacts on stream flow and ground water recharge (Wilcox 2002), and livestock production. More recently, the effects of this change in land cover has been shown to have implications for carbon sequestration, and land surface-atmosphere interactions (Schlesinger et al. 1990; Archer et al. 2001; Wessman et al. 2004). Warmer, drier climates with more frequent and intense droughts are likely to favor xerophytic shrubs over mesophytic native grasses, especially when native grasses are preferentially grazed by livestock. However, invasions by non-native grasses are markedly changing the fire regime in arid lands and impacting shrub cover.

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**Figure 3.13** Top-down view of native sagebrush (*Artemesia tridentata*) steppe (right) invaded by cheatgrass (*Bromus tectorum*), an exotic annual grass (left).

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Non-native plant invasions, promoted by enhanced nitrogen deposition (Fenn et al. 2003), will have a major impact on how arid land ecosystems respond to climate and climate change. Once established, non-native annual and perennial grasses can generate massive, high-continuity fine-fuel loads that predispose arid lands to fires more frequent and intense than those with which they evolved (Figure 3.13). The result is the potential for desert scrub, shrub-steppe, and desert grassland/savanna biotic communities to be quickly and radically transformed into monocultures of invasive grasses over large areas. This is already well underway in the Cold Desert region (Knapp 1998) and is in its early stages in Hot Deserts (Williams and Baruch 2000; Kupfer and Miller 2005; Salo 2005; Mau-Crimmins 2006). By virtue of their profound impact on the fire regime and hydrology, invasive plants in arid lands will trump direct climate impacts on native vegetation where they gain dominance. There is a strong climate-wildfire synchrony in forested ecosystems of western North America (Kitzberger et al. 2007). As the areal extent of fire-prone exotic grass communities increases, low elevation arid ecosystems will likely experience similar climate-fire synchronization where none previously existed, and spread of low elevation fires upslope may constitute a new source of ignition for forest fires. Exurban development (Nelson 1992, Daniels 1999) will be a major source for exotic species introductions by escape from horticulture.

### 3.9.7 A Systems Perspective

As reviewed in the preceding sections, the response of arid lands to climate and climate change is contingent upon the net outcome of several interacting factors (Fig 3.9). Some of these factors may reinforce and accentuate climate effects (e.g., soils, grazing); others may constrain, offset or override climate effects (e.g., soils, atmospheric $CO_2$ enrichment, fire, exotic species). Furthermore, extreme climatic events can themselves constitute disturbance (e.g., soil erosion and inundation associated with high intensity rainfall events and flooding; burial abrasion and erosion associated with high winds, mortality caused by drought and extreme temperature stress). Climate effects should thus be viewed in the context of other factors, and simple generalizations regarding climate effects should be viewed with caution. This is not to say, however, that we do not have data and theory to guide prediction of future outcomes. 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. Given the concomitant changes in climate, atmospheric $CO_2$, nitrogen deposition, and species invasions, it also seems likely that novel wildland and managed ecosystems will develop (Hobbs et al. 2006). In novel ecosystems, species occur in combinations and relative abundances that have not occurred previously within our experience base in a given biome. These novel ecosystems will present novel challenges and opportunities for conservation and management.

The following sections will address specific climate/land use/land cover issues in more detail. Section 3.10 will discuss climate and climate change effects on species distributions and community dynamics and Section 3.11 will review the consequences for ecosystem processes. Section 3.12 will focus on climate change implications for structure and function of riparian and aquatic ecosystems in arid lands. Implications for wind and water erosion will be reviewed in 3.13.

## *3.10 Species Distributions and Community Dynamics*

### 3.10.1 Climate-Fire Regimes

The climate-driven dynamic of the fire cycle is likely to become the single most important feature controlling future plant distributions in U.S. arid lands. Rising temperatures, decreases in precipitation and a shift in its seasonality and variability, and increases in atmospheric $CO_2$ and nitrogen deposition (Sage 1996) coupled with invasions of exotic grasses (Brooks et al. 2004; Brooks and Berry 2006) will accelerate the grass-fire cycle in arid lands and promote development of near monoculture stands of invasive plants (D'Antonio and Vitousek 1992). The frequency of fire in the Mojave Desert has dramatically increased over the past 20 years and effected a dramatic conversion of desert shrubland to degraded annual-plant landscapes (Bradley et al. 2006, Brooks and Berry 2006). Given the episodic nature of desert plant establishment and the high susceptibility of the new community structure to additional fire, it will be exceedingly difficult to recover native plant dominance. A similar conversion has occurred in many Great Basin landscapes (Knapp 1995), and given the longer period of non-native annual plant presence (Novak and Mack 2001), the pattern is much more advanced and has lowered ecosystem carbon storage (Bradley et al. 2006). Contemporary patterns in natural settings (Wood et al. 2006) and field experiments (Smith et al. 2000) suggest non-native response to climate change will be extremely important in the dynamics of arid land fire cycle, and changes in climate that promote fires will exacerbate land cover change in arid and semi-arid ecosystems.

There is some debate as to how climate contributed to a non-native component of this vegetation-disturbance cycle over the first half of the 20th century. For the upper

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elevations in the Sonoran Desert, Lehmann lovegrass (*Eragrostis lehmanniana*), a perennial African grass introduced for cattle forage and erosion control, has spread aggressively and independently of livestock grazing (McClaran 2003). Its success relative to native grasses appears related to its ability to more effectively utilize winter moisture and greater seedling drought tolerance. Relatively wet periods associated with the Pacific Decadal Oscillation appear to have been more important than increases in N-deposition or $CO_2$ concentrations in the spread of the species (Salo 2005).

More recently, warm, summer-wet areas in northern Mexico (Sonora) and the Southwestern U.S. have become incubators for perennial African grasses such as buffelgrass (*Pennisetum ciliare*), purposely introduced to improve cattle forage in the 1940s. These grasses escape plantings on working ranches and, like exotic annual grasses, initiate a grass-fire cycle (Williams and Baruch 2000). In the urbanized, tourism-driven Sonoran Desert of southern Arizona, buffelgrass invasion is converting fireproof and picturesque desert scrub communities into monospecific, flammable grassland. Buffelgrass, like other neotropical exotics, is sensitive to low winter temperatures. The main invasion of buffelgrass in southern Arizona happened with warmer winters beginning in the 1980s, and its range will extend further north and upslope as minimum temperatures continue to increase (Arriaga et al. 2004). This is complicated further by ongoing germplasm research seeking to breed more drought- and cold-resistant varieties. For example, a cold-resistant “Frio” variety of buffelgrass recently released by USDA-Agricultural Research Service has been planted 40 km south of the Arizona border near Cananea, Mexico. Escape of "Frio" north of the United States-Mexico border may extend the potential niche of buffelgrass a few hundred meters in elevation and a few hundred kilometers to the north.

### 3.10.2 Drought and Vegetation Structure

Over the past seventy-five years, the drought of the 1950s and the drought of the early 2000s represent two natural experiments for understanding plant community response to future environmental conditions. While both had similar reductions in precipitation, the 1950s drought was typical of many Holocene period droughts throughout the Southwest, whereas the drought that spanned the beginning of the 21st century was relatively hot (with both greater annual temperatures and greater summer maximum temperatures) (Breshears et al. 2005). The 1950s drought caused modest declines in the major shrubs in the Sonoran Desert, whereas the 2000s drought caused much higher mortality rates in numerous species, including the long-lived creosote bush (*Larrea tridentata*), which had shown essentially no response to the 1950s drought (Bowers 2005). A similar pattern was seen in comparing the two time periods for perennial species in the Mojave Desert, where dry periods close to the end of the 20th century were associated with reductions in shrubs and perennial grass species (Hereford et al. 2006). Thus, the greater temperatures predicted to co-occur with drought portend increased mortality for the dominant woody vegetation typical of North American deserts; and open the door for establishment of exotic annual grasses. These patterns are mostly driven by changes in winter precipitation, but in systems where summer rainfall is abundant, woody plant-grass interactions may also be important. Given an increase in the frequency of these “global

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warming type" droughts (e.g., Breshears et al. 2005), increases in summer active, non-native C4 grasses (such as *Pennisetum ciliare* in the Sonoran Desert (Franklin et al. 2006)), and the increased probability of fire, a similar pattern of a wide-spread woody vegetation conversion to degraded non-native grasslands can be anticipated for the hot deserts of North America – a pattern similar to that already seen in the Great Basin (Bradley et al. 2006).

### 3.10.3 Plant Functional Group Responses

Annual plants are a major source of plant diversity in the North American deserts (Beatley 1967), but exotic annuals are rapidly displacing native annuals. The density of desert annuals in the Sonoran Desert, at Tumamoc Hill in Tucson, AZ, has been reduced by an order of magnitude since 1982 (from ~ 2,000 plants $m^{-2}$ to ~150 plants $m^{-2}$) (Venable and Pake 1999). Similar reductions have been recorded for the Nevada Test Site (Rundel and Gibson 1996a). At the same time, there has been an increase in the number of non-native annuals (Hunter 1991; Salo et al. 2005; Schutzenhofer and Valone 2006). High $CO_2$ concentrations benefit non-native grasses more so than native species (Huxman and Smith 2001, Nagel et al. 2004). Thus, when rainfall is relatively high in the Mojave Desert, non-natives comprise about six percent of the flora and ~66 percent of the community biomass, but when rainfall is restricted, they comprise ~27 percent of the flora and > 90 percent of the biomass (Brooks and Berry 2006). Competition between annuals and perennials for soil nitrogen during relatively wet periods can be intense (Holzapfel and Mahall 1999). At the western fringe of the Mojave and Sonoran Deserts, nitrogen deposition is tipping the balance toward the annual plant community (typically non-native) with the resulting loss of woody native species (Wood et al. 2006).

Rising atmospheric $CO_2$ and increasing temperature are predicted to shift the competitive ability of C3 versus C4 plants, altering the current pattern of C4 dominance in many semi-arid ecosystems (Long 1991; Ehleringer et al. 1997; Poorter and Navas 2003). Photosynthesis and stomatal conductance in mixed C3/C4 communities often show a greater proportional response in C3 as compared to C4 species at elevated $CO_2$ (Polley et al. 2002). However, community composition and productivity do not always reflect leaf level patterns. It is likely that whole-system water budgets are significantly altered and more effectively influence the competitive interaction as compared to any direct $CO_2$ effects on leaf function (Owensby et al. 1993; Polley et al. 2002).

Where C3 species have increased in abundance in elevated $CO_2$ experiments, the photosynthetic pathway variation also reflected differences in herbaceous (C4) and woody (C3) life forms. $CO_2$ enhancement of C3 woody plant seedling growth, as compared to growth of C4 grasses, may facilitate woody plant establishment (Polley et al. 2003). Reduced transpiration rates from grasses under higher $CO_2$ may also allow greater soil water recharge to depth, and favor shrub seedling establishment (Polley et al. 1997). Changes in both plant growth and the ability to escape the seedling-fire-mortality constraint are critical for successful shrub establishment in water-limited grasslands (Bond and Midgley 2000). However, interactions with other facets of global change may constrain growth form and photosynthetic pathway responses to $CO_2$ fertilization.

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Increased winter temperatures would lengthen the C4 growing season. Greater primary production at elevated $CO_2$ combined with increased abundance of non-native grass species may alter fire frequencies (see 2.2.2.A). Nitrogen deposition may homogenize landscapes, favoring grassland physiognomies over shrublands (Reynolds et al. 1993). Changes in the occurrence of episodic drought may alter the relative performance of these growth forms in unexpected ways (Ward et al. 1999). Predicting changes in C3 versus C4 dominance, or changes in grass versus shrub abundance in water-limited ecosystems, will require understanding of multifactor interactions of global change.

### 3.10.4 Charismatic Mega Flora

Saguaro (*Carnegiea gigantea*) density is positively associated with high cover of perennial vegetation (except for *Larrea tridentata*) and mean summer precipitation; but total annual precipitation and total perennial cover are the best predictors of reproductive stem density (Drezner 2006). Because of the importance of episodic freezing events, the northeastern (high winter precipitation) and western (dry) portions of the southwestern U.S. have lower saguaro densities than the southeastern (high summer precipitation) areas, while the Northeast and Southeast both have very high reproductive stem densities relative to the West. Despite predicted reductions in the number of freezing events (Weiss and Overpeck 2005), predicted increases in annual temperature, loss of woody plant cover from a greater frequency of 'global warming-type' droughts, and increasing fire resulting from non-native grass invasions (Figure 3.14) suggest a restriction of the Saguaro's geographic range and reductions in abundance within its historic range.
The direct effects of rising $CO_2$ on climatic tolerance and growth of *Yucca brevifolia* also suggest important shifts in this Mojave Desert species' range (Dole et al. 2003). Growth at elevated $CO_2$ improves the ability of seedlings to tolerate periods of cold temperature stress (Loik et al. 2000). When applied to downscale climate outputs and included in the rules that define species distribution, this direct $CO_2$ effect suggests the potential for a slight increase in geographic range. However, like all long-lived, large-statured species in the North American deserts, the frequency of fire will be a primary determinant of whether this potential will be realized.

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**Figure 3.14** Buffelgrass invasion of saguaro stand in the Tucson Mountains, Arizona (left); fire-damaged saguaro (right). (Photos: Ben Wilder)

## 3.11 Ecosystem Processes

### 3.11.1 Net Primary Production and Biomass

Semi-arid and arid ecosystems of the western United States are characterized by low plant growth (NPP), ranging from 20 to 60 g/m$^2$/yr in the Mojave Desert of Nevada (Rundel and Gibson 1996b) to 100 to 200 g/m$^2$/yr (aboveground) in the Chihuahuan Desert of New Mexico (Huenneke et al. 2002). In most studies, the belowground component of plant growth is poorly characterized, but observations of roots greater than nine meters deep suggest that root production could be very large and perhaps underestimated in many studies (Canadell et al. 1996).

With water as the primary factor limiting plant growth, it is not surprising that the variation in plant growth among desert ecosystems, or year-to-year variation within arid ecosystems, is related to rainfall. Other factors, such as soil texture and landscape position, also affect soil moisture availability and determine plant growth in local conditions (Schlesinger and Jones 1984; Wainwright et al. 2002). Changes in the amount and seasonal distribution of precipitation with global climate change can be expected to have a dramatic impact on the dominant vegetation, NPP and carbon storage in arid lands.

Jackson et al. (2002) found that plant biomass and soil organic matter varied systematically in mesquite-dominated ecosystems across west Texas and eastern New Mexico, demonstrating some of the changes that can be expected with future changes in rainfall regimes. The total content of organic matter (plant + soil) in the ecosystem was greatest at the highest rainfall, but losses of soil carbon in the driest sites were compensated by increases in plant biomass, largely mesquite. Despite consistent increases in aboveground carbon storage with woody vegetation encroachment, a survey of published literature revealed no correlation between mean annual rainfall and changes in soil organic carbon pools subsequent to woody plant encroachment (Asner and Archer 2007). Differences in soil texture, topography and historical land use across sites likely confound assessments of precipitation influences on soil organic carbon pool responses to vegetation change.

### 3.11.2 Soil Respiration

Soil respiration includes the flux of $CO_2$ from the soil to the atmosphere from the combined activities of plant roots and their associated mycorrhizal fungi and heterotrophic bacteria and fungi in the soil. It is typically measured by placing small chambers over replicated plots of soil or estimated using eddy-covariance measurements of changes in atmospheric properties, particularly at night. Soil respiration is the dominant mechanism that returns plant carbon dioxide to Earth's atmosphere, and it is

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normally seen to increase with increasing temperature. Mean soil respiration in arid and semi-arid ecosystems is 224 g C/m$^2$/yr (Raich and Schlesinger 1992; Conant et al. 1998), though in individual sites, it can be expected to vary with soil moisture content during and between years.

### 3.11.3 Net Carbon Balance

The net storage or loss of carbon in any ecosystem is the balance between carbon uptake by plants (autotrophic) and the carbon released by plant respiration and heterotrophic processes. Although elegant experiments have attempted to measure these components independently, the difference between input and output is always small and thus measurement errors can be proportionately large. It is usually easier to estimate the accumulation of carbon in vegetation and soils on landscapes of known age. This value, NEP, typically averages about 10 percent of NPP in forested ecosystems. 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). Given the low NPP of arid lands, they are likely to result in only small amounts of carbon sequestration. Since soil organic matter is inversely related to mean annual temperature in many arid regions (Schlesinger 1982; Nettleton and Mays 2007), anticipated increases in regional temperature will lead to a loss of soil carbon to the atmosphere, exacerbating increases in atmospheric carbon dioxide. Recent measurements of NEP by micrometeorological techniques, such as eddy covariance, across relatively large spatial scales confirm these relatively low carbon uptake for arid lands (Grunzweig et al. 2003), but point to the role of life-form (Unland et al. 1996), seasonal rainfall characteristics (Hastings et al. 2005, Ivans et al. 2006), and potential access to groundwater as important modulators of the process (Scott et al. 2006).

In many areas of desert, the amount of carbon stored in inorganic soil carbonates greatly exceeds the amount of carbon in vegetation and soil organic matter, but the formation of such carbonates is slow and not a significant sink for carbon in its global cycle (Schlesinger 1982, Monger and Martinez-Rios 2000). Some groundwater contains high (supersaturated) concentrations of carbon dioxide, which is released to the atmosphere when this water is brought to the Earth's surface for irrigation, especially when carbonates and other salts precipitate (Schlesinger 2000). Thus, soil carbonates are unlikely to offer significant potential to sequester atmospheric carbon dioxide in future warmer climates.

### 3.11.4 Biogeochemistry

Arid-land soils often have limited supplies of nitrogen, such that nitrogen and water can "co-limit" the growth of vegetation (Hooper and Johnson 1999). These nitrogen limitations normally appear immediately after the receipt of seasonal rainfall. The nitrogen limitations of arid lands stem from small amounts of N received by atmospheric deposition and nitrogen fixation and rather large losses of N to wind erosion and during microbial transformations of soil N that result in the losses of ammonia ($NH_3$), nitric oxide (NO), nitrous oxide ($N_2O$), and nitrogen gas ($N_2$) to the atmosphere (Schlesinger et

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al. 2006). These microbial processes are all stimulated by seasonal rainfall, suggesting that changes in the rainfall regime as a result of climate change will alter N availability and plant growth. N deposition is spatially variable, being greater in areas downwind from major urban centers such as Los Angeles, increasing the abundance of herbaceous vegetation and potentially increasing the natural fire regime in the Mojave Desert (Brooks 2003).

In arid lands dominated by shrub vegetation, the plant cycling of N and other nutrients in arid lands is often heterogeneous, with most of the activity focused in the soils beneath shrubs (Schlesinger et al. 1996). The dynamics of these “islands of fertility” will determine much of the response of desert vegetation to changes in climate. For instance, so long as there are localized patches of high soil nutrient availability, shrub-dominated vegetation may persist long after changes in climate might be expected to lead to the invasion of non-native grasses.

### 3.11.5 Trace-gases

In addition to significant losses of N trace gases, some of which confer radiative forcing on the atmosphere (e.g., $N_2O$), deserts are also a minor source of methane, largely resulting from activities of some species of termites, and VOC gases from vegetation and soils (Geron et al. 2006). VOCs can serve as precursors to the formation of tropospheric ozone and organic aerosols, thus influencing air pollution. Emissions of such gases have increased as a result of the invasion of grasslands by desert shrubs during the past 100 years (Guenther et al. 1999), and emissions of isoprene are well known to increase with temperature. The flux of these gases from arid lands is not well studied, but is known to be sensitive to temperature, precipitation, and drought stress. For example, total annual VOC emissions in deserts may vary three-fold between dry and wet years; and slight increases in daily leaf temperatures can increase annual desert isoprene and monoterpene fluxes by 18 percent and seven percent, respectively (Geron et al. 2006). Thus, changes in VOC emissions from arid lands can be expected to accompany changes in regional and global climate.

## *3.12 Arid Land Rivers and Riparian Zones*

River and floodplain (riparian) ecosystems commonly make up less than one percent of the landscape in arid regions of the world. Their importance, however, belies their small areal extent (Fleischner 1994). They are highly productive ecosystems embedded within much lower productivity upland ecosystems. They provide essential wildlife habitat for migration and breeding, and these environments are critical for breeding birds, threatened and endangered species, and arid-land vertebrate species. Riparian vegetation in arid lands can occur at scales from isolated springs to ephemeral and intermittent watercourses, to perennial rivers (Webb and Leake 2006). The rivers and riparian zones of arid lands are dynamic ecosystems that are highly responsive to changing hydrology, geomorphology, human utilization, and climate change. As such, river and riparian ecosystems will likely prove to be responsive components of arid landscapes to future climate change.

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Global climate change can potentially impact river and riparian ecosystems in arid regions through a wide variety of mechanisms and pathways (Regab and Prudhomme 2002). Three pathways in which riverine corridors in arid lands are highly likely to be affected are particularly important. The first is the impact of climate change on water budgets. Both sources of water and major depletions will be considered. The second is competition between native and non-native species in a changing climate. The potential importance of thresholds in these interactions will be explicitly considered. The third mechanism pertains to the role of extreme climate events (e.g., flood and droughts) in a changing climate. Extreme events have always shaped ecosystems, but the interactions of a warmer climate with a strengthened hydrologic cycle are likely to be significant structuring agents for riverine corridors in arid lands.

### 3.12.1 Water Budgets

Analysis of water budgets under a changing climate is one tool for assessing the impact of climate change on arid-land rivers and riparian zones. Christiansen et al. (2004) have produced a detailed assessment of the effects of climate change on the hydrology and water resources of the Colorado River basin. Hydrologic and water resources scenarios were evaluated through coupling of climate models, hydrologic models, and projected greenhouse gas scenarios for time periods from 2010-2039, 2040-2069, and 2070-2099. Average annual temperature changes for the three periods were 1.0, 1.7, and 2.4°C, respectively, and basin-average annual precipitation was projected to decrease by three, six, and three percent for the three periods, respectively. These scenarios produced annual runoff decreases of 14, 18, and 17 percent from historical conditions for the three designated time periods. Such decreases in runoff will have substantial effects on human populations and river and riparian ecosystems, particularly in the lower elevation arid land compartments of this heavily appropriated catchment (e.g., Las Vegas and Southern California).

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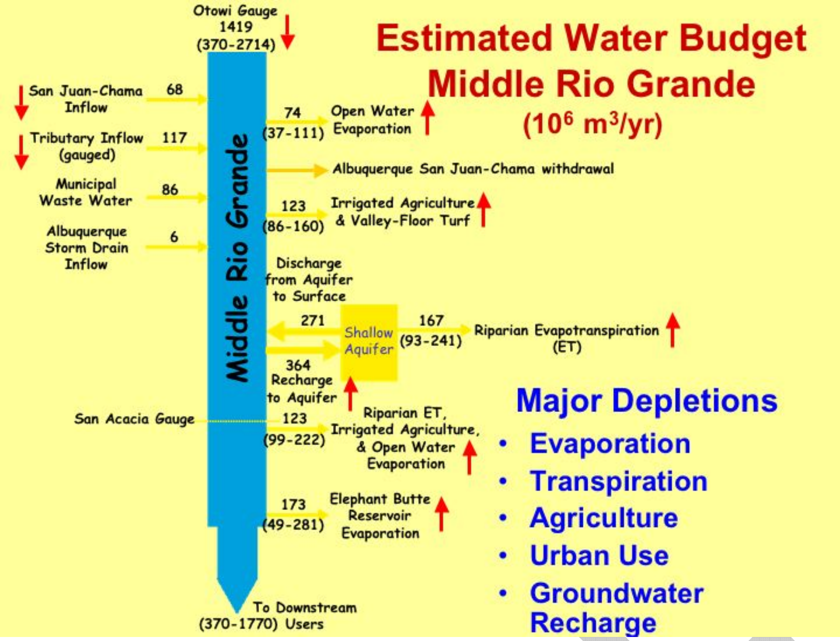

**Figure 3.15** A water budget for a 320 km segment of the Middle Rio Grande of New Mexico, USA, with water sources on the left and top, depletions on the right, and downstream output on the bottom (Dahm et al. 2002). The red arrows indicate the direction of change for various water sources and depletions predicted with a warmer climate.

Changing climate also can have a significant effect on major depletions of surface waters in arid regions. Dahm et al. (2002) examined major depletions along a 320-km reach of the Rio Grande in central New Mexico. Major depletions were reservoir evaporation, riparian zone evapotranspiration, agriculture, groundwater recharge, and urban/suburban use. All of these depletions are sensitive to climate warming. Reservoir evaporation is a function of temperature, wind speed, and atmospheric humidity. Riparian zone evapotranspiration is sensitive to the length of the growing season, and climate warming will lengthen the period of time that riparian plants will be actively respiring (Goodrich et al. 2000; Cleverly et al. 2006), and also increase the growing season for agricultural crops dependent on riparian water. Temperature increases positively affect groundwater recharge rates from surface waters through changes in viscosity (Constantz and Thomas 1997, Costanz et al. 2002). The net result of climate warming is greater depletion of water along the riverine corridor (Figure 3.15). Global warming will place additional pressure on the major depletions of surface water in arid regions, in addition to likely effects on the supply side of the equation.

### 3.12.2 Native and Non-Native Plant Interactions

Competition between native and non-native species in a changing climate is a second area where climate change is predicted to have a substantial effect on riparian zones of arid lands. Riparian zones of arid lands worldwide are heavily invaded by non-native species of plants and animals (Prieur-Richard and Lavorel 2000; Tickner et al. 2001). Salt

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cedar (*Tamarix spp.*) and Russian olive (*Elaeagnus angustifolia*) are particularly effective invaders of the arid land riparian zones of the western United States (Brock 1994, Katz and Shafroth 2003). Shallow ground water plays an important role in structuring riparian plant communities (Stromberg et al. 1996) and groundwater level decline, whether by human depletions or intensified drought in a changing climate, will alter riparian flora. Stromberg et al. (1996) describe riparian zone "desertification" from a lowered water table whereby herbaceous species and native willows and cottonwoods are negatively impacted. Horton et al. (2001a, b) describe a threshold effect where native canopy dieback occurs when depth to ground water exceeds 2.5-3.0 meters. Non-native salt cedar (*Tamarix chinensis*), however, are more drought tolerant when water tables drop, and readily return to high rates of growth when water availability again increases. Plant responses like these are predicted to shift the competitive balance in favor non-native plants and promote displacement of native plants in riparian zones under a warmer and changing climate.

Another example of a threshold effect on river and riparian ecosystems in arid lands is the persistence of aquatic refugia in a variable or changing climate. Hamilton et al. (2005) and Bunn et al. (2006) have shown the critical importance of waterhole refugia in the sustenance of biological diversity and ecosystem productivity in arid-land rivers. Arid regions worldwide, including this example from inland Australia, are dependent on the persistence of these waterholes during drought. Human appropriation of these waters or an increase in the duration and intensity of drought due to climate change would dramatically affect aquatic biodiversity and the ability of these ecosystems to respond to periods of enhanced water availability. For example, most waterhole refugia throughout the entire basin would be lost if drought persisted for more than two years in the Cooper Creek basin of Australia, or if surface diversions of flood waters reduced the available water within refugia in the basin (Hamilton et al. 2005; Bunn et al. 2006). Desiccation of waterholes could become more common if climate change increases annual evapotranspiration rates of if future water withdrawals reduce the frequency and intensity of river flows to waterholes. Roshier et al. (2001) pointed out that temporary wetland habitats throughout arid-lands in Australia are dependent upon infrequent, heavy rainfalls and are extremely vulnerable to any change in frequency or magnitude. Climate change that induces drying or reduced frequency of large floods would deleteriously impact biota, particularly water birds that use these temporary arid-land habitats at broad spatial scales.

### 3.12.3 Extreme Events

The role of extreme events (e.g., flood and droughts) in a changing climate is predicted to increase with a warmer climate (IPCC 2007). Extreme climatic events are thought to strongly shape arid and semi-arid ecosystems worldwide (Holmgren et al. 2006). Climate variability, such as associated with the El Niño Southern Oscillation (ENSO) phenomenon, strongly reverberates through food webs in many arid lands worldwide. Riparian vegetation is especially sensitive to the timing and magnitude of extreme events, particularly the timing and magnitude of minimum and maximum flows (Auble et al. 1994). GCMs do not yet resolve likely future regional precipitation regimes or future

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temperature regimes. A stronger overall global hydrologic cycle, however, argues for more extreme events in the future (IPCC 2007). The ecohydrology of arid-land rivers and riparian zones will certainly respond to altered precipitation patterns (Newman et al. 2006) and the highly variable climate that characterizes arid-lands is likely to become increasingly variable in the future.

## 3.13 Wind and Water Erosion

Due to low and discontinuous cover, there is a strong coupling between vegetation in arid lands and geomorphic processes such as wind and water erosion (Wondzell et al. 1996). Erosion by wind and water has a strong impact on ecosystem processes in arid regions (Valentin et al. 2005, Okin et al. 2006). Erosion impacts the ability of soils to support plants and erosion can deplete nutrient-rich surface soils, thus reducing the probability of plant establishment and recruitment. Although erosion by water has received by far the most attention in the scientific literature, the few studies that have investigated both wind and water erosion have shown that they can be of similar magnitude under some conditions (Breshears et al. 2003).

### 3.13.1 Water Erosion

Water erosion primarily depends on the erosivity of precipitation events (rainfall rate, and drop size) and the erodibility of the surface (infiltration rate, slope, soil, and vegetation cover). Climate change may impact all of these except slope. For instance, it is well established that the amount of soil that is detached (and hence eroded) by a particular depth of rain is related to the intensity at which this rain falls. Early studies suggest soil splash rate is related to rainfall intensity and raindrop fall velocity (Ellison 1944; Bisal 1960). It is also well established that the rate of runoff depends on soil infiltration rate and rainfall intensity. When rainfall intensity exceeds rates of infiltration, water can runoff as inter-rill flow, or be channeled into rills, gullies, arroyos, and streams. The intensity of rainfall is a function of climate, and therefore may be strongly impacted by climate change. The frequency of heavy precipitation events has increased over most land areas, including the United States, which is consistent with warming and observed increases in atmospheric water vapor (IPCC 2007). Climate models predict additional increases in the frequency of heavy precipitation, and thus highly erosive events. Warming climates may also be responsible for changes in surface soils themselves, with important implications for the erodibility of soils by water. In particular, higher temperatures and decreased in soil moisture, such as those predicted in many climate change scenarios, have been shown to decrease the size and stability of soil aggregates, thus increasing their susceptibility to erosion (Lavee et al. 1998).

By far the most significant impact of climate change on water erosion is via its effects on vegetation cover. The widespread conversion of grasslands to shrublands throughout the desert Southwest (Van Auken 2000) has resulted in significantly greater erosion. Flow and erosion plots in the Walnut Gulch Experimental Watershed in Arizona and the Jornada LTER site in New Mexico have demonstrated significant differences in water erosion between grasslands and shrublands (Wainwright et al. 2000). For instance,

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greater splash detachment rates (Parsons et al. 1991, 1994, 1996), and inter-rill erosion rates (Abrahams et al. 1988) are observed in shrublands compared to grasslands; and shrubland areas are more prone to develop rills, which are responsible for significant increases in overall erosion rates (Luk et al. 1993). Episodes of water erosion are often associated with decadal drought-interdrought cycles because depressed vegetation cover at the end of the drought makes the ecosystem vulnerable to increased erosion when rains return (McAuliffe et al. 2006).

The arid regions of the United States have already experienced dramatic increases in erosion rates due to widespread losses of vegetation cover. These changes have created conditions where anticipated increases in precipitation intensity, coupled with reductions in soil aggregate stability due to net warming and drying, will increase potential erosion rates dramatically in the coming decades.

### 3.13.2 Wind Erosion

As with water erosion, the magnitude of wind erosion is related to both the erosivity of the wind and the erodibility of the surface. However, the impact of increased wind erosion in deserts can have continental-scale impacts because the resulting dust can travel long distances with significant impacts to downwind ecosystems, air quality, and populations. Both hemispheres have experienced strengthening of mid-latitude westerly winds since the 1960s (IPCC 2007). This trend is likely to continue into the near future. Thus, desert regions of the United States are likely to experience more erosive conditions in the near future.

The susceptibility of soil to erosion by wind is determined by both the erodibility of the surface soil and the amount of vegetation present to disrupt wind flows and shelter the surface from erosion. As discussed above, anticipated net aridification in the desert Southwest is likely to lead to a decrease in soil aggregate size and stability. Increased temperatures and drought occurrence will result in lower relative humidity in arid lands. Because the top few millimeters of soil are in equilibrium with soil moisture in the overlying air, the decrease in relative humidity may result in soils that require less wind power to initiate erosion (Ravi et al. 2006). Increased drought occurrence throughout the western United States can further lead to lower soil moisture content, which can also increase the erodibility of the soil (Bisal 1960; Cornelis et al. 2004).

Short- term changes in vegetation cause significant changes in the wind erodibility of the surface. For instance Okin and Reheis (2002) and Reheis (2006) have shown that annual variation in wind erosion on a regional scale is related to variation in precipitation. There appears to be a one-year lag in this effect, with low precipitation one year resulting in significant wind erosion and dust emission the following year. This lag is hypothesized to be due to the fact that the effect of low precipitation must propagate through the system by first affecting vegetation cover. This one-year lag effect has been observed in other arid systems (Zender and Kwon 2005). In addition, dust emission from playas in the desert Southwest also appears to occur after years of particularly intense rainfall. This phenomenon seems to result from the increased delivery of fine-grained sediment to these

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playas during especially wet years or years with intense rainfall events. Anticipated climatic changes in the coming decades include both increase drought frequency and also increased precipitation intensity during rain events (IPCC 2007). Both of these effects are likely to increase wind erosion and dust emission in arid regions due to, in the first case, suppression of vegetation and, in the second case, greater water erosion resulting in increased delivery of fines to dry lakes.

Long-term and ongoing vegetation changes in arid regions, namely the conversion of grasslands to shrublands, have dramatically increased wind erosion and dust production due to increased bare areas in shrublands compared to the grasslands they replaced. Measurements of aeolian sediment flux in the Chihuahuan Desert have shown nearly ten-fold-greater rates of wind erosion and dust emission in mesquite-dominated shrublands compared to grasslands on similar soils (Gillette and Pitchford 2004). Large-scale conversion of grasslands to shrublands, coupled with anticipated changes in climate in the coming decades, increases in wind speed, temperature, drought frequency, and precipitation intensity, contribute to greater wind erosion in and dust emission from arid lands.

### 3.13.3 Impacts of Water and Wind Erosion

Dust can potentially influence global and regional climate by scattering and absorbing sunlight (Sokolik and Toon 1996) and affecting cloud properties (Wurzler et al. 2000), but the overall effect of mineral dusts in the atmosphere is likely to be small compared to other human impacts on the Earth's climate system (IPCC 2007). Desert dust is thought to play a major role in ocean fertilization and $CO_2$ uptake (Duce and Tindale 1991; Piketh et al. 2000; Jickells et al. 2005), terrestrial soil formation, and nutrient cycling (Swap et al. 1992; Wells et al. 1995; Chadwick et al. 1999), and public health (Leathers 1981; Griffin et al. 2001). In addition, desert dust deposited on downwind mountain snowpack has been shown to decrease the albedo of the snowpack, thus accelerating melt by as much as 20 days (Painter et al. 2007).

In arid regions, erosion has been shown to increase sediment delivery to large rivers (e.g., the Rio Grande), and can change the flow conditions of those rivers (Jepsen et al. 2003). Transport of eroded sediment to streams can change conditions in waterways, impacting water quality, riparian vegetation and water fauna (Cowley 2006).

## *3.14 Indicators and Observing Systems – Arid Lands*

### 3.14.1 Existing Systems

**Long-Term Ecological Research (LTER) Sites**
Jornada Basin [Las Cruces, NM – http://jornada-www.nmsu.edu/]
Sevilleta [Albuquerque, NM – http://sev.lternet.edu/]

**National Ecological Observatory Network (NEON)**

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Santa Rita Experimental Range [Tucson, AZ – http://www.sahra.arizona.edu/santarita/]
Onaqui-Benmore [Salt Lake City, UT – http://www.neoninc.org]

**International Biome Project (IBP) Sites**
Rock Valley [Nevada Test Site, NV – archived at University of California, Los Angeles, CA]
Silverbell [Arva Valley, AZ – archived at University of Arizona, Tucson, AZ]

**Free-Air $CO_2$ Enrichment (FACE) Site**
Nevada Desert FACE [Nevada Test Site, NV – http://www.unlv.edu/Climate_Change_Research/]

**Land-Surface Flux Assessment Sites**
Audobon Ranch, Ameriflux Sites [http://public.ornl.gov/ameriflux/]
Semi-arid Ecohydrology Array (SECA) [http://eebweb.arizona.edu/faculty/huxman/seca/]
ARS Flux Tower Network [http://edcintl.cr.usgs.gov/carbon_cycle/FluxesResearchActivities.html]

**Rainfall Manipulations**
ARS Rainout Shelter [Burns, OR] (Svejcar et al. 2003)
Nevada Global Change Experiment [http://www.unlv.edu/Climate_Change_Research/]

**Long-Term Ecological Data**
National Phenology Network [http://www.uwm.edu/Dept/Geography/npn/]
TRENDS Project [http://fire.lternet.edu/Trends/]
UA Desert Laboratory at Tumamoc Hill Permanent Plots [Tucson, AZ – http://wwwpaztcn.wr.usgs.gov/home.html]
The Portal Project [Portal, AZ – http://biology.unm.edu/jhbrown/Portal-LTREB/PortalFront.htm]

**National Park Service Inventory & Monitoring Program**
The NPS has recently initiated I&M program as many of its Parks and Monuments in arid lands (http://science.nature.nps.gov/im/)

**Repeat Photography**
Repeat photography is a valuable tool for documenting changes in vegetation and erosion. Hart and Laycock (1996) present a bibliography listing 175 publications using repeat photography and information on the ecosystems photographed, where they are located, number of photographs, and dates when the photographs were taken. More recent publications have added to this list (e.g., Webb 1996; McClaran 2003; Webb et al. 2007), and Hall (2002) has published a handbook of procedures. Time-series aerial photographs dating back to the 1930s and 1940s are also a useful source for

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quantifying landscape-scale changes in land cover (e.g., Archer 1996; Asner et al. 2003).

## 3.15 Needs

While the deserts of North America have been the site of many important ecological studies, there have been relatively few long-term monitoring sites at an appropriate spatial representation that allow us the means to access changes in ecosystem structure and function in response to global change. Coordinated measurements of plant community composition in plots across the North American deserts would enhance our ability to detect change and relate that to aspects of climate. Several important data sets stand as benchmarks – the long-term photographic record at the Santa Rita Experimental Range, the long-term perennial plant and winter annual plant studies at Tumamoc Hill, the long-term data collected from large-scale ecosystem manipulations at Portal Arizona, and the new Mojave Desert Climate Change Program. Greater spatial representation of such efforts is important in future assessment of change in these biomes.

Soil moisture is a key indicator and integrator of ecological and hydrological processes. However, as noted in the Water Resources chapter (Chapter 4), there is a dearth of information on the long-term patterns and trends in this important variable. Even on well-instrumented watersheds in arid lands (e.g., Lane and Kidwell 2003; NWRC 2007; SWRC 2007) soil moisture records are only erratically collected over time and are limited in their spatial coverage and depth. Thus, there is a pressing need for a distributed network of soil moisture sensors in arid lands. Ideally, such a network would also include collection of plant, soil and precipitation samples for determination of the stable isotope composition of C, O, and H. Such isotope data would provide important clues regarding when and where plants were obtaining soil moisture and how primary production and WUE are being affected by environmental conditions (e.g., Boutton et al. 1999; Roden et al. 2000; Williams and Ehleringer 2000).

Most land-surface exchange research has focused on forested systems. There is, however, a need for understanding the seasonal carbon dynamics, biomass, annual productivity, canopy structure, and water use in deserts (Asner et al. 2003; Farid et al. 2006; Sims et al. 2006). Part of this derives from our relatively poor understanding of non-equilibrium processes in ecological systems - desert ecosystem function is driven by highly episodic inputs of precipitation (Huxman et al. 2004). Part derives from the importance of the strong, two-way coupling between vegetation phenology and the water cycle, which is critical for predicting how climate variability influences surface hydrology, water resources, and ecological processes in water-limited landscapes (e.g., Scanlon et al. 2005). Shifts in phenology represent an integrated vegetation response to multiple environmental factors, and understanding of vegetation phenology is prerequisite to inter-annual studies and predictive modeling of land surface responses to climate change (White et al. 2005). Along these lines, the ability to detect ecosystem stress and impacts on vegetation structure will be requisite to understanding regional aspects of drought (Breshears et al. 2005) that result in substantial land use and land cover changes.

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In regions where the eroded surfaces are connected to the regional hydraulic systems (e.g., not in closed basins), sediment delivery to streams and streambeds is an excellent indicator of integrated erosion in the catchment. There is currently no integrated monitoring system in place for the measurement of bedload, but the USGS National Water Information System (http://waterdata.usgs.gov/nwis) does collect water quality data that could inform sediment loads. Unfortunately, there are very few sites in the arid U.S. that are monitored continuously. Additional arid region rivers could be instrumented and sampled to provide further monitoring of water erosion. In closed basins, or the upland portion of open basins, the development and expansion of rills and gullies is the clearest indicator of water erosion. There is no system in place for the monitoring of these features (Ries and Marzolff 2003), but high resolution remote sensing (~1-meter resolution) might be used to monitor the largest of these features.

The most important indicator of wind erosion is the dust that it produces. Because dust is transported long distances, even a sparse network of monitoring sites can identify dust outbreaks. For instance, Okin and Reheis (2002) have used meteorological data collected as part of the COOP network to identify dust events and to correlate them to other meteorological variables. The expansion of this network to include observations in more locations, and especially at locations downwind of areas of concern, would be a significant improvement to monitoring wind in the arid portions of the United States. This existing observation network might also be integrated with the Aeronet aerosol monitoring network and radar or lidar systems deployed throughout the region, but particularly near urban centers and airports. In addition, there are several remote sensing techniques that can be used to identify the spatial extent and timing of dust outbreaks (Chomette et al. 1999; Chavez et al. 2002l Miller 2003), though there is no system in place to integrate or track the evolution of dust sources through time.

## 3.16 Findings and Conclusions – Arid Lands

**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)) may include contraction of the overall boundary of the Sonoran Desert in the southeast, and expansion northward, eastward, and upward in elevation, and 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 that shrub recruitment at woodland-grassland ecotones along elevation gradients will be favored by increases in summer precipitation, but will 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.

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- "Global warming type" droughts, such as those early in the 21st Century, will 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 will predispose sites to fire resulting in a loss of native woody plants and charismatic mega flora. Low elevation arid ecosystems will henceforth experience climate-fire synchronization where none previously existed (Figure 3.16).
- By virtue of their profound impact on the fire regime and hydrology, invasive plants in arid lands will 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 portend increased 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 anticipated for the hot deserts of North America
- The main invasion of exotic buffelgrass in southern Arizona happened with warmer winters beginning in the 1980s, and its range will extend further north and upslope as minimum temperatures continue to increase (Arriaga et al. 2004). This upslope and northward extension will be promoted by the introduction of cold-resistant cultivars
- Exurban development will 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 will 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 N-deposition.
- N deposition is spatially variable, being greater in areas downwind from major urban centers,
- Emissions of volatile organic carbon gases have increased as a result of the displacement of grasslands by desert shrubs during the past 100 years

**Riparian Systems**

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- Climate change will place increasing pressure on montane water sources to arid land rivers and increase the magnitude of all major water depletions in arid land river and riparian ecosystems.
- The net result of climate warming will be greater depletion of water along riverine corridors
- The balance of competition between native and non-native species in riparian zones will continue to shift towards favoring exotics as temperatures increase, as the timing and amount of water shifts, and as the intensity of disturbances are magnified (Figure 3.17).
- 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 the 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 increase water erosion from uplands and delivery of nutrient-rich sediment to riparian areas (Figure 3.18).
- Increases in wind speed and gustiness will 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 reduce the stability of surface soil aggregates, making the surface more erodible.

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**Figure 3.16** Mojave Desert scrub near Las Vegas, NV (foreground); and area invaded by the exotic annual grass (*Bromus madritensis*) background following a fire that carried from desert floor upslope into pinyon-juniper woodlands (photo: T.E. Huxman).

**Figure 3.17** Non-native salt cedar (right) has invaded and displaced native cottonwood and poplar forests (left) in many southwestern riparian corridors.

**Figure 3.18** Dust storm in Arizona.

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# 4 Water Resources

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## 4.1 Introduction

Water managers have long understood the implications of variability in water sources resulting from weather and climatic variations at time scales ranging from days to months and years, and have developed sophisticated methods to simulate and respond to such variability in water resource system design and operation. A distinguishing feature of these methods is that they assume that an observed record of streamflow is statistically stationary, that is, the probability distribution(s) from which the observations are drawn does not change with time. *In the era of climate change this assumption is no longer tenable*. The challenge facing water managers is to determine reasonable ways of assessing plausible ranges of future conditions for purposes of hydrologic design and operation. Such assessments are also needed to understand how changes in the availability and quality of water will affect animals, plants, and ecosystems.

## 4.2 Hydroclimatology of the U.S, and the role of water management

The primary driver of the land surface hydrologic system is precipitation. Precipitation varies widely, not only in total annual amount, but in seasonal distribution, and space-time variability across the United States. Proceeding from east to west, the semi-humid conditions of the eastern U.S. yield to drier conditions to the west, with the increasing dryness eventually interrupted by the Rocky Mountains, and then amplified in the intermountain west and Southwest. These extremely arid conditions give way as one proceeds west and north to the more humid conditions of the coastal west. Runoff patterns, for the most part, follow those of precipitation. The runoff ratio (runoff divided by precipitation) decreases from east to west, and the decline in runoff with aridity is sharper than it is for precipitation. The ratio of maximum annual snow accumulation to annual runoff is an index to the relative fraction of runoff that is derived from snowmelt. This number is high in the mountainous areas of the West, and to a more limited extent, in the northern tier of states, and low elsewhere. The coefficient of variation of annual runoff is a measure of the variability of runoff. Its spatial pattern generally follows that of precipitation coefficient of variation; it is highest where runoff (and precipitation) is lowest.

The water resources of the continental U.S. are heavily managed, mostly by surface water reservoirs. The most important metric of storage is the ratio of usable reservoir storage to mean annual reservoir inflows. Storage to runoff ratio of one is usually taken as the division between reservoirs that are primarily used to shape within-year variations in runoff, and those that are primarily used to buffer interannual variations in runoff. Within the United States, most reservoir storage can be classified as within-year; the major exceptions where reservoir storage is over-year are the Colorado, and upper Missouri River basins.

## 4.3 Trends in U.S. water use

With respect to water use, U.S. water withdrawals have decreased (slightly) over the last 20 years in virtually all categories. This is despite substantial population growth during the same period, which suggests that per capita water withdrawals (and by implication, consumptive use) have decreased markedly. These changes follow a period of rapid growth in water withdrawals in the mid-20th century. The reasons for these reductions in water withdrawals arise both from regulatory considerations (e.g., imposition of minimum instream flow standards, and higher WUE appliances), and economic considerations. For instance, in the case of irrigation, there has been a transition from flood to sprinkler irrigation. Irrigation water use has also been affected by the cost of electric power. Industrial water use efficiency gains have been driven by pollution control regulations, which encourage reduction of wastewater discharge, and hence more recycling.

## 4.4 Observed trends in U.S. water resources

Over most of the United States, streamflow increased over the second half of the 20th century. This is true for all but the highest (flood) flows, for which there were relatively few statistically significant trends. Those trends that have been observed cannot necessarily be attributed to climatic warming, however the spatial coherence in the trends suggests that non-climatic causes (e.g., land cover change), are not likely the cause. The western U.S. constitutes an important apparent reversal in the trend toward increasing U.S. streamflow, with an indication of an onset of dry conditions beginning in the 1980s. However, this apparent pattern may well be associated with decadal scale climate variability. There has, however, been a trend toward reduced mountain snowpack, and earlier spring snowmelt runoff peaks across much of the western U.S., and this trend increasingly appears to be attributable to long-term warming, rather than to decadal scale variability. Furthermore, there is some indication that the variability of streamflow in the

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western U.S. has increased over the last two decades.

Several studies have found that pan evaporation decreased over the last 50 years, whereas some studies suggest that actual evapotranspiration during the same period has increased. Two explanations have been advanced; one is the so-called evaporation paradox, which holds that microclimatic conditions in the vicinity of evaporation pans lead to decreased pan evaporation as actual evaporation increases. The second is that actual ET may also have declined due to reduced net radiation, resulting from increased cloud cover. The latter hypothesis appears to be inconsistent with some published work that has found that actual evaporation, as estimated by the difference between river basin precipitation and runoff, has increased in many river basins.

With respect to drought, consistent with streamflow and precipitation observations, most of the continental U.S. became wetter over the 20th century, with inferred reductions in drought severity and duration. However, there was some evidence of trends in the opposite direction (that is, increases) in drought severity and duration in the western and southwestern U.S., which apparently results from increased actual evaporation dominating the trend towards increased soil wetness. Paleo reconstructions of droughts show that much more severe droughts have occurred over the last 2,000 years than those that have been observed in the instrumental record (notably, the Dust Bowl drought of the 1930s, and extensive drought in the 50s).

Water quality is sensitive both to increased water temperatures, and changes in patterns of precipitation. However, most observed changes in water quality across the continental U.S. are attributable to causes other than climate change. These include, for instance, changes in land cover, and changes in pollutant loadings. Some work has, however, shown that temperatures have increased in some western U.S. streams over the second half of the 20th century. Some of these changes are associated with changes in runoff patterns, e.g., earlier snowmelt runoff leads to reduced summer flows, at a time when radiative and other forcings leading to increased water temperatures are the greatest.

## *4.5 Projected future changes in U.S. water resources*

The most recent (IPCC AR4) climate model simulations project increased runoff over the eastern U.S., gradually transitioning to little change in the Missouri and lower Mississippi, to substantial decreases in annual runoff in the interior of the west (Colorado and Great Basin). Runoff changes along the west coast (Pacific Northwest and California) are also negative, but smaller in absolute value than in the western interior basins. The projected drying in the interior of the West is quite consistent among models (the only projections that are more consistent among models are for runoff increase in Alaska). These changes are, very roughly, consistent with observed trends in the second half of the 20th century, which show increased streamflow over most of the United States, but sporadic decreases in the West.

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## *4.6 Findings and conclusions*

1) Precipitation over much of the continental U.S. increased in recent decades, and this trend toward increased wetness is evident in a predominance of upward trends in stream discharge, especially for flows from the lower end to the middle of the streamflow distribution (that is, extreme low flows, through median flows). The preponderance of upward trends vanishes toward the upper end of the streamflow distribution (floods), and there is no evidence of increases in floods within the range of basin sizes represented by the USGS Hydroclimatic Data Network (HCDN; mostly thousands to tens of thousands of square km drainage area).

2) The trend toward increased wetness is also evident in simulated soil moisture (unfortunately not verifiable from observations due to short record lengths) over most of the country, and as a consequence, 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.

3) Pan evaporation declined over most of the United States over the second half of the 20th century. These declines are 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.

4) Snowpacks 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 zero degrees C ("transient" rain-snow conditions). These trends toward reduced winter snow accumulation, and earlier spring melt are also reflected in a tendency toward earlier runoff peaks in the spring, a shift that has not occurred in rainfall-dominated watersheds in the same region.

5) 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 to increased fire hazard. This tendency is, however, confounded by the effects of fire suppression over the same period.

6) Climate model projections for increased temperatures, and (averaged across many models) modest increases in precipitation are expected to lead to streamflow declines. Because of the uncertainty in climate model projections of precipitation change, the hydrologic consequences are highly uncertain across most of the United States  One exception is watersheds that are dominated by spring and summer snowmelt, most of which are in the western U.S. In these cases, where shifts to earlier snowmelt peaks

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and reduced summer and fall low flows have already begun to be detected, continuing shifts in this direction are quite likely, and may 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.

7) 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. Changes that will be most evident during low flow periods, when stream temperature changes are of greatest concern.

8) 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 due to various improvements in water use efficiency related both the 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. These trends seem likely to continue in the coming decades. Pressures for reallocation of water will be greatest in areas of highest population growth, notably the Southwest. These trends toward declining water consumption will help to mitigate the impacts of climate change on water resources.

## *4.7 Background*

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. These, in turn, are 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 all such streamflow synthesis, or stochastic hydrology methods, however, is that they assume that an observed record of streamflow is statistically stationary – that is, the probability distribution(s) from which the observations are drawn does not change with time. As noted by Arnell (2002), Lettenmaier (2003), NRC (1998), and others, in the era of climate change this assumption is no longer tenable. The challenge 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

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ecosystems.

In this chapter, we first briefly review the current status of U.S. water resources, both in terms of characteristics of the physical system(s), trends in water use, and observed space-time variability in the recent past. We then review changes to the natural hydrologic system (primarily streamflow, but also evapotranspiration and snow water storage) over recent decades for four regions of the United States (the West, Central, Northeast, and South and Southeast, each of which is defined as aggregates of USGS Hydrologic Regions). Finally, we review recent studies, based on climate model projections archived for the 2007 IPCC report, which project the implications of climate change for these four major U.S. regions.

## *4.8 Hydroclimatic variability in the United States*

The primary driver of the land surface hydrologic system is precipitation. Figure 4.1 shows variations in mean annual precipitation and its variability (expressed as the coefficient of variation, defined as the standard deviation divided by the mean) across the continental U.S. As is well known, the semi-humid conditions of the eastern U.S. yield to drier conditions to the west, with the increasing dryness eventually interrupted by the Rocky Mountains. The driest climates, however, exist in the Intermountain West, and the Southwest, which give way as one proceeds west and north to more humid conditions on the upslope areas of the Cascade and Coast mountain ranges, especially in the Pacific Northwest. The bottom panel of Figure 4.1, which shows the coefficient of variation of precipitation, indicates that precipitation variability generally is lowest in the humid areas, and highest in the arid and semi-arid West, with a tendency toward lower variability in the Pacific Northwest, which is more similar to that of the East than the rest of the West.

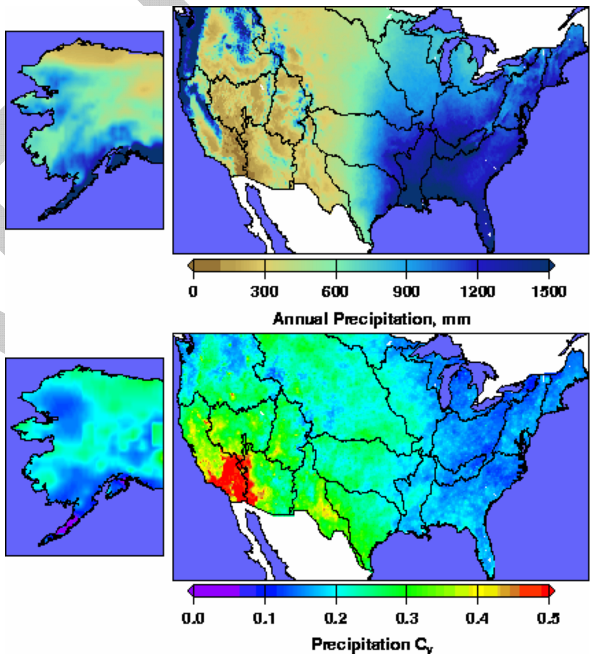

**Figure 4.1** Mean and coefficient of variation of annual precipitation in the continental U.S. and Alaska. Data replotted from Maurer et al. (2002).

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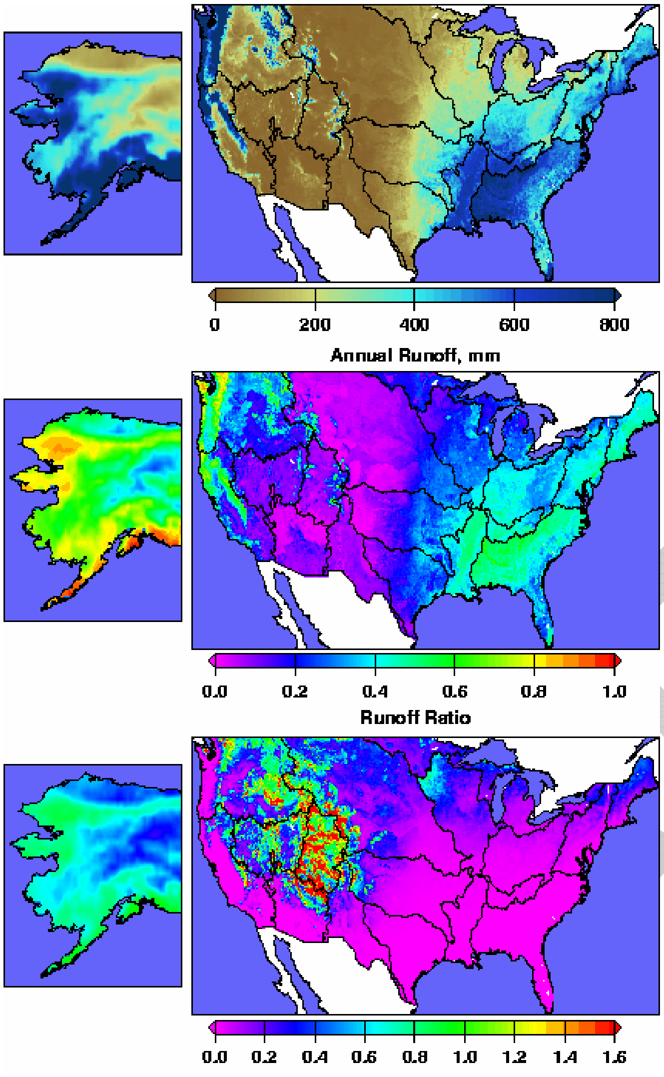

**Figure 4.2** Mean annual runoff, runoff ratio (annual mean runoff divided by annual mean precipitation), and ratio of maximum mean snow accumulation to mean annual runoff in the continental U.S. and Alaska. Data replotted from Maurer et al. (2002).

Figure 4.2 (upper panel) shows that runoff patterns, for the most part, follow those of precipitation. The runoff ratio (annual runoff divided by annual precipitation; second panel in Figure 4.2) generally decreases from east to west, which suggests that the decline in runoff with aridity is sharper than it is for precipitation. The runoff ratio increases in headwaters regions of the mountainous source areas of the west, and more generally in the Pacific Northwest. This increase in runoff ratio with elevation is critical to the hydrology of the West, where a large fraction of runoff originates in a relatively small fraction of the area – much more so than in the semi-humid East and Southeast, where runoff generation is relatively uniform spatially. The bottom panel in Figure 4.2 shows the ratio of maximum annual snow accumulation to annual runoff, and can be considered an index to the relative fraction of runoff that is derived from snowmelt. This panel emphasizes the critical roll of snow processes to the hydrology of the western U.S., and to a more limited extent, in the northern tier of states.

Upper panel replotted from Maurer et al. (2002);
lower panel from Vogel et al. (1998)

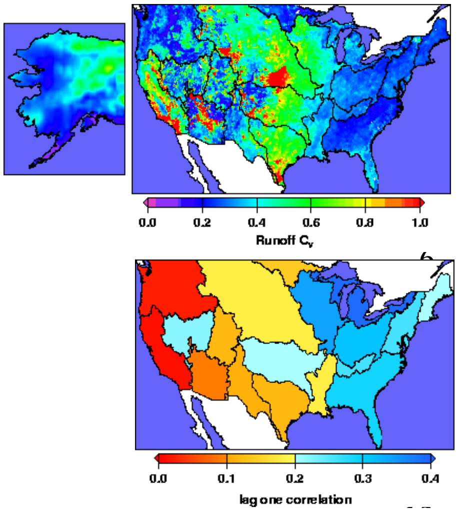

**Figure 4.3** Coefficient of variation of annual runoff (upper panel) and lag one correlation of annual runoff (lower panel). Upper panel replotted from Maurer et al. (2002); lower panel from Vogel et al. (1998)

Figure 4.3 shows two key aspects of runoff variability – the coefficient of variation of annual runoff, and its persistence in time (the latter expressed as the lag one correlation coefficient). The coefficient of variation of annual runoff generally follows that of precipitation; however, it is higher for the most part as the hydrologic system tends to amplify variability (due in part to the fact that the runoff ratio is less than one-half over most of the United States). Annual runoff persistence is generally low, but tends to be higher in the East (and generally in more humid areas) than in the western U.S. The differences between regions are, however, slight, and Vogel et al. (1998) argue in terms of homogeneity that most of the United States can be considered to be a "homogeneous region" in terms of the serial correlation of runoff. It is nonetheless interesting that there is a general gradient downward in serial correlation of runoff from east to west, which is not reversed in the generally more humid areas of the northwest and Pacific Coast regions.

### 4.8.1 Characteristics of managed water resources in the United States

The water resources of the continental U.S. are heavily managed, mostly by surface water reservoirs. During the period from about 1930 through 1980, dams were constructed at most technically feasible locations, with the result that aside from headwater regions, the flow of most rivers, especially in the western U.S., has been heavily altered by reservoir management. Figure 4.4 (modified from Graf, 1999) shows the extent of reservoir storage across the continental U.S. From the standpoint of water management, the lower panel in Figure 4.4, which shows variations in the ratio of reservoir storage to mean annual flow, is most relevant. Although the figure scale is in terms of quartiles, the lowest quartile has storage divided by mean annual runoff ratios in the range 0.25 – 0.36, and the upper quartiles 2.18-3.83 (see Graf, 1999; Table 4.1). A storage to runoff ratio of one is usually taken as the division between reservoirs that are primarily used to shape within-year variations in runoff (small storage to runoff ratios; orange colors in Figure 4.4, lower panel) and those that are primarily used to smooth interannual variations in runoff (large storage to runoff ratios; dark blue I Figure 4.4 lower panel). As we will see in subsequent sections, these differences in storage capacity, coupled with the characteristics of the hydrologic systems, are critical in defining the sensitivity of water resources to climate change.

#### *1.1.1.21 U.S. water use and water use trends*

The U.S. Geological Survey compiles, at five-year intervals, information about the use of water in the United States. The most recent publication (USGS 2004) is for the period

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through 2000. The update to this publication, through 2005, unfortunately was not available as of the time of this writing. The data compiled by the USGS are somewhat limiting in that they are for water withdrawals, rather than consumptive use. The distinction is important, as one of the largest uses of water is for cooling of thermoelectric power plants, and much of that water is returned to the streams from which it is withdrawn (use of water for hydroelectric power generation, virtually none of which is consumptively used, is not included in this category). On the other hand, a much higher fraction of the water withdrawn for irrigation is consumptively used.

Despite these limitations, the two key figures in the 2004 USGS publication, reproduced here as Figure 4.4, are instructive in that they further define the trends noted by Gleick et al. (2000) – U.S. water withdrawals have decreased slightly over the last 20 years in virtually all categories, and appear to have stabilized since about 1985. This is despite substantial population growth during the same period (see Figure 4.4, upper panel).

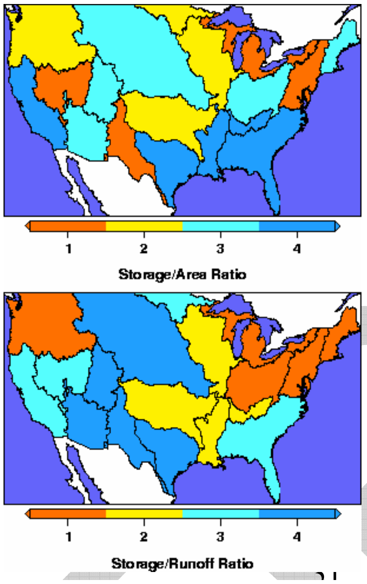

**Figure 4.4** Reservoir storage in the continental U.S. per unit area (upper panel) and storage/runoff ratio (lower panel). Colors are for four quartiles of cumulative probability distribution. Replotted from Graf (1999).

These changes, which follow a 30-year period of rapid growth in water withdrawals, have occurred for somewhat different, but related reasons. Water withdrawals from many streams are now limited, particularly during periods of low flow, by environmental regulations. Furthermore, economic considerations have driven more efficient use of water. In the case of irrigation, there has been a transition from flood to sprinkler irrigation, and (albeit in a much smaller number of cases) much more efficient drip irrigation. Irrigation water use has also been affected by economic considerations, such as the cost of electric power to pump irrigation water.

Industrial water use efficiency gains have been driven by pollution control regulations, which encourage reduction of wastewater discharge, and hence more recycling. Municipal water use reductions have been driven by improved efficiency of in-house appliances and plumbing fixtures, as well as trends to higher density housing which reduces use of water for landscape irrigation. Economic considerations have also had an effect on municipal water use, especially in municipalities where the cost of wastewater treatment is linked to water use. The combined result, as shown in Figure 4.5, is that total U.S. water withdrawals have been stable, which implies that per capita water use has declined.

One might ask whether continuation of this trend toward reduced per capita water use is feasible. Comparison of U.S. per capita water use (see Gleick 1996) with that elsewhere globally shows that U.S. water use is much higher than elsewhere globally, even comparing with other industrialized parts of the world like Europe. Therefore, it does not

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seem unreasonable that this overall trend toward reduced per capita use of water will continue, at least over the next decade or two.

## *4.9 Observed changes in U.S. water resources*

We review briefly in this section observed trends in U.S. water resources – both physical aspects, and water quality. In general, much more work has been done evaluating trends in physical aspects of the land surface hydrologic cycle than for water quality, and more attention has been focused on the western U.S. than elsewhere. For this reason, we review studies of physical aspects by region, but water quality in aggregate.

### 4.9.1 Observed streamflow trends

The most comprehensive study of trends in U.S. streamflow to date is reported by Lins and Slack (1999; 2005). It follows an earlier study by Lettenmaier et al. (1994) that dealt also with precipitation and temperature, but in less detail with streamflow. Given that the Lins and Slack study concentrates more directly on streamflow, and is somewhat more current, we focus on it. Although the methodologies, record lengths, locations, etc differ somewhat for the two studies, to the extent that the results can be compared they are generally consistent.

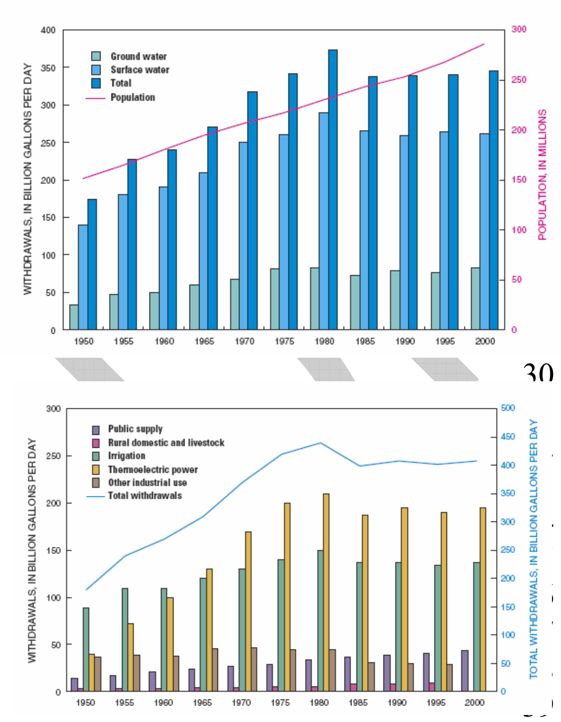

**Figure 4.5** Trends in U.S. water withdrawals, 1950-2000. Upper panel: trends in population, groundwater, and surface water withdrawals. Lower panel: withdrawals by sector. Figure from Hutson et al., 2004.

Lins and Slack (1999) analyzed long-term streamflow records for a set of 395 stations across the continental U.S. for which upstream effects of water management were minimal, and which had continuous (daily) records for the period 1944-93 (updated to 435 stations for the period 1940-99 by Lins and Slack (2005). For each station, they formed time series of minimum and maximum flows, as well as flows at the 10th, 30th, 50th, 70th, and 90th percentiles of the flow duration curve. They found, consistent with Lettenmaier et al. (1994) that there was a preponderance of upward trends (many more than would be expected due to chance) in all but the highest flows (see Figure 4.6), for which the number of upward and downward trends was about the same. In addition to the 50-year period 1944-93, similar analyses were conducted for the smaller number of stations having 60, 70, and 80 years of record (all ending in 1993), and the fraction of upward and downward trends was about the same as

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for the analysis of the larger number of stations with at least 50 years of record. Lins and Slack (2005) update the analysis to a "standard" 60-year period, 1940-99, but unlike their earlier paper, do not consider longer periods with smaller numbers of stations. Neither the 1999 nor the 2005 papers attempt to attribute the observed trends to climatic warming, although the spatial coherence in the trends suggest that non-climatic causes (e.g., land cover change), are not likely the cause. However, as noted in Cohn and Lins (2006), hydroclimatic records by nature reflect long term persistence associated with climate variability over a range of temporal scales, as well as low frequency effects associated with land processes, so the mere existence of trends in and of itself does not necessarily imply a causal link with climate change. Summaries of the Lins and Slack results are shown in Figure 4.7a-c, which plot the location and strength (as significance level) of trends at a subset of HCDN stations, with the longest records (note that in Figure 4.7, green indicates no significant trend at the 0.05 significance level).

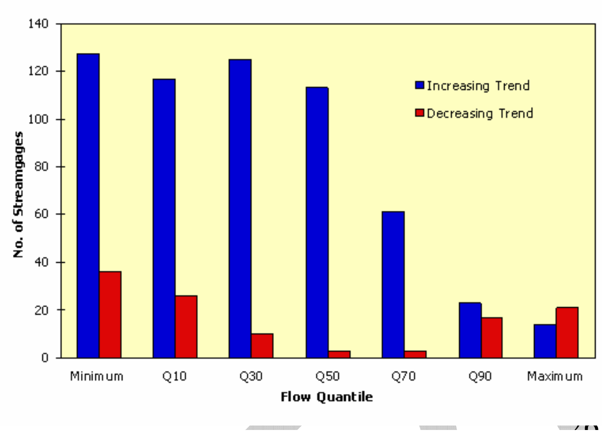

**Figure 4.6** Number of increasing and decreasing trends in continental U.S. streamflow records for a range of flow quantiles. From Lins and Slack (1999).

Mauget (2003) used a method based on running time windows of length six to 30 years applied to streamflow records for the 1939-98 period extracted from the same USGS Hydro-Climatic Data Network as were used by Lins and Slack (1999). The Mauget et al. (2003) analysis was based only on the 167 stations for which data were available for the period 1939-98, and hence make up a somewhat different station set than was used by Lins and Slack. (It is worth noting that many of the stations used in the Mauget et al. study are likely the same as those used by Lins and Slack in their 60-year (1934-93) set of 193 stations. It should also be noted that the Mauget study is based on mean annual flow, and Lins and Slack use percentiles of the annual flow distribution, including the median). The results of the Mauget et al. (2003) study are broadly similar to Lins and Slack (1999) to the extent that comparisons are possible. Mauget finds evidence of high streamflows being more likely toward the end of the record than the beginning in the eastern U.S., especially in the 1970s, and "a coherent pattern of high-ranked annual flow … beginning during the later 1960s and early 1970s, and ending in either 1997 o 1998." By contrast, he found a more or less reverse pattern in the western U.S., with an onset of dry conditions beginning in the 1980s.

### 4.9.2 Evaporation trends

Several studies have been performed to assess changes in evapotranspiration, another major term in the land surface water balance. Unfortunately, there are no long-term ET observations – methods that enable direct measurements, e.g., via eddy flux methods, have only been available for about 20 years, and are still used more in the realm of

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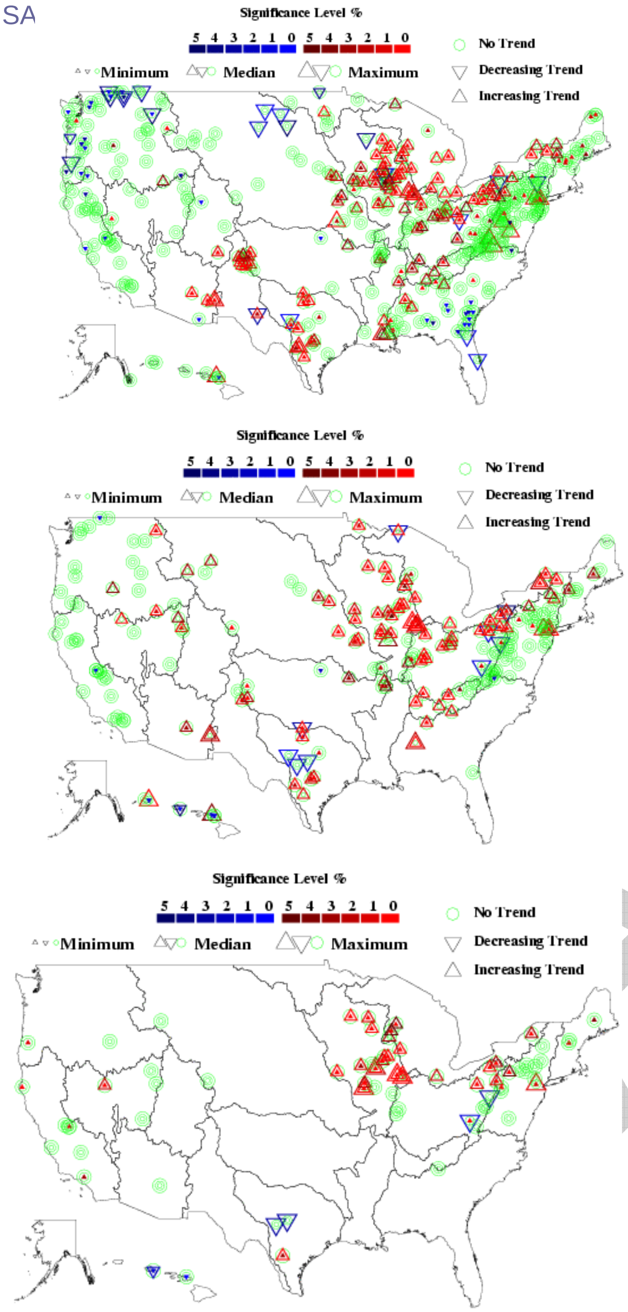

**Figure 4.7**. Statistically significant trends in streamflow across the continental U.S. At each station location, direction of trend and significance level (if statistically significant at less than 0.05 level) are plotted for minimum, median, and maximum of the annual flows. Upper panel: 393 stations at which data were available from 1944-93; middle panel: same for 1934-93; lower panel: same for 1924-93. Data replotted from Lins and Slack (1999).

intensive research observations than long-term. Another source of evaporation data are records from evaporation pans, which are generally located in agricultural areas and have been used as an index to potential evaporation. These records are generally longer; a number (several hundred over the continental U.S.) have record lengths approaching 50 years. Several studies (e.g., Peterson et al. 1995; Golubev et al. 2001) have shown that pan evaporation records over the United States generally had downward trends over the second half of the 20th century. This is contrary to the expectation that a generally warming climate would increase land surface evaporation.

Two explanations have been advanced. The first is the so-called evaporation paradox (Brutsaert and Parlange, 1998), which holds that increasing evaporation alters the humidity regime surrounding evaporation pans, causing the air over the pan to be cooler and more humid. This "complementary hypothesis" suggests that trends in pan and actual evaporation should be in the opposite direction. Observational evidence, using U.S. pan evaporation data and basin-scale actual evaporation, inferred by differencing annual precipitation and runoff, suggests that trends in U.S. pan and actual evaporation have in fact been in opposite directions (Hobbins et al. 2004).

The second hypothesis is that actual ET may also have declined due to reduced net radiation, resulting from increased cloud cover. This hypothesis is consistent with observed downward trends in the daily temperature range (daily minimum temperatures have generally increased over the last 50 years, while daily maxima have increased more slowly, if at all), and the temperature range is generally related to downward solar radiation, which would therefore have decreased. Unfortunately, as with actual evaporation, long-term records of surface solar radiation are virtually nonexistent, so indirect estimates (such as cloud cover, or daily temperature range) must be relied on. Roderick and Farquahr (2002) argue that decreasing net solar irradiance resulting from increased cloud cover and aerosol concentrations is a more likely cause for the observed changes, and that actual evaporation should generally have decreased, consistent with the pan evaporation trends.

Brutsaert (2006) argues that "the significance of this negative trend [in pan evaporation], as regards terrestrial evaporation, is still somewhat controversial, and its implications for the global hydrologic cycle remain unclear. The controversy stems from the alternative views that these evaporative changes resulted either from global radiative dimming, or from the complementary relationship between pan and terrestrial evaporation. Actually, these factors are not mutually exclusive, but act concurrently. He derives a theoretical relationship between trends in actual evaporation, net radiation, surface air temperature, and pan evaporation, and shows that the observed trends are generally consistent, accounting for the generally observed downward trend in net radiation ("global dimming," albeit from sparse observations),

### 4.9.3 U.S. drought trends

Andreadis and Lettenmaier (2006) investigated trends in droughts in the continental U.S. using a method that combined long-term observations with a land surface model. Their approach was to use gridded observations of precipitation and temperature that were adjusted to have essentially the same decadal variability as the Hydroclimatic Data Network (HCDN) stations – which have been carefully quality controlled for changes in observing methods – to force a land surface model, and then used to evaluate trends in several drought characteristics, in both model-derived soil moisture and runoff. Results show that the spatial character of trends in the model-derived runoff is in general consistent with the observed streamflow trends from Lins and Slack (1999). Andreadis and Lettenmaier also show that, generally, the continental U.S. became wetter over the period analyzed (1915-2003), which was reflected in trends in soil moisture as well as drought severity and duration. However, there was some evidence of trends in the opposite direction (that is, increases) in drought severity and duration in the western and southwestern U.S., which was interpreted as increased actual evaporation dominating the trend toward increased soil wetness, which was evident through the rest of the United States.

Prior to the instrumental record of roughly 100 years, there is evidence that much more severe droughts have occurred in North America. For instance, Woodhouse and Overpeck (1998), using paleo indicators (primarily tree rings) find that many droughts over the last 2,000 years have eclipsed the major U.S. droughts of the 1930s and 1950s, with much more severe droughts occurring as recently as the 1600s. Although the nature of future drought stress remains unclear, for those areas where climate models suggest

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drying, such as the Southwest (see e.g., Seager et al. 2007), droughts more severe than those encountered in the instrumental record may be increasingly likely.

## 4.9.4 Regional assessment of changes in U.S. water resources

For purposes of this section, we partition the United States into four "super-regions" using aggregations of the USGS hydrologic regions (Figure 4.8) as follows: West (Pacific Northwest, California, Great Basin, Upper Colorado, Lower Colorado, Rio Grande, and upper Missouri); Central (Arkansas-Red, lower Missouri, Upper Mississippi, Souris-Red-Rainy, and Great Lakes); Northeast (New England, Mid Atlantic, Ohio, and northern half of South Atlantic-Gulf); and South and Southeast (Tennessee, Lower Mississippi, Texas-Gulf, and southern half of South Atlantic-Gulf), as well as Hawaii and Alaska, which are treated separately. Observed changes over each of these parts of the country are summarized below.

### *1.1.1.22 West*

As noted above, the western U.S. has been more studied than any of the other regions in terms of both observed climate-related changes in hydrology and water resources, and the future implications. This is probably because a) the western U.S. is, in general, more water-limited than is the rest of the United States, hence any changes in the availability of water have more immediate and widespread consequences, and b) much of the runoff in the western U.S. is derived from snowmelt, and therefore western U.S. streamflow is more sensitive to ongoing and future climate change in ways that are more readily observable than elsewhere in the United States

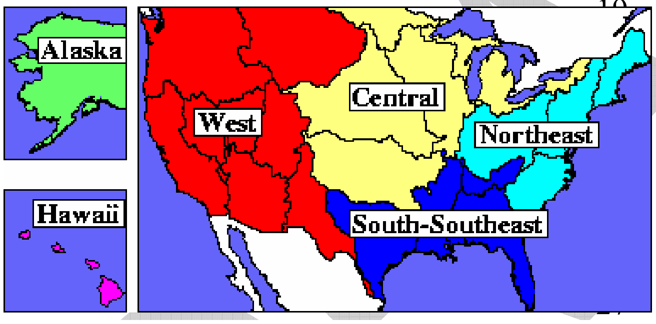

**Figure 4.8** Super-regions as aggregates of USGS hydrologic regions.

Much of the recent work on observed changes in the hydrology of the western U.S. has focused on changes in observed snowpack. Mote (2003) analyzed 230 time series of snow water equivalent in the Pacific Northwest (defined as the states of Washington, Oregon, Idaho, and Montana west of the Continental Divide, and southern British Columbia) for the period 1950 to 2000 (and in some cases longer). These records orginate mostly from manual snow courses at which snow cores were taken at about the same time each year (in some cases, more than once, but at most locations around April 1), primarily for the purpose of predicting subsequent spring and summer runoff for water management purpose. Mote (2003) found that over this region, there was a strong preponderance of downward trends, especially in the Cascade Mountains, where winter temperatures were generally higher than elsewhere in the region. Also, the decreases were generally larger in absolute value at lower than at higher elevations. He noted that

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changes in precipitation, as well as decadal scale variability (especially the widely acknowledged shift in the Pacific Decadal Oscillation (PDO) in about 1977) may have contributed to the observed trends, but argued that the PDO shift alone could not explain changes in SWE over the period analyzed. He also concluded that while regional warming has played a role in the decline in SWE, "… regional warming at the spatial scale of the Northwest cannot be attributed statistically to increase in greenhouse gasses."

Mote et al. (2005) expanded the analysis of Mote (1999) to the western U.S., and used a combination of modeling and data analysis (similar to the approach used by Andreadis and Lettenmaier in their continental U.S. drought analysis) to analyze changes in SWE over the western U.S. for the period 1915 to 2003. They used the snow accumulation and ablation model in the Variable Infiltration Capacity (VIC) macroscale hydrology model (Liang et al. 1994) to simulate SWE over the entire western U.S. for the period of interest, and then compared simulated trends and their dependence on elevation and average winter temperature with snow course observations. They found, notwithstanding considerable variability at the scale of individual snow courses, that the spatial and elevation patterns of trends agreed quite well over the region. They then analyzed reconstructed records for the entire period 1915-2003 and evaluated trends in the reconstructed records. The advantage of this approach is that the longer 1915 to 2003 period spans several phase changes in the PDO, and therefore effectively filters our its effect on long-term trends. They found that over the nearly 80-year period, there had been a general downward trend in SWE over most of the region. The exception was the southern Sierra Nevada, where an apparent upward trend in SWE, especially at higher elevations, appeared to have resulted from increased precipitation, which more than compensated for the generally warming over the period.

Hamlet et al. (2005) extended the work of Mote et al. (2005) and through sensitivity analysis, determined that most of the observed SWE changes in the western U.S. can be attributed to temperature, rather than precipitation changes. Hamlet et al. (2007) used a similar strategy of driving the VIC hydrological model with observed precipitation and temperature and found, over the 1916 to 2003 period, that trends in soil moisture, ET, and runoff generally can be traced to shifts in snowmelt timing associated with a general warming over the period. In a companion paper, Hamlet and Lettenmaier (2007) assessed changes in flood risk using a similar approach. This analysis showed that in cold (high elevation, and continental interior) river basin flood risk was reduced due to overall reductions in spring snowpack. In contrast, for relatively warm rain-dominant

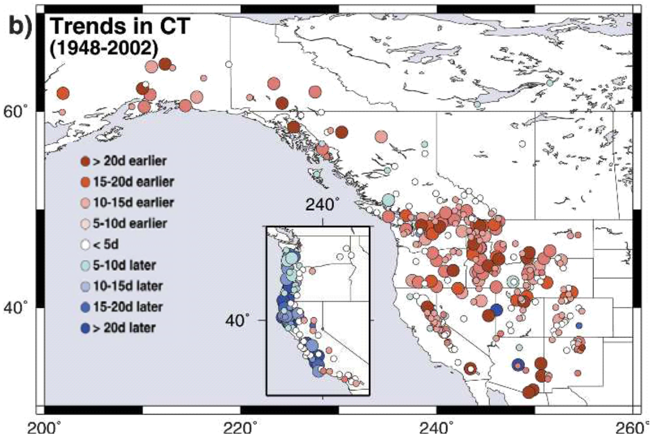

**Figure 4.9** Changes in western U.S. snowmelt runoff timing, 1948-2002. Source: Stewart et al. (2005).

basins (mostly coastal and/or low elevation) where snow plays little role, little systematic change in flood risk was apparent. For intermediate basins, a range of competing factors such as the amount of snow prior to the onset of major storms, and the contributing basin area during storms (i.e., that fraction of the basin for which snowmelt was present) controlled flood risk changes, which were less easily categorized.

Stewart et al. (2005) analyzed changes in the timing of spring snowmelt runoff across the western U.S. They computed several measures of spring runoff timing using 302 streamflow records across the western U.S., western Canada, and Alaska for the period 1948 to 2002. The most useful was the center of mass timing (CT), which is the centroid of the time series of daily flows for a year. As shown in Figure 4.9, they found consistent shifts earlier in time of CT for snowmelt dominated (mostly mountainous) river basins, but little change (or changes toward later runoff) for coastal basins without a substantial snowmelt component. Although they noted the existence of the PDO shift part way through their period of record, Stewart et al. (2005) argue that the variance in CT is explained both by temporal changes in the PDO and a general warming in the region, and that variations in PDO alone are insufficient to explain the observed trends. This finding is supported by the absence of coherent shifts in CT for non-snowmelt dominated streams.

Pagano and Garen (2005) found that the variability of April-September streamflow at 141 unregulated sites across the western U.S. has generally increased from about 1980 onward. This contrasts with a period of markedly low variability over much of the region from about 1930 through the 1970s. Although such shifts at decadal time scales have been observed before, and are even expected due to the nature of decadal scale variability, increased streamflow variability is a major concern for water managers, as it tends to diminish the reliability with which water demands can be satisfied.

#### *1.1.1.23 Central*

There has been relatively little work evaluating hydrologic trends in the central U.S. more specific than the U.S.-wide work of Lins and Slack (1999), and Mauget (2003). Garbrecht et al. (2004) analyzed trends in precipitation, streamflow, and evapotranspiration over the Great Plains. They found, in an analysis of 10 watersheds in Nebraska, Kansas, and Oklahoma with streamflow records starting from 1922 to 1950 (median start year about 1940) and all ending in 2001, a common pattern of increasing annual streamflow in all watersheds, most of which occurred in spring and winter (notwithstanding that most of the annual precipitation in these basins occurs in spring and summer). Garbrecht et al. also found that the relative changes in annual streamflow were much larger than in annual precipitation, with an average 12-percent increase in precipitation, leading to and average 64-percent increase in streamflow, but only a 5-percent increase in evapotranspiration. They also note that the large increases in streamflow had mostly occurred by about 1990, and in some (but not all) of the basins appeared to have reversed in the last decade of the record. Mauget (2004) analyzed annual streamflow records at 42 USGS Hydro-Climatic Data Network stations in a large

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area of the central and southern U.S. (stations included were as far west as eastern Montana and Colorado, as far east as Ohio, as far north as North Dakota, and as far south as Texas). They used an approach somewhat similar to that of Mauget (2003), based on a moving average (six to 30 year window) of the non-parametric Mann-Whitney U-statistic computed from the annual streamflow series for the same 1939-98 period used by Mauget (2003). Although the patterns vary somewhat across the stations, in general higher flow periods tended to occur more toward the end of the period than the beginning, indicating general increases in streamflow over the period. A more detailed analysis of daily streamflows indicate negative changes in the incidence of drought events (defined as sequences of days with flows below a station-dependent threshold) and increases in the incidence of "surplus" days (days with flows above a station-dependent surplus threshold). These results are broadly consistent with those of Lins and Slack (1999), and Andreadis and Lettenmaier (2006).

#### *1.1.1.24 Northeast*

The Northeast region is distinctive in that many records relating to hydrologic phenomena are relatively long. Burns et al. (in press) report that, based on data from 1952 to 2005, in the Catskill region of New York State (the source of most of New York City's water supply), peak snowmelt generally shifted from early April at the beginning of the record, to late March at the end of the record, "consistent with a decreasing trend in April runoff and an increasing trend in maximum March air temperature." Burns et al. also report increases in regional mean precipitation and regional mean potential evapotranspiration (PE), with generally increased regional runoff.

Hodgkins et al. (2003) and Hodgkins and Dudley (2006) studied high flows in rural, unregulated rivers in New England, where snowmelt dominates the annual hydrological cycle. They showed significantly earlier snowmelt runoff (using methods similar to those applied in the western U.S. by Stewart et al. (2005), with most of the change (advances of center of volume of runoff by one to two weeks) occurring in the last 30 years. Hodgkins et al. (2002) also noted reductions in ice cover in New England. Spring ice-out (when lake ice-cover ends) records between 1850 and 2000 indicate an advancement of nine days for lakes in northern and mountainous regions, and 16 days for lakes in more southerly regions. These changes were generally found to be related to warmer air temperatures.

Huntington et al. (2004), analyzed the ratio of snow to precipitation (S/P) for Historical Climatology Network (HCN) sites in New England and found a general decrease in the ratio, and decreasing snowfall amounts, which are consistent with warming trends. Hodgkins and Dudley (2006) found that 18 of 23 snow course sites in and near Maine with records spanning at least 50 years had decreases in snowpack depth, or increases in snowpack density, changes that are also consistent with a warming climate.

The Ohio Basin, also included within our northeast "super-region," is relatively understudied in terms of climate change (Liu et al. 2000) despite its economic and demographic (population 25 million) importance, and the significance of its flow (it

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contributes 49 percent of the total Mississippi flow at Vicksburg). The Lins and Slack (1999) study of streamflow trends across the United States found increases in minimum and median flows at several locations in the Ohio basin, but no trend in maximum flows. McCabe and Wolock (2002) describe a step change (increases) in about 1970 in U.S. streamflow, which was most prevalent in the eastern U.S., including the Ohio. They related this apparent shift to a possible change in climate regime. Easterling and Karl (2001) note that during the 20th century there was a cooling of about 0.6°C in the Ohio basin, with warming in the northern Midwest of about 2°C for the same period. But they also report that the length of the snow season in the Ohio Valley over the second half of the 20th century decreased by as much as 16 days. In a study of evaporation and surface cooling in the Mississippi basin (including the Ohio), Milly and Dunne (2001) suggest that high levels of precipitation were caused by an internal forcing, and that a return to normal precipitation could reveal warming in the basin.

Moog and Whiting (2002) studied the relationship of hydrologic variables (precipitation, streamflow and snow cover) to nutrient exports in two basins adjacent to the northern boundary of the Ohio (Maumee and Sandusky Rivers). While not focused on climate-related changes directly, it is nonetheless of interest since it allows inferences to be made of how climate change might impact water quality in the basin. Antecedent precipitation and streamflow were found to be negatively correlated to pollution loading, and snow cover to be correlated with deferring loads. These results suggest how shifts in seasonal streamflow, and the increases in low and median flows observed by Lins and Slack (1999), might impact nutrient export from the basin.

### *1.1.1.25 South and Southeast*

No studies were found that dealt specifically with hydrologic trends in the South and Southeast, although the national study of Lins and Slack shows generally increasing streamflow over most of this region in the second half of the 20th century. This result is consistent with Mauget (2003) and the part of the domain studied by Mauget (2004) that lies in the South and Southeast super-region. A related study by Czikowsky and Fitzjarrald (2004) analyzed several aspects of seasonal and diurnal streamflow patterns at several hundred USGS stream gauge stations in the east and southeastern U.S., as they might be related to evapotranspiration changes that occur at the onset of spring. These measures included the difference between precipitation minus runoff, the median of the daily runoff hydrographs recession time constant following storms, and the amplitude of diurnal streamflow variations. They found a general shift in runoff patterns earlier in the spring in Virginia (as well as in New England, and New York), but not in Pennsylvania and New Jersey.

### *1.1.1.26 Alaska*

Hinzman et al. (2005) review evidence of changes in the hydrology and biogeochemistry of northern Alaska (primarily arctic regions). They showed decreases in warm season

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surface water supply, defined as precipitation minus potential evapotranspiration, at several sites on the Arctic coastal plain over the last 50 years. Precipitation was observed, and potential evapotranspiration was computed using observed air temperature. These downward trends were related primarily to increased air temperature, as precipitation trends generally were not statistically significant over the period. Permafrost temperatures (from borehole measurements at 20-meter depth) have increased over the last half century, with the increases most marked over the last 20 years. The authors also found some evidence of increasing discharge of Alaskan Arctic rivers over recent decades, although short records precluded a rigorous trend analysis. Records of snow cover at Barrow indicate that the last day of snow cover has become progressively earlier, by about two weeks over 60 years. Stewart et al. (2005), in their study of seasonal streamflow timing, included stations in Alaska (mostly south and southeast), and found that the shifts toward earlier timing of spring runoff in the western U.S. extended into Alaska (see Figure 4.8). Lins and Slack (1999) included a handful of HCDN stations in southeast Alaska, for which there did not appear to be significant trends over the periods they analyzed.

#### *1.1.1.27 Hawaii*

Oki (2004) analyzed 16 long-term USGS streamflow records from the islands of Hawaii, Maui, Molokai, Oahu, and Kauai for the period 1913 to 2002. They found that for all stations, there were statistically significant downward trends in low flows, but that trends were generally not significant in the annual or higher flows. When segregated into baseflow and total flow, baseflow trends were significant across almost the entire distribution (mean as well has high and low percentiles). In general, low and base flows increased from 1913 to about the early 1940s, and decreased thereafter. Oki also found that streamflow was strongly linked to the El Niño-Southern Oscillation (ENSO), with winter flows tending to be low following El Niño events, and high following La Niña events, a signal that is modulated to some extent by the PDO, and is most apparent in the total flows, and to a lesser extent in baseflows. Oki (2004) noted that changes in ENSO patterns could be responsible for the observed long-term trends, but did not attempt to isolate the portion of the observed trends that could be attributed to interannual and interdecadal variability attributable to ENSO and the PDO.

## *4.10 Water quality*

Water quality reflects the chemical inputs from air and landscape and their biogeochemical transformation within the water (Murdoch et al. 2000). The inputs are determined by atmospheric processes and movement of chemicals via various hydrologic flowpaths of water through the watershed, as well as the chemical nature of the soils within the watershed. Water quality is also broadly defined to include indicators of ecological health (e.g. sensitive species). Regional scale variation in natural climatic conditions (precipitation pattern, and temperature) and local variation in soils generates spatial variation in “baseline” water quality and specific potential response to a given scenario of climate change. A warming climate is, in general, expected to increase water

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temperatures and modify regional patterns of precipitation, and these changes can have direct effects on water quality. However, a major challenge in attributing altered water quality to climate change is the fact that water quality is very sensitive to other, nonstationary human activities, particularly land use practices that alter landscapes and modify flux of water as well as thermal and nutrient characteristics of water.

In general, water quality is sensitive to temperature and water quantity. Higher temperatures enhance rates of biogeochemical transformation and physiological processes of aquatic plants and animals, thereby influencing measures of water quality. As temperature increases, the ability of water to hold dissolved oxygen declines, and as water becomes anoxic, animal species begin to experience suboptimal conditions. Nutrients in the water enhance biological productivity of algae and plants, which increases oxygen concentration by day, but at night these producers consume oxygen and oxygen sags can impose suboptimal anoxic conditions. Greater volumes of water can dilute nutrient concentrations and thus diminish excessive biological production, and higher flows can flush excess nutrients from sources of origin in a stream.

Most studies examining the responses of water quality over time have focused on nutrient loading, as this factor has changed significantly over time and there are specific U.S. laws (Clean Water Act) designed to reduce nutrient inputs into surface waters to increase their quality. For example, Alexander and Smith (2006) examined trends in concentrations of total phosphorus and total nitrogen and the related change in the probabilities of trophic conditions from 1975 to 1994 at 250 river sites in the United States with drainage areas > 1,000 km$^2$. Concentrations in these nutrients generally declined over the period, and most improvements were seen in forested and shrub-grassland watersheds compared to agricultural and urban watersheds. Ramstack et al. (2004) reconstructed water chemistry before European settlement for 55 Minnesota lakes. They found that lakes in forested regions showed very little change in water quality since 1800. By contrast, about 30 percent of urban lakes and of agricultural lakes showed significant increases in chloride (urban) or phosphorus (agricultural). These results indicate the strong influence of land use on water quality indicators. Detecting the effects of climate change requires the identification of reference sites that are not influenced by the very strong effects of human land use activities.

Recent historical assessments of changes in water quality due to temperature trends have largely focused on salmonid fishes in the western U.S. For example, Bartholow (2005) used USGS temperature gauges to document a 0.5°C per decade increase in water temperatures in the lower Klamath River from the early 1960s to 2001, driven by basin-wide increase in air temperatures. Such changes may be related to Pacific Decadal Oscillation. Increases in water temperature can directly and indirectly influence salmon through negatively affecting different life stages. Crozier and Zabel (2006) reported that air temperatures have risen 1.2°C from 1992 to 2003 in the Salmon River Basin in Idaho. Because water temperatures show a correlation with air temperature, smaller snowpacks that reduce autumn flows and cause higher water temperatures are expected to reduce salmon survival. Temperature effects can be indirect as well. For example, Petersen and Kitchell (2001) examined climate records for the Columbia River from 1933-1996 and

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observed variations of up to a 2°C between "natural" warm periods and cold periods. Using a bioenergetics model, they showed that warmer water temperatures are associated with an expected higher mortality rate of young salmon due to fish predators.

## 4.11 Attribution of changes

Trend attribution essentially amounts to attempting to answer the question "if trends were observed, what caused them?" Among the various agents of hydrologic change, the most plausible are a) changing climate, b) changing land cover and/or land use, c) water management, and d) instrumentation changes, or effects of other systematic errors – although certainly others could be hypothesized. Among the causes of streamflow trends (the variable assessed by most studies reviewed in this chapter), water management changes are the easiest to deal with. With respect to changes in streamflow (the variable analyzed by most of the studies reviewed above), the studies cited have all used streamflow records selected to be as free as possible of water management effects. For instance, USGS HCDN stations, used by Lins and Slack (1999; 2005), as well as several other studies reviewed, were selected specifically based on USGS metadata that indicate the effects of upstream water management. Certainly, it is not impossible for the metadata to be in error. An earlier study by Lettenmaier et al. (1994) used a set of USGS records that pre-dated HCDN, which was selected using similar methods, identified some stations where there were obvious water management effects upstream, despite metadata entries to the contrary. However, the number of such stations was small, and in any event the clear spatial structure in the Lins and Slack results shown in Figure 4.7, for instance, if attributable to water management, would require a corresponding spatial structure to errors in the metadata, which seems unlikely. In short, while it could be that some of the detected trends are attributable to undocumented water management effects, it is highly unlikely that the same could be said for the general patterns, or conclusions.

Changes in instrumentation are always of concern in trend detection studies, as shifts in instrumentation often are implemented at a particular time, and hence can easily be confounded with other trend causes. This is a problem, for instance, with precipitation measurement, where changes in gauge types, wind shields, and other particulars complicate trend attribution (it should be noted that these problems are addressed in precipitation networks like the U.S. Historical Climatology Network, which has had adjustments made for observing system biases). For streamflow observations, in contrast, the methods are relatively straightforward – the measured variable is river stage, which is converted to discharge via a stage-discharge relationship, formed from periodic coincident measurements of discharge and stage. The USGS has well established protocols for updating stage-discharge relationships, especially following major floods, which may affect the local hydraulic control. Therefore, while there almost certainly are cases where bias is introduced into discharge records following rating curve shifts, it is unlikely that such shifts would persist though a multi-decadal record, and even more unlikely that observed spatial patterns in trends could be caused by rating curve errors.

Distinguishing between the two remaining possible causes of trends – land cover and/or land use change and climate – is a much more difficult problem. Some land cover/land

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use change effects have striking effects on runoff. Urbanization is one such change agent, which typically decreases storm response time (the time between peak precipitation and peak runoff), increases peak runoff following storms, and decreases base flows (as a result of decreased infiltration). However, urban areas are generally avoided in selection of stations to be included in networks like HCDN, so urbanization is probably not a major contributor. Other aspects of land cover change, however, such as conversion of land use to or from agriculture, and forest harvest tend to affect much larger areas, and often occur over many decades, hence have time constants that are similar to decadal and longer scale climate variability. Relatively few studies have been performed that have attempted to quantify the effects on runoff of large-scale vegetation change. Matheussen et al. (2000) studied land cover change in the Columbia River basin from 1900 to 1990, and estimated that changes to annual runoff from forest harvest and fire suppression were at most 10 percent (to one of eight sub-basins analyzed, more typical changes were of order five percent) over this time period. On the other hand, studies of smaller basins, where a large fraction of the basin can be perturbed over relatively short periods of time, have projected or measured much larger changes (see, e.g., Bowling and Lettenmaier (2001) for an example of modeled changes of forest harvest, and Jones and Grant (1996) for an observational study). Over basins the size of which have been analyzed within networks like HCDN, however, more modest changes are likely, and over such moderate (typical drainage areas hundreds to thousands of km$^2$ and up) efforts to isolate vegetation change from climate variability have been complicated by signal-to-noise ratios that are usually smaller for the vegetation than the climatic signal (see Bowling et al. 2000 for an example). In so arguing, though, it must be acknowledged that some studies have reported changes in the hydrologic response of intermediate sized drainage basins, such as those included in the HCDN, that appear to be attributable to land cover, rather than climate change (see e.g. Potter, 1991). In summary, we view it as unlikely that the hydrologic trends detected in the various studies reviewed above can be attributed, at least in large part, to land cover and land use change – but we cannot refute such a contention definitively.

The final cause to which long-term hydrological trends might be attributed is climate change. Although it is essentially impossible to demonstrate cause and effect, streamflow (and other land surface hydrological variables) clearly are highly sensitive to climate, especially precipitation. Hence, it is possible to compare trends in precipitation, for instance, with those in runoff, and in fact most efforts to do so (some explicit, others more indirect) show a general correspondence, at least in the continental U.S., between changes in precipitation and runoff. Certainly, this effect is clear in the Lins and Slack (1999; 2005) results, where generally increased streamflow over most percentiles of the flow frequency distribution (and to the annual minima) seem to correspond to generally upward trends in precipitation across much of the continental U.S. For the annual maxima (floods), the correspondence to precipitation is less obvious. While various studies have shown increases in intense precipitation across the continental U.S. (e.g., Groisman et al., 1999), the absence of corresponding increases in flood incidence has remained a somewhat open question. Groisman et al. (2001) performed an analysis to show that shifts in the probability distribution of extreme precipitation in general correspond to shifts in flood distributions, however the fact remains that few changes

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were detected in extreme floods in the Lins and Slack analysis, and of those changes the number of downtrends and uptrends was nearly equal. One possible reason for the discrepancy is that the "floods" analyzed by Groisman et al. (2001) are not of the same general magnitude as the annual maxima series analyzed by Lins and Slack (1999) (which is the basis for estimation of the frequency distribution of extreme floods commonly used for risk analysis, e.g., the 100-year flood plain used for land use planning). Another reason that has been advanced is that the shifts in intense precipitation observed by Groisman et al. (1999) and others occur mostly during periods of the year when extreme floods are uncommon.

Notwithstanding these difficulties related to the upper tail of the streamflow distribution, most streamflow trends do, at least generally, correspond to observed trends in precipitation. The question then becomes, are these changes evidence of climate change, or decadal (or longer) scale variability. This is a question that cannot be addressed through hydrologic analysis alone. There is a close link between decadal and longer scale variability. As just one example, observed downward trends in streamflow in the Pacific Northwest are difficult to discriminate from changes associated with a mid-70s shift in the PDO, especially because this change occurred at about the mid-point of many streamflow records (many stations in the Pacific Northwest date to the late 1940s). The most promising way to deal with this issue is through use of model reconstructions (see e.g. Mote et al. 2005; Hamlet et al. 2007), which attempt to segregate decadal scale variability from longer term (century or longer) shifts. Most of the studies reviewed in this chapter do not incorporate such methods, however, and must be qualified (as the authors have explicitly in many cases) to the effect that while the studies identify trends, they do not attempt attribution.

## *4.12 Future changes and impacts*

We review briefly in this section recent work that has assessed potential impacts of climate change over the next several decades (formally, to the mid-21st century) on the water resources and water quality of the United States. Numerous studies of the impacts of climate change on U.S. water resources have been performed, many of which are reviewed in, for instance, special issues of journals (see, for instance, Gleick 2000) and IPCC reports (e.g. Arnell and Liu 2001). An exhaustive review of this considerable body of research is beyond the scope of this chapter, and in any event, would be duplicative. Instead, we limit our review here to work that derives directly from climate scenarios archived for the 2007 IPCC assessment.

This recent work has several particular features. First, the global greenhouse gas emissions scenarios used in global model runs archived for use with the 2007 IPCC assessment are, in general, more consistent across models than in previous IPCC studies. Most models were run with transient scenarios (that is, global greenhouse gases increasing over time from an initial condition that typically is consistent with conditions as of about 2000) as specified in the IPCC (2000) Special Report on Emissions Scenarios (SRES). Although this report was issued prior to the 2001 IPCC Third Assessment Report, the full effect of the SRES report was not felt until the IPCC Fourth Assessment

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Report (2007) because of the lag time of several years that is required to run GCMs (often incorporating model improvements) and to archive their output. Second, the GCM physical parameterizations have improved with time, as has the spatial resolution, notwithstanding that the spatial resolution of most models is still coarse relative to the spatial scales required for regional impact assessments. Third, the length of GCM model runs has generally increased, with most modeling centers that have made runs available for IPCC analyses now producing simulations of length at least 100 years, and in many cases with multiple ensembles for each of several emissions scenarios. Finally, archiving model runs at the Lawrence Livermore National Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI) in common formats has greatly facilitated user access to the climate model scenarios.

Milly et al. (2005) evaluated global runoff from a set of 24 model runs (some were multiple ensembles from the same GCM, and global emission scenarios) archived for the IPCC AR4. They pre-screened model results by comparing model-estimated runoff from 20th century retrospective runs (GCM runs using estimated global emissions during the 20th century) with observations. The 12 models (total of 65 model runs, including multiple ensembles for some models) that had the lowest root means square error (RMSE) of runoff per unit area over 165 large river basins globally, for which observations were available, were retained for evaluation of 21st century projections. The rationale for retaining only those models with plausible reproductions of 20th century runoff globally was that future projections for models that are unable to reproduce past runoff characteristics may be called into question. For the same 12 models, a set of 24 model runs was extracted from the PCMDI archive. Each of the model runs was performed by the parent global modeling center using the IPCC A1B global emissions scenario, which reflects modest reductions in current global greenhouse gas emissions trends over the 21st century (somewhat similar to what has been termed "business as usual" scenarios in the past). There were 24 runs for the 12 models because multiple ensembles were available for some models.

Milly et al. (2005) show, in Figure 4.4, projected changes in runoff globally for the 24 model runs, as both mean changes in fractional runoff for the future period 2041 to 2060 relative to the period 1900 to 1970 in the same model's 20th century run, and in the difference between the number of models showing increases less the number showing decreases. In Figure 4.10, we show the same results, plotted by Dr. Milly's group at Geophysical Fluid Dynamics Laboratory (GFDL) for the 18 USGS water resources regions in the continental U.S., plus Alaska. In Figure 4.10, the shading identifies the median fractional change in runoff over the 24 model run pairs for 2041 to 2060 relative to 1901-1970 (using the median, rather than the mean as in the original paper, which results in slightly improved statistical behavior). Figure 4.10 shows that, taken over all 24 of the model run pairs, the projections are for increased runoff over the eastern U.S., gradually transitioning to little change in the Missouri and lower Mississippi, to substantial (median decreases in annual runoff approaching 20 percent) in the interior of the West (Colorado and Great Basin). Runoff changes along the West Coast (Pacific Northwest and California) are also negative, but smaller in absolute value than in the Western Interior basins.

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Figure 4.10 also shows, in a manner similar to Figure 4.4 in Milly et al. (2005), the consistency in the direction of changes across the 24 model pairs. In particular, the percentages given in the figure body are the fraction of model pairs for which the change was in the same direction as the indicated change in the model median. Hence, for Alaska, all 24 model pairs (100 percent) showed runoff increases, whereas for the Pacific Northwest, 16 pairs (67 percent) showed runoff decreases, whereas eight pairs (33 percent) showed runoff increases.

It is important to note several caveats and clarifications with respect to these results. First, the results for the various GCMs were interpolated to the USGS water resources regions, and some of the regions are small and are not well resolved by the GCMs (the highest resolution GCMs are somewhat less than three degrees latitude-longitude; most are somewhat coarser). Therefore, important spatial characteristics, such as mountain ranges in the western U.S., are only very approximately accounted for in these results. Second, there is, for some regions, considerable variability across the models as indicate above. In some cases (for instance, see the example for the Pacific Northwest above), there may be a substantial number of models that do not agree with the median change direction (on the other hand, it is impressive that 23 of 24 model pairs showed runoff decreases for the upper Colorado, which is the source of most of the runoff for the entire Colorado basin).

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In the remainder of this section, we review studies that have used essentially the same model results pool (although not necessarily the same specific group of models) as in Milly et al. (2005). These studies use downscaling methods (generally statistical, meaning that relationships between a higher spatial resolution grid mesh and the lower resolution GCM grid are "trained" using historical observations) to produce forcings (usually precipitation and temperature, as well as, in some cases, other variables downscaled from the GCMs) for a land hydrology model. The advantage of these "off line" approaches is that the higher resolution land scheme is able to resolve spatial features, such as topography in the western U.S., which may control runoff response. As just one example, in mountainous areas, there are strong seasonal differences in the period of maximum runoff generation and ET with elevation, and these differences are not captured at the coarse spatial resolution of

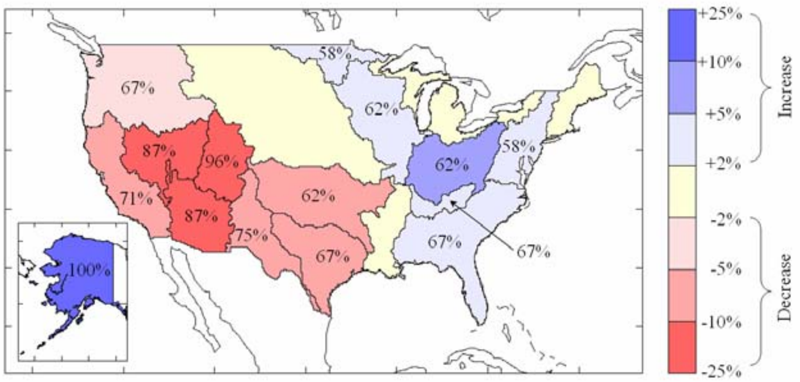

**Figure 4.10** Median changes in runoff interpolated to USGS water resources regions from Milly et al. (2005) from 24 pairs of GCM simulations for 2041-2060 relative to 1901-1970. Percentages are fraction of 24 runs for which differences had same sign as the 24-run median. Results replotted from Milly et al. (2005) by Dr. P.C.D. Milly, USGS.

the GCM. Therefore, the regional simulations may capture certain negative feedbacks in the response to global warming (e.g., warming leads to earlier snowmelt runoff, hence earlier maximum soil moisture, which occurs at a time when net radiation is lower, hence reducing ET, and arguably reducing the sensitivity of runoff to increasing temperatures). The downside of the off-line approaches, however, is that they do not, in general, preserve the water balance at the large (GCM) scale. At this point, the nature of high-resolution feedbacks to the large (continental and global) scale remains an area for research. We believe it is important to view results of the regional studies discussed below in the context of the continental scale results shown in Figure 4.10, however.

## 4.13 Hydrology and water resources

As in Section 2.4, we partition the United States into the four "super-regions" shown in Figure 4.7. For each of these super-regions, we review the relatively small number of recent studies that have evaluated hydrologic and water resources implications of the IPCC AR4 archived model results.

### ***Western United States***

Two recent studies have used IPCC AR4 multimodel ensembles to evaluate climate change effects on hydrology of the western U.S.  Maurer (2007) used statistical downscaling methods applied to eleven 21st century AR4 simulations to produce one-eighth degree latitude-longitude forcings for the VIC macroscale hydrology model over the Sacramento and San Joaquin River basins of California. The GCM runs used reflected SRES A2 and B1 emissions scenarios. They focused on four river basins draining to California's Central Valley from the Sierra Nevada, more or less along a transect from north to south:  The Feather, American, Tolumne, and Kings Rivers. Their work primarily emphasized the variability across the ensembles relative to current conditions, and statistical significance of implied future changes given natural variability. All ensembles for both emissions scenarios are warmer than the current climate, whereas changes in precipitation are much more variable from model to model – although in the ensemble mean there are increases in winter precipitation and decreases in spring precipitation. These result in shifts in peak runoff earlier in the year, most evident in the higher elevation basins in the southern part of the domain. Notwithstanding variability across the ensembles, these runoff shifts are generally statistically significant, i.e., outside the bounds of natural variability, especially later in the 21st century (three periods are considered:  2011 to 2041, 2041 to 2070, and 2071 to 2100).

Although not considered explicitly in the paper, the results presented for 2041-2070 and emissions scenario A2 (which generally yields larger precipitation and temperature changes than B1) imply changes in ensemble mean runoff for the four basins as follows: +6.8 percent (increase) for the Feather; +3.1 percent for the American, +2.2 percent for the Tolumne, and -3.4 percent for the Kings River. By comparison, the Milly et al. results (for emissions scenario A1B, which results in slightly less warming than the A2 scenario used by Maurer) indicate reductions in annual runoff of -5 to -10 percent for California.

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Christensen and Lettenmaier (2007) used similar methods to Maurer (2007) for the Colorado River basin. The eleven GCM scenarios, two emissions scenarios, and the statistical downscaling methods used in the two studies were identical. Christensen and Lettenmaier (2006) found that in the multimodel ensemble average for emission scenario A2 for 2040 to 2069, discharge for the Colorado River at Lees Ferry was predicted to decrease by about six percent, with a larger decrease of 11 percent indicated for 2070-2099. By comparison, the Milly et al. results suggest approximately 20 percent reductions in Colorado River runoff by mid-century.

The differences in the two downscaled studies as compared with the global results raise the question of why the off-line simulations (that is, simulations in which a hydrology model is forced with GCM output, rather than extracting hydrologic variables directly from a coupled GCM run) imply less severe runoff reductions (or in the case of three of the four California basins, increases rather than decreases) than do the GCM results. First, it must be said that the comparisons between Milly et al.'s (2005) global results and the off-line results from Maurer (2007) and Christensen and Lettenmaier (2007) should be interpreted with care; as indicated above, the emissions scenarios are slightly different, as are the models that make up the ensembles in the two studies. However, these factors do not seem likely to be the primary reason for the differences. As noted above, there is a negative feedback, reflected in the macroscale hydrology model results for snowmelt runoff under rising temperatures. Because this feedback is specific to the relatively high elevation headwaters portions of western U.S. watersheds, it is not well resolved at the GCM scale. However, while this feedback does appear to be present in the model results, it remains to evaluate whether the extent of the feedback in the model is consistent with observations. Second, spatial resolution issues also imply that precipitation (and temperature) gradients are less in the GCM than in either the off-line simulations or the true system, for instance the GCM resolution tends to "smear out" precipitation over a larger area, and hence nonlinear effects (such as much higher runoff generation efficiency at high elevations) are lost at the GCM scale. A third factor is the role of the seasonal shift (present in both California and the Colorado basin) from spring and summer to winter precipitation. Although this shift is present in the GCMs, the differential effect may well be amplified in the off-line, higher resolution runs, where increased winter precipitation leads to much larger increases in runoff than would the same amount of incremental precipitation spread uniformly over the entire basin. It should be emphasized, as indicated in Section 4.0, that these possible explanations should be cast as hypotheses, and not as definitive explanations.

### ***4.13.1 Central***

However, a general idea of potential impacts of climate change on the Central super-region can be obtained from the global results from Milly et al. (2005) as plotted to the USGS regions in Figure 4.9. This figure shows a general gradation in the ensemble mean from increased runoff toward the eastern part of the Central super-region (e.g., Ohio, which has the largest ensemble mean runoff increases within the continental U.S.), to neutral (slightly lower to slightly higher) in the upper Mississippi, to moderately negative in the Arkansas-Red. The concurrence among models is generally modest – i.e., typically

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at most two-thirds of the models are in agreement as to the direction of runoff changes, so even in the Ohio basin where the ensemble mean shows increased annual runoff of 10-25 percent, about one-third of the models show downward annual runoff (this contrasts, for instance, to the higher preponderance of models showing drying in the southwestern U.S.). Also, the results shown in Figure 4.9 are for annual runoff, and seasonal patterns vary. Due to increased summer evaporative stress, some (although certainly not all) models that predict increases in annual runoff may predict decreased summer runoff.

Jha et al. (2004) used a regional climate model to downscale a mid-21st century global simulation of the HADCM2 global climate model to the upper Mississippi River basin. This is a relatively old GCM simulation (not included in AR4), and as the authors note, is generally wetter and slightly cooler than other GCMs (and relative to the AR4 ensemble means shown in Figure 4.10). Their simulations showed that a 21-percent increase in future precipitation lead to a 50-percent net increase in surface water yield in the upper Mississippi River basin (this contrasts with the much smaller two to five percent increase in the multimodel mean runoff in Figure 4.10). Takle et al. (2006), using an ensemble of seven IPCC AR4 models, showed results that are more consistent with Figure 4.10 for the Upper Mississippi basin, specifically a multimodel mean increase in runoff of about three percent for the end of the 21st century. They found that these hydrologic changes would likely decrease sediment loading to streams, but that the implications for stream nitrate loading were indeterminate.

Schwartz et al. (2004) analyzed projections of Great Lakes levels associated produced by three GCMs run in the late 1990s for the IPCC TAR. Two of the three GCMs projected declines in lake levels, and one projected a slight increase. Declining lake levels were associated with increased harbor dredging costs, and some loss in vessel capacity. However, low confidence must be ascribed to the projected declines in lake levels, as FAR model output shows runoff changes in the multimodel mean (see Figure 4.10) to be on the margin between slightly negative and slightly positive, with nearly as many models projecting increases as decreases.

### *4.13.2 Northeast*

Several studies have evaluated potential future climate changes and impacts in the Northeast using climate model simulations performed for the IPCC's AR4. Hayhoe et al. (2006) produced climate scenarios for the Northeast (which they defined as the 9-state area from Pennsylvania through Maine) using output from nine atmosphere-ocean general circulation models (AOGCMs) archived in the IPCC AR4 data base. Three IPCC emissions scenarios were included: B1, A2, and A1F1, which represent low, moderately high, and high global greenhouse gas emissions over the next century. Results were presented as model ensemble averages for two time periods: 2035 to 2064 and 2070 to 2099. For the earlier period, the model ensemble averages for increases in temperature (°C) are from 2.1 to 2.9, and for increases in annual precipitation, five percent to eight percent. The authors also used hydrologic modeling methods to evaluate the corresponding range of hydrologic variables for the period 2035-2064. They found increases in ET ranging from +0.10 to +0.16 mm/day; increases from 0.09 to 0.12

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mm/day; advances in the timing of the peak spring flow centroid from five to eight days; and decrease in the mean number of snow days/month ranging from 1.7 to 2.2. The authors conclude that “the model-simulated trends in temperature and precipitation-related indicators …are reasonably consistent with both observed historical trends as well as a broad range of future model simulations.”

Rosenzweig et al. (in press) use a similar approach applied to a smaller geographic region to determine how a changing climate might impact the New York City watershed region, which feeds one of the largest water systems in the United States. The authors used five models, also from the IPCC AR4 archive. Three emissions scenarios were used: B2, A1B and A2, representing low, moderate and relatively high emissions, respectively (A2 is also used in Hayhoe et al. 2006). The scenarios were downscaled to the New York watershed region using a weighting procedure for adjacent AOGCM gridboxes, and were evaluated using observed data. For the 2050s, temperature increases (°F) in the range 2 to 5.5°F were indicated relative to the 1970-1999 baseline period, with a median range of 3.5 to 4°F. Precipitation changes ranged from -2.5 percent to +12.5 percent, compared to the baseline, with the median in the range five to 7.5 percent. This study also produced scenarios of local sea level rise, a factor that impacts groundwater through salt water intrusion, river withdrawals for water use through the encroachment of the salt front, and sewer systems of coastal cites and wastewater treatment facilities (typically located on the coasts) through higher sea levels and storm surges.

Several studies have been performed of potential future climate change and impacts that are relevant to the Ohio River basin, but none are based on the most recent IPCC AR4 scenarios with multiple models and emissions scenarios. McCabe and Wolock (2002b) used prescribed future changes in climate, in this case an increase in monthly temperatures of 4°C, to examine changes in mean annual precipitation minus mean annual potential evapotranspiration (P-PE) and potential evapotranspiration (PE). In the Ohio basin, the drop in the first is relatively low, and the increase in the latter is moderate, reflecting the greater impact on PE (and thus P-PE) in warm regions as compared to cooler regions. Another study used a 4°C benchmark to examine land use effects relating to climate change. It found that land use conversion from commercial to low-density residential use decreased runoff (Liu et al. 2000). The early scenarios cited by Easterling and Karl (2001) suggest decreases of up to 50 percent in the snow cover season in the 21st century, and it is possible that by the end of the 21st century sustained snow cover (more than 30 continuous days of snow cover) could disappear from the entire southern half of the Midwest. However, these scenario results and others given by Easterling and Karl are based on earlier GCMs, and a comprehensive multimodel, multi-emissions AR4 scenario evaluation for the Ohio needs to be undertaken.

### *4.13.3 South and Southeast KH*

No studies were identified that have assessed the implications of IPCC AR4 scenarios for the hydrology of the South and Southeast super-region. However, a general idea of potential impacts can be obtained from the global results of Milly et al. (2005) as plotted to the USGS regions in Figure 4.10. This figure shows a general gradation in the

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ensemble mean from east to west, with slightly increased runoff in the Southeast, near zero change in the lower Mississippi, and moderate decreases in the Texas drainages. As for the Central super-region, the concurrence among models is modest – for all regions within the South and Southeast super-region, two-thirds of the models are in agreement as to the direction of runoff changes, meaning that even for the Texas basins where moderate decreases in runoff are predicted in the ensemble mean, one-third of the models predicted increases. Furthermore, as for the Central sub-region, it should be emphasized that these results are for annual runoff, and shifts in the seasonality of runoff (generally higher summer evaporative stress will tend to decrease the fraction of runoff occurring in summer, and increase the fraction occurring at other times of the year, especially winter and spring, although this pattern certainly will not be present in all models).

### *4.13.4 Alaska*

No studies were identified that have assessed hydrologic changes for Alaska associated with the AR4 scenarios. However, Figure 4.10 shows that relatively large runoff increases are suggested in the global model output for Alaska, a result that is consistent with the generally higher increases in temperature expected toward the poles. This, in turn, results in higher precipitation, in part because of increased moisture holding capacity of the atmosphere at higher temperatures, which results, in most model physics, in increased precipitation. Large increases in runoff (10-25 percent, larger than anywhere in the continental U.S.) are predicted in the ensemble mean, and all models (100 percent) concur that runoff will increase over Alaska (note also that such 100 percent agreement is not present anywhere else in the continental U.S.). Nonetheless, it should be noted that Alaska is a large area that covers several much different climatic regions, so considerable subregional, as well as seasonal, variability in these results should be expected.

### *4.13.5 Hawaii*

No studies were identified that have assessed hydrologic changes for Hawaii associated with the AR4 scenarios. Furthermore, the Hawaiian Islands are far too small to be represented explicitly within the GCMs, so any results that are geographically appropriate to Hawaii are essentially for the ocean, and not the land. This is important as precipitation, and hence runoff, over this region are strongly affected by orography, and the nature of broader shifts in precipitation, as well as evaporative demand over land, interact in ways that can only be predicted accurately with regional scale modeling – an exercise that has not yet, to our knowledge, been undertaken.

## *4.14 Water quality*

The larger scale implications for increasing water temperature across the nation are illustrated by a couple of modeling studies. Eaton and Scheller (1996) calculated that cool-water and cold-water fishes will shift their distributions nationwide, and streams and rivers currently supporting salmonids may become inhospitable as temperatures cross critical thresholds (see Keleher and Rahel 1996). Stefan et al. (2001) simulated the

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warming effects of a doubling of $CO_2$ on 27 lake types (defined by combinations of three categories of depth, area, and nutrient enrichment) across the continental United States, and examined the responses of fish species to projected changes in lake temperature and dissolved oxygen. They found that suitable habitat would be reduced by 45 percent for coldwater fish, and 30 percent for cool-water fish, relative to historical conditions (before 1980). Shallow and medium-depth lakes (maximum depths of four meters and 13 meters, respectively) were most affected. Habitat for warm-water fish was projected to increase in all lake types investigated.

Warmer temperatures will also enhance algal production, and most likely the growth of nuisance species, such as bluegreen algae, which diminish water quality. Modeling results suggest that increased temperatures associated with climate warming will increase the abundance of bluegreen algae, and thus reduce water quality. This effect is exacerbated by nutrient loading, pointing to the importance of human response to climate change in mediating some aspects of water quality (Elliott et al. 2006). Increased temperatures, coupled with lower water volumes and increased nutrients, would further exacerbate the problem.

Because warmer waters support more production of algae, many lakes may become more eutrophic due to increased temperature alone, even if nutrient supply from the watershed remains unchanged. Warm, nutrient-rich waters tend to be dominated by nuisance algae, so water quality will decline in general under climate change (Murdoch et al. 2000; Poff et al. 2002). The possible increase in episodes of intense precipitation projected by some climate change models implies that nutrient loading to lakes from storm-related erosion could increase. Further, if freshwater inflows during the summer season also are reduced, the dissolved nutrients will be retained for a longer time in lakes, effectively resulting in an increase in productivity. These factors will independently and interactively contribute to a likely increase in algal productivity.

A warmer and dryer climate will reduce streamflows and increase water temperatures. Expected consequences would be a decrease in the amount of dissolved oxygen in surface waters and an increase in the concentration of nutrients and toxic chemicals due to a reduced flushing rate (Murdoch et al. 2000). Reduced inputs of dissolved organic carbon from watershed runoff into lakes can increase the clarity of lake surface waters and allow biological productivity to increase at depth and ultimately deplete oxygen levels and increase the hypolimnetic stress in deeper waters (Schindler et al. 1996).

A warmer-wetter climate could ameliorate poor water quality conditions in places where human-caused concentration of nutrients and pollutants currently degrades water quality (Murdoch et al. 2000). However, a wetter climate, characterized by greater storm intensity and long inter-storm duration, may act to episodically increase flushing of nutrients or toxins into freshwater habitats. For example, Curriero et al. (2001) reported that 68 percent of the 548 reported outbreaks of waterborne diseases during the period of 1948 to 1994 were statistically associated with the 80 percent increase in precipitation intensity, implying that increased precipitation intensity in the future carries a health risk via polluted runoff into surface waters.

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In general, an increase in extreme events will likely reduce water quality in substantial ways. More frequent floods and prolonged low flows would be expected to induce water quality problems through either episodic flushing of accumulated nutrients/toxins on the landscape followed by their retention in water bodies (Murdoch et al. 2000, Senhorst and Zwolsman 2005). Clearly, human actions in response to climate change will influence the ultimate affect of climate on water quality. In a modeling example, Chang (2004) used the HadCM2 scenario for five subbasins in southeastern Pennsylvania for projected changes in 2030 and found that climate change alone would slightly increase mean annual nitrogen and phosphorus loads, but concurrent urbanization would further increase N loading by 50 percent. This example illustrates how human land use activity interacts with warming climate and altered precipitation patterns to induce synergistic water quality changes.

### 4.14.1 Hydrology-landscape interactions

Across much of the continental U.S., annual precipitation increased during the 20th century, and especially in the second half of the century (the average precipitation increase was estimated as about seven percent by Groisman (2004)). Andreadis and Lettenmaier (2006) found that as a result, droughts generally became shorter, less frequent, and covered a smaller part of the country toward the end of the 20th century than toward the beginning (although they noted that the West and Southwest were apparent exceptions). Dai (2004) found that the fraction of the country under extreme (either wet or dry) conditions was increasing. Walter et al. (2004) found that ET has increased (by an average of about 55-millimeters) in the last 50 years in the conterminous U.S., but that stream discharge in the Colorado and Columbia River basins has decreased since 1950 (also coincidentally a period of major reservoir construction).

The most direct and observable connection between climate and terrestrial ecosystems is in life cycle timing of seasonal phenology, and in plant growth responses, annually in primary productivity, and decadally over changes in biogeographical range. These impacts on seasonality and primary productivity then cascade down to secondary producers and wildlife populations. The vegetation growing season as defined by continuous frost-free air temperatures has increased by, on average, two days/decade since 1948 in the conterminous U.S., with the largest change in the West, and with most of the increase related to earlier warming in the spring (Easterling 2002; Feng and Hu 2004). Global daily satellite data, available since 1981, has detected similar changes in earlier onset of spring “greenness” of 10-14 days in 19 years , particularly over temperate latitudes of the Northern Hemisphere (Myeni et al., 1997; Lucht et al. 2002). Honeysuckle first bloom dates have advanced 3.8 days/decade at phenology observation sites across the western United States (Cayan et al. 2001) and apple and grape leaf onset have advanced two days/decade at 72 sites in the northeastern U.S. (Wolfe et al. 2004).

As a result of these climatic and hydrologic changes, forest growth appears to be slowly accelerating ( <1 percent/decade ) in regions of the United States where tree growth is

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limited by low temperatures and short growing seasons, which are gradually being alleviated (McKenzie et al. 2001; Joos et al. 2002; Casperson et al. 2000). On the other hand, radial growth of white spruce in Alaska has decreased over the last 90 years due to increased drought stress on the dry, southern aspects they occupy (Barber et al. 2000). Semi-arid forests of the Southwest also showed a decreasing growth trend since 1895, which appears to be related to drought effects from warming temperatures (McKenzie 2001).

Climatic constraints on ecosystem activity can be generalized as variable limitations of temperature, water availability, and solar radiation, the relative impacts of which vary regionally and even locally (e.g., south vs north aspects) (Nemani et al. 2003; Jolly et al. 2005). Where a single climatic limiting factor clearly dominates, such as low temperature constraints on the growing season at high latitudes, or water limitations of deserts, ecosystem responses will be fairly predictable. However, where a seasonally changing mix of temperature and water constraints is possible, projection of ecosystem responses depends both on temperature trends, and the land surface water balance. While temperature warming trends for North America are well documented, the land water balance trends over the past half century suggest that roughly, the western half of the continent is getting drier and the eastern half wetter (see e.g. Andreadis and Lettenmaier 2006).

These changes have important implications for wildfires, especially in the western U.S., but elsewhere as well. From 1920 to 1980, the area burned in wildfires in the continental U.S. averaged about 13,000 km$^2$/yr. Since 1980, average annual burned area has almost doubled to 22,000 km$^2$ /yr, and three major fire years have exceeded 30,000km$^2$ (Schoennagel et al. 2004). The forested area burned from 1987-2003 is 6.7 times the area burned for the period 1970-1986, with a higher fraction burning at higher elevations (Westerling et al. 2006). Warming climate encourages wildfires by drying of the land surface, allowing more fire ignitions, and desiccated vegetation, and hot dry weather allow fires to grow exponentially more quickly, ultimately determining the area burned (Westerling et al. 2003). Relating climatic trends to fire activity is complicated by regional differences in seasonality of fire activity. Most fires occur in April to June in the Southwest and Southeast, and July to August in the Pacific Northwest and Alaska. Earlier snowmelt, longer growing seasons, and higher summer temperatures observed particularly in the western U.S. are synchronized with increase of wildfire activity, along with dead fuel buildup from previous decades of fire suppression activity (Westerling et al. 2006).

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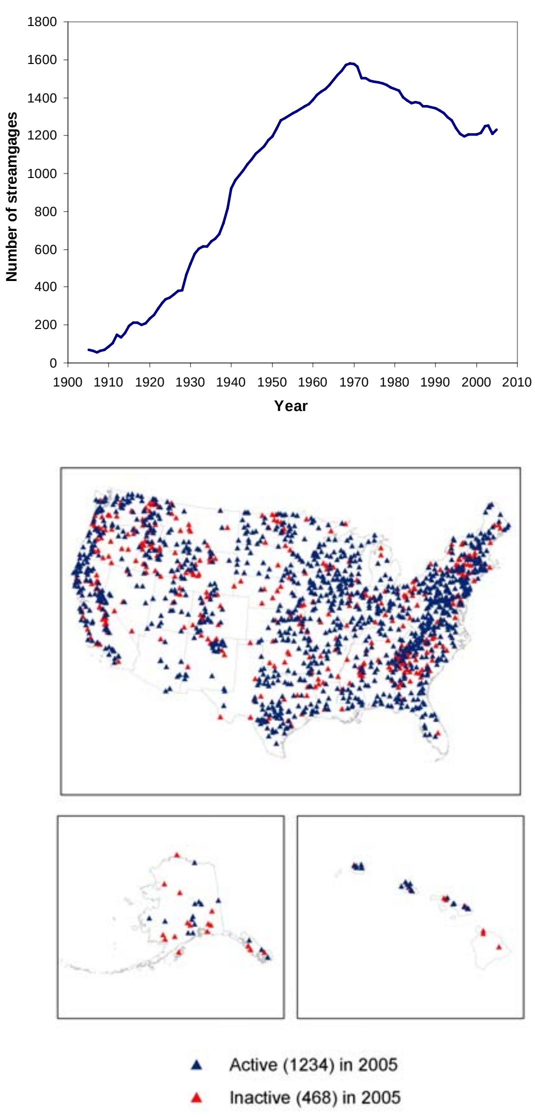

**Figure 4.11** Number of HCDN active stations 1905-2005 (upper panel), and location of discontinued stations as of 2005. Figure courtesy U.S. Geological Survey.

Insects and diseases are a natural part of all ecosystems; however, in forests periodic insect epidemics can erupt and kill millions of hectare of trees, providing dead, desiccated fuels for large wildfires. The dynamics of these epidemic outbreaks are related to insect life cycles that are tightly tied to climate fluctuations and trends (Williams and Liebhold 2002). Many of the northern insects have a two-year life cycle, and warmer winter temperatures now allow a higher percentage of overwintering larvae to survive. Recently, Volney and Flemming (2000) found that spruce budworm in Alaska have successfully completed their life cycle in one year, rather than two. Earlier warming spring temperatures allow a longer active growing season, and higher temperatures directly accelerate the physiology and biochemical kinetics of the life cycles of the insects (Logan et al. 2003). The mountain pine beetle has expanded its range in British Columbia into areas previously too cold to support their survival (Carroll et al. 2003). Multi-year droughts also reduce the available carbohydrate balance of trees, and their ability to generate defensive chemicals to repel insect attack (Logan et al. 2003).

## 4.14.2 Observing system

Essentially no aspect of the current hydrologic observing system was designed specifically for purposes of detecting climate change or its effects. However, a major purpose of the stream gauging network when it was first established in the late 1800s was to provide basic information on water resource availability, a major aspect of which was water supply. More specifically, stream gauges were installed to help determine the natural variability of runoff, from which decisions about how much water could be extracted from a reservoir or reservoirs of a given size could be made. Over time, as the era of dam construction waned in the 1960s and 1970s, the purpose of the stream gauge network shifted as well, to focus more on water management than on design. Arguably, the network now is configured more to address accounting issues (i.e., stations are situated above and below major water management structures and/or diversions) than to address questions of long-term change, which requires location of stations where the confounding effects of water management, as well as other anthropogenic influences, are minimized. The HCDN is a subset of the USGS stream gauges first identified by Langbein and Slack (1982), with (then) record lengths of at least 20 years, which were considered "suitable for the study of variation of surface-water conditions in relation to climate variation" (see also Slack et al. 1993). The stations are intended to be mostly free of major anthropogenic influences, especially regulation by dams. Originally, more than 1,600 stations were included in this network, however the number of active stations is now substantially smaller (see Figure 4.11) due to discontinuation of stations over the years. (In most cases, HCDN stations are not supported, at least in their entirety, by federal funds. The most common funding mechanism is the USGS Cooperative (Co-op) Program, in which states and local agencies share the cost of station operation. Although the Co-op program allows leveraging of federal funds and hence operation of a much larger stream gauging program than would be possible from federal funds alone, it makes the station network susceptible to short-term budget issues in the cooperating agencies, and the loss of stations indicated in Figure 4.11 is, in large part, the result of such issues.) It is important to note that essentially all of the studies reviewed in this chapter that have analyzed long-term streamflow trends in the United States (e.g., Lettenmaier et al. 1994; Lins and Slack, 1999, 2005; Garbrecht et al. 2004; Mauget 2004; and McCabe and Wolock 2002a, among others) have been based on subsets of the HCDN network, hence the absence of a long-term strategy is of critical concern, and needs to be addressed.

Another key hydrologic variable that especially affects the western U.S. (in addition to parts of the upper Midwest and Northeast) is snow, and specifically snow water equivalent or SWE. In the western U.S., SWE has historically been observed at manual snow courses, at which observations were mostly taken by Natural Resources Conservation Service (NRCS) (in California, observations have been taken by the Department of Water Resources). These observations are relatively costly to collect, as they involve travel to remote, mostly mountainous areas, and for this reason observations were collected only a few times per year (usually around April 1, at about the time of maximum snow accumulation. In the early 1980s, NRCS began to transition to an automated network of snow pillows (which essentially record the weight of snow on a pressure sensor, which is then converted to SWE). In California, there has been a similar transition from manual snow course to snow pillows, although California's Department of Water Resources continues to collect manual snow course data as well. The major advantage of the snow pillows is that data are essentially continuous, and the data transmission system provides additional channels that allow other variables (typically temperature and precipitation) to be transmitted as well. Analyses of long-term snow trends have faced the problem of merging the snow course and SNOTEL data. There are a variety of problems in so doing – for instance, thermodynamic properties of snow sensors are different from those of the surrounding natural landscape, and this can affect the rate of spring melt, and hence statistics like "last date of snow." Furthermore, standard protocol for snow course measurements is to average a number (usually at least 10) of manual cores taken along a transect – or transects – that cover a larger area than do the snow pillows, so the representation of local spatial variability differs (see e.g.

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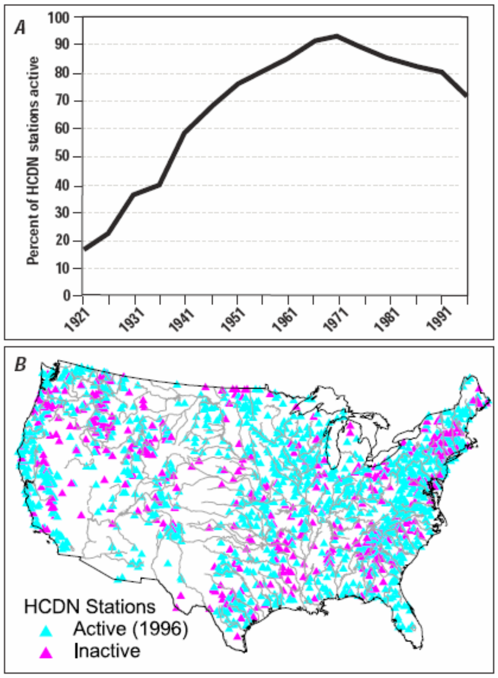

**Figure 4.12** Number of HCDN active stations 1921-1996, and location of discontinued stations (Figure courtesy USGS, to be updated).

Dressler et al. 2006). Pagano et al. (2004) have shown how the transition from manual snow courses to the SNOTEL network has affected the accuracy of seasonal streamflow forecasts across the west.

Like HCDN, the purpose of the snow course (and SNOTEL) networks was not monitoring of climate change and variability, but rather support of water management through provision of basic data used in water supply forecasting. However, as demands for information related to long-term climate-related shifts in snow properties have grown, the network(s) have begun to be used increasingly for these purposes. NRCS' National Water and Climate Center has initiated a study to evaluate effects of changes in SNOTEL instrumentation (e.g. metal or hypalon pillows), their comparison with manual snow courses, as well as systematic changes in snow courses and SNOTEL sites related to changes in vegetation and other site-specific characteristics, to provide better background information as to sources of systematic errors in long-term SWE records. A significant number of SNOTEL sites have been augmented with soil moisture and soil temperature sensors to improve spring runoff forecasts and basin-specific water management. The SNOTEL network also supports snow depth, relative humidity, wind speed/direction, and solar radiation measurements.

As noted in Section 4.4, evaporation pans do not provide a direct measurement of either actual or potential evaporation. Nonetheless, they provide a relatively uncomplicated measuring device, and the existing long-term records, taken together with the analyses discussed in Section 4.4, do provide a land surface data record that has some value. Pan evaporation data are most commonly collected at agricultural experiment stations, and are archived by the National Climatic Data Center.

Actual evaporation can be measured in several ways. One is weighing lysimeters, which, generally, are only practical for relatively short vegetation, such as crops, and are complicated by the disturbance to the surface inherent in their construction. The second is Bowen ratio sensors, which measure the gradient of humidity and air temperature close to the surface, the ratio of which, under an assumption that bulk transfer coefficients for latent and sensible heat are identical, is equal to the ratio of sensible to latent heat (the Bowen ratio). The Bowen ratio is used to partition the residual of net radiation and ground heat flux (both of which must be measured) into latent heat (equal to evapotranspiration, when adjusted by a proportionality factor) and sensible heat. Another method of estimating evapotranspiration (or more accurately, latent heat) directly is through eddy correlation, which essentially measures high frequency variations in the

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vertical component of wind and humidity, the product of which, when averaged over time, is the latent heat flux. Both the Bowen ratio and eddy correlation methods require some assumptions (see Shuttleworth, 1993), however the eddy correlation method, which is somewhat more direct, seems to have gained favor recently. The AmeriFlux network consists of about 200 stations across the continental U.S. at which evapotranspiration (mostly by the eddy correlation method) is measured. The longest term records at these stations are somewhat longer than 10 years – not nearly long enough for meaningful trend analysis. Furthermore, instrumentation has evolved over time, and there is a need for careful calibration and maintenance of the instrumentation, as well as quality control to assure, for instance, that the measured energy flux terms (some, but not all, Ameriflux stations measure downward and reflected solar and longwave radiation, as well as latent, sensible, and ground heat flux) balance. In the long-term, however, the quality (and reliability) of the instrumentation will improve, and this network appears to offer the best hope for direct, long-term measurements of evapotranspiration.

Soil moisture is a key indicator of the hydrologic state of the land system. However, until recently, there was no national soil moisture network, and the NRCS SCAN (Soil Climate and Analysis Network) dates only to 1998, and at present consists of fewer than 150 stations (although eventually, if fully funded, plans exist to create 1,000 stations). The most established soil moisture network is operated by the state of Illinois, and for about 25 years has produced data at about 20 stations statewide. More recently, the Oklahoma Mesonet network has observed soil moisture on a county by county basis in Oklahoma, and a few other state networks have been initiated. These networks will become increasingly important as time passes, particularly given concerns over possible effects of climate change on drought, and steps are needed to assure the longevity of a core network of soil moisture stations with an appropriate national distribution.

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# 5 Biodiversity

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## 5.1 Introduction and Framework

The potential impacts of climate change on biological diversity at all levels of biological and ecological organization have been of concern to the scientific community for some time (Lovejoy and Peterson 198x, IPCC 1990). However, in recent years, the scientific literature has additionally focused on a variety of observed changes in biodiversity, as well as continuing to explore the potential for changes due to changes in the physical climate system (IPCC 2002 2007; Millennium Ecosystem Assessment 2005). In this chapter, we summarize and evaluate the current knowledge-base on both observed and potential impacts with respect to the following topics:

- Changes in Species Distributions and Phenologies
- Changes in Community Composition
- Changes in Rare or Sensitive Ecosystems

In doing so, our focus is mainly, although not exclusively, on ecosystems within the United States. We also begin to explore the implications of changes in biological diversity for the provisions of ecosystem services (Millennium Ecosystem Assessment 2005), and finally, explore the implications of these findings for observation and monitoring systems.

## 5.2 Changes in Distribution and Phenologies in Terrestrial Ecosystems

### 5.2.1 Introduction

Terrestrial systems are already being demonstrably impacted by climate change. 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 (Walther 2002; Parmesan 2003). Using modeled climatic variables and observed species data, Root **(**2005**)** contends that human activities have contributed significantly to temperature changes, and that human-

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changed temperatures are associated with discernible changes in plant and animal traits. Evidence from two meta-analyses (143 studies, Root 2003; 1700 species, Parmesan 2003) and a synthesis (866 studies, Parmesan 2006) on species from a broad array of taxa suggest that there is a significant impact from recent climatic warming in the form of long-term, large-scale alteration of animal and plant populations (Root 2006, 2003; Parmesan 2003). If clear climatic and ecological signals are detectable above the background of climatic and ecological noise from a 0.6°C increase in global mean temperature, by 2050 the impacts on ecosystems will be dramatic (Root 2006).

### 5.2.2 Growing season length and net primary production

There is evidence indicating a significant lengthening of the growing season and higher net primary productivity (NPP) in the higher latitudes of North America where temperature increases are relatively high. Over the last 19 years, global satellite data indicates an earlier onset of spring across the temperate latitudes by 10-14 days (Myeni 2001; Lucht 2002 #7767), an increase in summer photosynthetic activity (NDVI satellite estimates, Myeni 2001)) and an increase in the amplitude of annual $CO_2$ cycle (Keeling, 1996), all supported by climatological and field observations. In the higher latitudes in Europe, researchers detected a lengthening of the growing season of 1.1 to 4.9 day per decade since 1951, based on an analysis of climate variables (Menzel 2003). Numerous field studies have documented consistent earlier leaf expansion (Wolfe 2005; Beaubien 2000) and earlier flowering (Schwartz 2000; Cayan 2001) across different species and ecosystem types. Accordingly, NPP in the continental U.S. increased nearly 10 percent between 1982-1998 (Boisvenue 2006). The largest increases in productivity have been documented in croplands and grasslands of the central U.S., as a consequence of favorable changes in water balance (Lobell 2002; Nemani 2002; Hicke 2004). Forest productivity, in contrast, generally limited by low temperature and short growing seasons in the higher latitudes and elevations, has been slowly increasing at less than one percent per decade (Boisvenue 2006; Joos 2002; McKenzie 2001; Caspersen 2000). The exception to this pattern is in forested regions that are subject to drought from climate warming, where growth rates have decreased since 1895 (McKenzie 2001). Recently, widespread mortality over 12,000 $km^2$ of lower elevational forest in the Southwest demonstrates the impacts of increased temperature and the associated multiyear drought (Breshears 2005) even though previous studies had found productivity at treeline had increased (Swetnam 1998). Disturbances created from the interaction of drought, pests, diseases, and fire are projected to have increasing impacts on forests and their future distributions (IPPC FER SPM 2007). These changes in forests and other ecosystems will cascade through trophic impacting other species.

## 5.3 *Biogeographical and phenological shifts*

Movement of species in regions of North America in response to climate warming is expected to result in shifts of species ranges poleward, and upward along elevational gradients (Parmesan 2006). Species differ greatly in their life-history strategies,

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physiological tolerances, and dispersal abilities, which underlie the high variability in detecting species responses to climate change. Many animals have evolved powerful mechanisms to regulate their physiology, thereby avoiding some of the direct influences of climate change and instead interact with climate change through indirect pathways involving their food source, habitat, and predators (Schneider 1996). Consequently, most distributional studies tend to focus on animals while phenological studies focus on plants. Although most studies tend to separate distributional and phenological effects of climate change, it is important to keep in mind that the two are not independent and interact with other changing variables to determine species impacts (Parmesan 2006). In addition, most of the observed species responses have described changes in species phenologies (Parmesan 2006). This section will cover both by major taxa type.

Parmesan (2006) describes three types of studies documenting shifts in species ranges: (1) those that measure the an entire species range, (2) those that infer large-scale range shifts from observations across small sections of the species' range, and (3) those that infer large-scale range shifts from small-scale change in species abundances within a local community. Although very few studies have been conducted at a scale the encompasses an entire species' range (amphibians, (Pounds, 1999, 2006), pikas, (Beever 2003) birds, (Dunn, 1999), and butterflies (Parmesan 2006, 1996), there is a growing body of evidence that have inferred large shifts in species range across a very broad array of taxa. In an analysis of 866 peer-reviewed papers exploring the ecological consequences of climate change, nearly 60 percent of the 1598 species studied exhibited shifts in their distributions and/or phenologies over the 20- and 140-year timeframe (Parmesan 2003). Field-based analyses of phenological responses of a wide variety of different species have reported shifts as great as 5.1 days per decade (Root 2003) with an average of 2.3 days per decade across all species (Parmesan 2003).

### 5.3.1 Migratory birds

For migratory birds, the timing of arrival on breeding territories and over-wintering grounds is an important determinant of reproductive success, survivorship, and fitness. Climate variability and on interannual and longer time scales change can alter phenology and range of migratory birds by influencing the time of arrival and/or the time of departure. The earlier onset of spring has consequences for the timing of migration and breeding in birds which evolved to match peak food availability (Visser 2006). We should expect that the timing of migration would track temporal shifts in food availability caused by changes in climate and the advancement of spring.

The phenology of migration to summer and wintering areas may be disrupted for long-distance, continental migrations as well regional local or elevational migrations. Since short-distance migrants respond to changes in meteorological cues whereas long-distance migrants rely on photoperiod, it has been assumed that the climate signature on changes in phenological cycles would be stronger in short distance than long distance migrants (Lehikoinen 2004). If true, this would lead to greater disruption in the timing of migration relative to food availability for long distance, continental migrants relative to short

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distance migrants. Recent studies of long-distance migration provide evidence to the contrary. In continental-scale study of bird phenology that covered the entire United States and Canadian breeding range of a tree swallow (*Tachycineta biocolor*) from 1959 to 1991, Dunn and Winkler documented a 9-day advancement of laying date which correlated with the changes in May temperatures (Winkler 2002; Dunn, 1999). In a study of the first arrival dates of 103 migrant bird species (long-distant, and very long-distant migrants) in the Northeast during the period 1951-1993 compared to 1903-1950, all migrating species arrived significantly earlier, but the birds wintering in the southern U.S. arrived on average 13 days earlier while birds wintering in South America arrived four days earlier (Butler 2003). Conversely, in a reversal of arrival order for short- and long-distance passerines, Jonzen (2006) showed that long-distance migrants have advanced their spring arrival into Scandinavia more than short-distance migrants, based on data from 1980 to 2004. Similarly, in a 42-year analysis of 65 species of migratory birds through Western Europe, researchers found autumn migration of birds wintering south of the Sahara had advanced while migrants wintering north of the Sahara delayed autumn migration (Jenni 2003).

As these studies suggest, when spring migration phenology changes, migrants may be showing a direct response to trends in weather or climatic patterns on the wintering ground and/or along the migration route or there may be indirect microevolutionary responses to the selection pressures for earlier breeding (Jonzen 2006). A climate change signature is apparent in the advancement of spring migration phenology (Root 2003) but the indirect effects may be more important than the direct effects of climate in determining the impact on species persistence and diversity. Indeed, there is no *a priori* reason to expect migrants and their respective food sources to shift their phenologies at the same rate. A differential shift will lead to mistimed reproduction in many species, including seasonally breeding birds. There may be significant consequences of such mistiming if bird populations are unable to adapt (Visser 2004). Phenological shifts in migration timing in response to climate change may lead to the failure of migratory birds to breed at the time of abundant food supply (Visser 2006; Visser 2005; Stenseth 2002), and, therefore, may have implications for population success if the shift is not synchronous with food supply availability. Understanding where climate change-induced mistiming will occur and their underlying mechanisms will be critical in assessing the impact of global climate change on the success of migratory birds(Visser 2005). The responses across species will not be uniform across their ranges, and are thus likely to be highly complex and dependent on species-specific traits, characteristics of local microhabitats, and aspects of local microclimates.

A study of spring arrival and departure dates of 20 trans-Saharan migratory bird species to the United Kingdom found an 8-day advance in the arrival and the departure time to the breeding grounds, but with no change in the residence time. The timing of arrival advanced in relation to increasing winter temperatures in sub-Saharan Africa, whereas the timing of departure advanced in response to elevated summer temperatures in their breeding ground (Cotton 2003). But, without an understanding of how this change correlates with phenology of the food resource, it is difficult to discern what the long-term consequences might be (Visser 2005).

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***Mismatches and extinctions***

Migratory birds have adapted their timing of reproduction to the timing of the food resources. A careful examination of food resource availability relative to spring arrival and egg-laying dates will aid in the understanding of impacts of climate change. There is a suite of responses that facilitate an adaptive phenological shift: a shift in egg-laying date or a shift in the period between laying of the eggs and hatching of the chicks. In a long-term study of the migratory pied flycatcher (*Ficedula hypoleuca*), researchers found that the peak of abundance of their food resource (caterpillars) has advanced in the last two decades and, in response, the birds have advanced their laying date. In years with an early caterpillar peak, the hatching date was advance and the clutch sizes were larger. In this case, populations of the flycatcher have declined by about 90 percent over the past two decades in areas, where the food for provisioning nestlings peaks early in the season but not in areas with a late food peak (Both 2006). Climate change will lead to changing selection pressures on a wide complex of traits (Both 2005). It is the mistiming of the migration arrival, the provisioning of food resources and the lay dates that drive population declines. Predicting the long-term effects of ecological constraints and interpreting changes in life-history traits requires a better understanding of both adaptive and demographic effects of climate change. Exploring the risk of extinction of populations empirically related to parameters characterizing population dynamics for a set of 38 bird populations, environmental stochasticity had the most immediate effect on the risk of extinction (Saether 2005), whereas the long-term persistence of the population was most strongly affected by the specific population growth rate. Research focused on both will aid in the understanding of the impacts of climate change.

### 5.3.2 Butterflies

Since temperature determines timing of migration and distribution, it is not surprising that many studies have documented changes in phenology of migration and significant shifts in latitudinal and elevational distribution of butterflies in response to current day warming (cite). The migration of butterflies in the spring is highly correlated with spring temperatures and with early springs. Researchers have documented many instances of earlier arrivals (26 of 35 species in the United Kingdom, (Roy 2000); 17 of 17 species in Spain, (Stefanescu 2004); and 16 0f 23 species in central California (Forister 2003). An analysis of 113-year record of nine migrating butterflies, and 20 migrating moths found increasing numbers of migrants with increasing temperature along the migration route in response to fluctuation in the North Atlantic Oscillation (Sparks 20059).

Butterflies are also exhibiting distributional and/or range shifts in response to warming. Across all studies included in her synthesis, Parmesan (2006) found 30-75 percent of species had expanded northward, less than 20 percent had contracted southward, and the remainder were stable (Parmesan 2006). In a sample of 35 non-migratory European butterflies, 63 percent have ranges that have shifted to the north by 35-240 km during this century and three percent have shifted to the south (Parmesan 1999). In North America,

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butterflies are experiencing both distributional shifts northward, with a contraction at the southern end of their historical range, and to higher elevations as climate changes. In a 1993-1996 recensus of Edith's checkspot butterfly (*Euphydryas editha*) populations, Parmesan et al. (1996) found that 40 percent of the populations below 2400 feet had become extinct despite the availability of suitable physical habitat and food supply, compared to only 15 percent extinct above the same elevation (Parmesan, 1996). An investigation of a skipper butterfly (*Atalopedes campestris*) found that 2-4°C warming had driven the northward range expansion over the past 50 years, driven by increases in winter temperatures (Crozier 2003, 2004). A study investigating the altitudinal and latitudinal movements of 51 British butterfly species related to climate warming found that species with northern and/or montane distributions have disappeared from low elevation sites, and colonized sites at higher elevations consistent with a climate warming, but found no evidence for a systematic shift northwards across all species (Hill 2002). A subsequent modeling exercise to project potential future distributions for the period 2070-2099 projects 65 and 24 percent declines in range sizes for northern and southern species, respectively (Hill 2002).

***Mismatches and Extinctions***

Like birds, changes in timing of migrations and distributions are likely to present resource mismatches that will influence population success and alter the probability of extinction. Predictions of climate-induced population extinctions are supported by geographic range shifts that correspond to climatic warming and a few studies have linked population extinctions directly to climate change. As populations of butterfly species become isolated by habitat loss, climate change is likely to cause local population extinctions. Modeling of butterfly distribution in the future under climate change found that while the potential existed to shift ranges northward under in response to warming, lack of habitat availability caused significant population declines (Hill 2002). Similarly, phenological asynchrony in a butterfly-host interactions in California led to population extinctions of the checkerspot butterfly (*E. editha*) during extreme drought and low-snowpack years (Singer, 1996; Thomas 1996; Ehrlich 1980; Singer, 1979). A modeling experiment of two populations of a checkerspot butterfly, suggested decline of the butterfly was hastened by increasing variability in precipitation associated with climate change. The changes in precipitation amplified population fluctuations leading to extinction in a region that allowed no distributional shifts because of persistent habitat fragmentation (McLaughlin 2002).

***Evolutionary change***

A study of the speckled wood butterfly (*Pararge aegeria*) in England, found evolutionary changes in dispersal were associated with reduced investment in reproduction, which affect the pattern and rate of expansion at range boundaries (Hughes 2003).

### 5.3.3 Wildlife and population contractions

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#### 1.1.1.28 Mammals

Mammals are likely to interact with climate through indirect pathways involving their food source, habitat and predators, perhaps more strongly than through direct effects on body temperature (Schneider and Root 2002). Climate change will likely alter the distribution and abundance of northern mammals through a combination of direct, abiotic effects (e.g., changes in temperature and precipitation) and indirect, biotic effects (e.g., changes in the abundance of resources, competitors, and predators).

#### 1.1.1.29 Amphibians

There is evidence that amphibian breeding is occurring earlier in some regions, and that global warming is likely the driving factor.(Beebee 2002; Blaustein 2001; Gibbs 2001). Some temperate-zone frog and toad populations show a trend toward breeding earlier, whereas others do not (Blaustein 2001). Statistical tests (Blaustein 2002) indicate that half of the 20 species examined by Beebee (1995), Reading (1998), Gibbs and Breisch (2001), and Blaustein et al. (2001) are breeding earlier. Of the half not exhibiting statistically significant earlier breeding, they are showing biologically important trends toward breeding earlier that, if continued, will likely become statistically significant (Blaustein 2002). When taken together, these important data suggest that global warming is indeed affecting amphibian breeding patterns in many species.

There is marked unevenness of climate-change effects on amphibian breeding. For example, *Bufo fowleri*, a late breeder, has bred progressively later in spring over the past 15 years on the north shore of Lake Erie (Blaustein 2001)

***Mismatches and extinctions***

***Evolutionary change***

## 5.4 Climate drivers (secular changes, changes invariability)

## 5.5 Impacts on services *<incomplete>*

Climate change and variability is very likely to have impacts on an array of ecosystem services in the United States in a variety of ways (cite).

#### 1.1.1.30 Recreational services

A changing climate and its impact on biodiversity will impact recreational services in the United States (cite). The United States has a $112 billion international tourism market and domestic outdoor recreation market (World Trade Organization 2002; Southwick Associates 2006).

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#### *1.1.1.31 Pollination services*

### 5.6.2 Needs

The ability of biologists to anticipate biotic responses is limited to some degree by lingering uncertainty on how regional climates will be affected by the complex, interactive effects of global changes in temperature, precipitation, and circulation patterns (IPCC 2007 FAR; Houghton 2001). But greater uncertainty lies in how species and their communities will respond. Temperature and seasonality are so fundamental to our understanding of the organization of biological communities, that further investigation of their effects can provide biological insights quite independent of issues related to climate change.

For insight into how climate change and variability over the next 40 years may impact species' phenologies and ranges, one can look at the affect that the PDO has had on ecological systems over the past few decades. By using time series of climatic indices and parameters of species populations, complex relationships between species and climate, researchers may be able to develop a deeper understanding of the ecological significance of the interactions

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## *5.8 Changes in Coastal and Near Shore Ecosystems* ***(focusing on the United States)***

Coastal and marine ecosystems have been the location of some of the most dramatic effects of climate change to date. In the tropics, coral bleaching and disease events have increased, and storm intensity has increased; in temperate regions, there are demonstrated range shifts and possible alterations of ocean currents and upwelling sites; and in the Arctic, there have been dramatic reductions in sea ice extent and thickness, as well as related coastal erosion. Marine species were the first to be listed as threatened species due to the effects of climate change. Coastal and near-shore ecosystems are vulnerable to a host of climate change-related effects, including increasing air and water temperatures, ocean acidification, altered terrestrial run-off patterns, altered currents, sea level rise, and altered human pressures due to these and other related changes (such as development, shipping, pollution, and adaptation strategy implementation).

This section will discuss some of the most prominent effects of climate change we have seen to date in the coastal and near-shore regions of the United States.

### 5.3.3 Coral Reefs

The United States has extensive coral reef ecosystems in both the Caribbean Sea and the Pacific Ocean. Coral reefs are very diverse ecosystems, home to a complex of species that support both local and global biodiversity and human societies. It has been estimated that coral reefs have a $30 billion value (Cesar et al. 2003). Corals and tropical regions where they live are experiencing increasing water temperatures, increasing storm intensity (Emmuel 2005), and a reduction in pH (Ravens et al. 2005), all while experiencing a host of other ongoing challenges from development/tourism, fishing, and pollution. The effects of climate change in marine systems is highlighted by the 2006 listing as Threatened under the Endangered Species Act of two species of corals in the Caribbean (Federal Register 2006). The major threats that motivated the listings of Elkhorn (*Acropora palmata*) and Staghorn (*A. cervicornis*) corals were disease, elevated sea surface temperatures, and hurricanes – all of which relate to climate change.

### *Increasing Temperature*

The El Niño-Southern Oscillation (ENSO) event of 1982-83 marked the first contemporary broad-scale coral reef bleaching and mortality event (Glynn 1984). Since then, there have been subsequent bleaching events including the 1997-98 ENSO. The rate of occurrence (annually in some cases), and almost global scale since the early 1980s is in stark contrast to the trend of the first half of the century in which bleaching events were localized and linked to local events (D'Elia 1991; Glynn 1993). From 1876-1979 only three bleaching events were recorded, whereas 60 are on record between 1980 and 1993 (Glynn 1993). Bleaching is considered to be a stress response caused primarily by increased water temperature (Glynn 1993) and synergistically enhanced by increased irradiance levels (Fitt and Warner 1995; Jokiel and Coles 1990; Lesser et al. 1990). Corals become stressed if exposed to slight increases in water temperature – temperatures need only increase by 1 to 2ºC over the average annual thermal maxima for days to weeks to result in a bleaching event (Hoegh-Guldberg 1999). Field studies have correlated increased temperatures with mass bleaching events (Brown 1997; Hoegh-Guldberg et al. 1997; Glynn 1993). Additionally, the National Oceanic and Atmospheric Administration (NOAA) "Hotspot" program (Goreau and Hayes 1994) predicted bleaching for most geographic regions where bleaching occurred in 1998, adding further weight to the assessment that elevated temperature is the primary trigger for bleaching (Hoegh-Guldberg 1999).

In 2005, the Caribbean basin saw unprecedented water temperatures and some very dramatic bleaching, followed by coral disease and mortality. The most dramatic monitored bleaching took place in the U.S. Virgin Islands, where National Park monitoring showed that at some sites 90 percent of the coral bleached. Then there appeared to be a period of recovery as water temperatures decreased. Unfortunately, this was short-lived as disease appeared in November on many of the previously bleached corals. To date there is an estimated 50 percent combined mortality from bleaching and disease in the Virgin Island National Park surveys. As of yet, there are no reports of recovery as amounts of mortality continue to increase (Eakin et al. In Prep). In the Florida Keys, equally massive bleaching was seen as imminent when temperatures exceeded nine-degree heating weeks in late August 2005 (NOAA Coral Reef Watch), and some bleaching was seen. But the arrival of Hurricanes Katrina and Rita reduced water temperatures and seemed to have provided some respite for corals in the Keys. However, the same pattern of disease was seen in the Keys in those corals that did bleach, with bleaching setting in around mid-August, followed by disease in early September (Brandt In Prep).

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Additionally as $CO_2$ concentrations increase in the atmosphere, more $CO_2$ is absorbed by the world's oceans. During the past 200 years, there has been a 30 percent increase in hydrogen ion concentration in the oceans and it is anticipated that this will increase by 300 percent by the end of this century (Ravens et al. 2005). There are predictions that oceans could become too acidic for corals – as well as other species – to produce calcium carbonate skeletons (Caldeira & Wickett 2003; Hoegh-Guldberg 2005; Kleypas et al. 1999).

Increasing sea surface temperatures are expected to continue as global temperatures rise. It is possible that these warmer waters are also increasing the intensity of the tropical storms in the region (Mann and Emmanuel 2006; Sriver and Huber 2006; Elsner 2006; Hoyos et al. 2006). As global temperatures rise, sea level will continue to rise providing additional challenges for corals. Increasing depths change light regimes and inundated land will potentially liberate additional nutrients and contaminants from terrestrial sources, especially agricultural and municipal.

### 5.3.4 Coastal Seashores

Some of the most valuable property in the United States is that located along seashores. This land is also vitally important for biodiversity as many species use the marine/terrestrial interface, including many endangered species such as sea turtles and sea birds. Projections for sea level rise by 2100 vary from 0.18 to 0.59 meters (±0.1-0.2) (IPCC 2007) to 0.5 to 1.4 m (Rahmstorf 2007). It has been estimated that a one-meter increase in sea level would lead to the loss of 65 percent of the coastal marshlands and swamps in the contiguous United States (Park et al. 1989). In addition to overt loss of land, there will also be shifts in "quality" of habitat in these regions. Prior to being inundated, coastal watershed will become more saline due to saltwater intrusion into both surface and groundwater.

Climate change will also 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. However, this will be a growing challenge for species that rely on coastal space or services for reproduction and feeding.

Some of this coastal habitat is on remote barrier islands, where the vulnerability to sea level rise is acute. In the Northwest Hawaiian Islands, recently made a National Monument, sea level rise is a threat to endangered beach nesting species and island endemics, including green sea turtles, Hawaiian monk seals, and the Laysan finch (Baker et al. 2006). Another example of an endangered island-locked species is the Key Deer, which is now limited to living on two islands in the Florida Keys. Their habitat is also at risk with most of the Keys at less than two meters above sea level. Median sea level rise

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coupled with storm surges would inundate most of the available habitat either permanently or episodically, either way further threatening this endangered species.

### 5.3.5 Arctic

Changes in the Arctic are resulting in substantial shifts in habitat, especially for sea ice-dependent species, where it is literally melting away. The sea ice, which provides habitat both below and above the ocean, has been in retreat for at least 30 years (Stroeve et al. 2005; Rothrock et al. 2003). It is estimated that a summer-ice-free Arctic Ocean is likely by the end of the century (Overpeck et al. 2005), with some models suggesting that this could occur as soon as 2040 (Holland et al. 2006).

Ice loss to date is already causing measurable changes in polar bear and ringed seal populations and fitness (Derocher et al. 2004; Ferguson et al. 2005; Stirling et al. 1999). There are also shifts in species ranges in the Arctic, both on land and in the water, and changes in phenology.

Many impacts are seen in coastal and near-shore ecosystems around the planet:

- Range shifts and phenological changes – Fish and planktonic species distribution in marine ecosystems are predominately determined by climatic variables (Hays et al. 2005; Roessig et al. 2004) and there is already evidence that marine species are moving poleward, and that timing of plankton blooms is shifting (Beaugrand et al. 2002; Hays et al. 2005; Richardson & Schoeman 2004). Similar patterns are seen with invertebrates and marine plants (CITATIONS).
- Invasive Species – Climate change will challenge thinking about invasive species as ranges shift and species are seen in new, but likely adjacent locales. Although most of the research beind done relates to terrestrial systems, those species more traditionally thought of as invasive species – i.e. more cosmopolitan species better adapted to dealing with a range of environmental parameters, especially temperature – are expected to have a competitive advantage as there is greater environmental variability and warming thermal regimes (Dukes and Mooney 1999; Carlton 2000).
- Mangroves and Sea Grasses – These coastal plants are found in tropical and temperate coastal regions around the world and both are already greatly degraded from other anthropogenic causes (CITATION). It has only been in recent years that their true value to coastal ecosystems was fully appreciated. Unfortunately climate change is expected to further compound their degradation. Mangroves will struggle as sea level rises, coastal storm-intensity increases, and terrestrial hydrological regimes change. Many sea grass species have limited thermal tolerances. In the Chesapeake Bay, for example, the dominant sea grass species (*Zostera marina*) is thought to be reaching its thermal maximum (Short and Neckles 1999), and this is playing a part in its decline.
- Currents and upwelling are expected to change as a result of climate change. Increased stratification and stability of the water column due to surface water

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warming can result in upwelling reductions, both near-shore and open-ocean (summarized in Soto 2002; Field et al. 2001). Decreased upwelling can decrease nutrient input to surface waters, reducing primary productivity. The food-web-level effects that such changes cause have been documented off the coast of Southern California following an abrupt and sustained increase in water temperature in the 1970s (reviewed in Field et al. 1999). Conversely, climate change may alter wind patterns in ways that increase offshore winds and thus upwelling (Bakun 1990). Additionally there may be altered current regimes including reduction in area and a coastward migration of shelf-tidal fronts, a reduction in strength of the Gulf Stream, and an increase in strength of the Labrador Current (Soto 2002). These changes will affect nutrient availability, species distribution and in some cases weather patterns.

## 5.4 Changes in Pests and Pathogens

### 5.4.1 Interactions of climate change with pests, pathogens, and invasive species

Increasing temperatures and other alterations in weather patterns (e.g., drought, storm events) resulting from climate change are likely to have significant effects on outbreaks of pests and pathogens in natural and managed systems, and are also expected to facilitate the establishment and spread of invasive alien species (IAS). Initially, the most noticeable changes in plant and animal communities will most likely result from direct effects of climate change (for example, range expansions of pathogens, and invasive plants). The longer term consequences, however, may be the result of indirect effects such as disruptions of trophic relationships or a species decline due to the loss of a mutualistic relationship (Parmesan 2006).

Interactions between increasing global temperature and pests and pathogens are of particular concern because of the rapid and sweeping changes these taxa can render. While it is still difficult to predict specifically how climate change will interact with insect pests, or plant and animal diseases, some recent events have provided glimpses into the kinds of impacts that might unfold.

#### *1.1.1.32 Mountain Pine Beetle Explosion*

The mountain pine beetle (*Dendroctonus ponderosae*) is a native species that has co-existed with western conifers for thousands of years, and plays an important role in the life cycle of western forests (Powell and Logan 2001). However, the magnitude of recent outbreaks is above historical levels and record numbers of Colorado's lodgepole pine (*Pinus contorta*) are being killed. For example, a recent outbreak caused the death of nearly five million lodgepole pines in Colorado in 2006, a four-fold increase from 2005. The infestation covers nearly half of all Colorado's forests. Such outbreaks are not confined to Colorado, but are also occurring in other parts of the United States and Canada, affecting tens of thousands of square miles of forest (http://cfs.nrcan.gc.ca/).

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A great deal of attention has been given to the role of climate change in these outbreaks, but some researchers are cautious about designating global warming as a causal factor (e.g., Romme et al. 2006). Several simultaneously occurring factors appear to explain the outbreaks. First, Colorado's lodgepole pines are primarily mature even-aged stands due to heavy logging of the region during settlement 100 years ago. Mountain pine beetles utilize mature trees and therefore they have an abundant food source. Second, long-term drought stresses trees and makes them more vulnerable to the beetles because they cannot effectively use their sap to defend themselves. Third, warmer summers provide additional stress and may increase growth rates of the insects, and, fourth, milder winters increase the chances of survival for the insect larvae (Romme et al. 2006). While there is not yet definitive proof that climate change is behind the high levels mountain pine beetle infestation, a recent study showed that over the last century Colorado's average temperatures have warmed (NRC 2007). It is therefore reasonable to expect warmer temperatures in the future may lead to similar or more intensive events than those that are now occurring.

### *1.1.1.33 Poleward migration of plant pests and pathogens*

Latitudinal gradients in plant defenses and herbivory are widely accepted but the basis for these defenses (i.e., genetic versus environment) are not fully understood. A potential outcome under warming global temperatures is a relatively rapid poleward migration of pests and pathogens, and a relatively slower rate of adaptation (e.g., increased defense against herbivory) for plants. Biogeographic theory predicts increased insect herbivory (i.e. greater loss of leaf area to herbivores) in the lower latitudes relative to higher latitudes (MacArthur 1972; Vermeij 1978; Jablonski 1993). As with the mountain pine beetle described above, higher population densities of other herbivorous insects and therefore herbivory occur because dormant season death (i.e., winter dieback) of herbivores is absent, or greatly reduced at warmer temperatures, and/or plant productivity is generally greater than at higher latitudes (Coley and Aide 1991; Coley and Barone 1996). Because of this greater herbivory, plants are thought to be better defended or otherwise less palatable at low latitudes as a result of natural selection (e.g., MacArthur 1972; Hay and Fenical 1988; Coley and Aide 1991; Coley and Barone 1996). Alternatively, plants at low latitudes could be better defended because high latitude populations have had fewer generations since the last glaciation to evolve such defenses (Fischer 1960).

### *1.1.1.34 Climate Change 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 world-wide, and decimating amphibian populations. A recent study by Pounds and colleagues (2006) showed that widespread amphibian extinction in the mountains of Costa Rica is positively linked to global climate change. To date, geographic range expansion of pathogens related to warming temperatures has been the most easily detected (Harvell et al. 2002), perhaps most readily for arthropod-borne infectious disease (Daszak et al.). However, a recent literature review found additional

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evidence gathered through field and laboratory studies that support hypotheses that latitudinal shifts of vectors and diseases are occurring under warming temperatures. Based on their review, Harvell et al. (2002) gathered evidence that:

- Arthropod vectors and parasites die or fail to develop below threshold temperatures
- Rates of vector reproduction, population growth, and biting increase (up to a limit) with increasing temperature; and
- Parasite development rates and period of infectivity increase with temperature.

Furthermore, Ward and Lafferty (2004) conducted an analysis that revealed that disease for some groups of marine species is increasing while others are not. Turtles, corals, mammals, urchins, and mollusks all showed increasing trends of disease, while none were detected for sea grasses, decapods, or sharks/rays. The authors note that the effects of increasing temperature on disease are complex, and can either increase or decrease disease depending on the pathogen. Nonetheless, the stress of increased temperatures may cause susceptibility of marine and terrestrial organisms to pathogens to increase, ultimately making outbreaks more frequent (Ward and Lafferty 2004).

It is important to note, however, that a range expansion of an invader may not always be simply explained by pointing to warming temperatures. For example, the northern expansion of the invasive European green crab (*Carcinus maenas*) in North America, from the Gulf of Maine to Cape Breton, Nova Scotia, was thought to have occurred because of warming sea temperatures, and/or adaptations of established more southerly populations to colder northern waters (Roman 2006). However, the application of molecular techniques to green crab populations in U.S. and Canadian waters revealed that introduction of new lineages of *C. maenas* to Nova Scotia from the northern end of its native range in Europe was more likely. These northern populations may be better adapted to the colder temperatures found in northern Nova Scotia, relative to more southerly waters (Roman 2006). Furthermore, the construction of a causeway and subsequent "super port" in the Strait of Canso, Nova Scotia, appear to be at the epicenter of the high diversity of new *C. maenas* haplotypes (Roman 2006).

### *1.1.1.35 Climate change and invasive plants*

Projected increases in $CO_2$ are expected to stimulate the growth of most plants species, and some invasive plants are expected to respond with greater growth rates than non-invasive plants (Dukes 2000; Ziska and George 2004; Moore 2004; Mooney et al. 2006). Some invasive plants may have higher growth rates, greater maximal photosynthetic rates relative to native plants under increased $CO_2$, but definitive evidence of a general benefit of $CO_2$ enrichment to invasive plants over natives has not emerged (Dukes and Mooney 1999). 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 (Vila et al. In Press).

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Finally, it is critical to recognize that other elements of climate change (e.g., nitrogen deposition, land conversion) will play a significant role in the success of invasive plants in the future, either alone or under elevated $CO_2$ (Vila et. al. In Press). For example, several studies have brought to light the role of increasing nitrogen availability and the success of invasive grass species (e.g., Huenneke et al. 1990; Brooks 2003). Disturbance at both global and local scales has been shown to be an important factor in facilitating species invasions (e.g., Sher and Hyatt 1999; Mooney and Hobbs 2001; D'Antonio and Meyerson 2002) and land conversion that occurred more than 100 years may play a role current invasions (Von Holle and Motzkin 2007). Interestingly, recent work by Hierro et al. (2006), which compared the effects of disturbance on *Centaurea solstitialis* in its native and introduced ranges, suggests that disturbance alone does not fully explain invasion success. Instead, it appears that, for *C. solstitialis*, it is the combination of disturbance and escape from soil pathogens in the native range that has encouraged invasion.

## 5.5 Climate change, marine fisheries and marine ecosystem change

The IGBP- GLOBEC program (GLOBal Ocean ECosystem Dynamics) was established in the early 1990s to investigate the potential impacts of global climate change on marine ecosystems. National programs were established in Europe (United Kingdom, France, Norway, Germany, Netherlands, Spain, Portugal, Italy, Turkey, and the Ukraine), North America (United States, Canada, and Mexico), South America (Peru, Chile, and Brazil) and the Far East (Japan, Korea, and China). The emphasis of all of these programs was on the coupling between physical forcing and biological responses in fisheries-rich ecosystems. All programs included long-term modeling and observation programs, as well as focused process studies. One of the challenges each program faced was that of unraveling the causes of recent changes in fisheries stocks to determine to what degree stock declines were due to fishing itself versus changes due to climate forcing? It was with varying degrees of success that each program was able to sort out these (sometime confounded) effects on fisheries. Regardless, clear linkages between climate variability, zooplankton (the forage base for many fisheries), and some fish stocks have been established by many of the GLOBEC national programs. Results shown below are the result of long time series of measurements of physical and biological variables. Without time series of ocean observations, study of impacts of climate variability on marine ecosystems would be far more difficult.

**Climate Regime Shifts**. It has been well established that the large, basin-scale atmospheric pressure systems that drive basin-scale winds can suddenly shift their location and intensity at decadal time scales, with dramatic impacts on winds and ocean circulation patterns. These low frequency oscillations are known as the North Atlantic Oscillation (NAO) and the PDO. Perhaps the greatest discovery of the past 10 years is that these shifts have dramatic impacts on marine ecosystems. The NAO, first discovered in the 1920s by Sir Gilbert Walker**,** refers to the fluctuations in the difference of atmospheric pressure between the Icelandic Low and the Azores High; these fluctuations control the strength and direction of westerly winds and storms across the North Atlantic. The NAO is one of the most important drivers of climate fluctuations in the North

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Atlantic and surrounding continents. When the NAO is in positive phase, stronger than normal westerly winds blow across the Atlantic, bringing moist air into Europe, resulting in cool summers, and mild winters with heavier, more frequent rainfall. When in negative phase, westerly winds are weaker than normal, temperature are more extreme in summer and winter, leading to heat waves, deep freezes, and reduced rainfall.

The NAO was in positive phase from 1910-1935, negative from 1935-1975, but then positive since 1975. It has been strongly positive since the 1980s. Increases in the strength of the winds, initiated in the late 1980s, resulted in dramatic impacts on Northeast Atlantic ecosystems. Examples include increased flow of oceanic water into the English Channel and North Sea, resulting in a northward shift in the distribution of zooplankton such that the zooplankton community became dominated by warm water species (Beaugrand 2004), with concomitant changes in fish communities from one dominated by whiting (hake) to one dominated by sprat (similar to a herring). Similar (and drastic) ecosystem changes are known for the Baltic Sea (Kenny and Mollman 2006), where dramatic changes in both zooplankton and fish communities were observed. Cod were replaced by sprat, and dominance in zooplankton switched from lipid-rich (and high bioenergetic content) species to lipid-poor species. Linkages between the NAO, zooplankton and fisheries have also been described for the Northwest Atlantic waters off eastern Canada and the United States. Pershing and Green (2007) report a decrease in salinity, and an increase in biomass of small copepods (zooplankton). They suggest that the recovery of the codfish populations, which collapsed in the early 1990s (presumably as a result of overfishing), may continue to be difficult due to negative changes in food chain structure of their forage base, the zooplankton.

In the North Pacific, the PDO refers to the east-west shifts in location and intensity of the Aleutian Low in winter (Mantua et al. 1997). When the PDO is in negative phase, the Aleutian Low sits over the western Pacific and is relatively weak; in positive phase it is centered over the Gulf of Alaska and has very deep low pressure. Shifts in location of the Aleutian Low results in changes in wind speed and direction and storm tracks. When in negative phase, winter winds tend to be more northerly, and winters are drier, whereas in positive phase, winter winds are usually southerly, and winters are wet. Changes in sign of the PDO have been noted in 1925 (to positive phase), 1947 (to negative phase), and 1977 (to positive phase).

Widespread ecological changes have also been discovered, including increased productivity of the Gulf of Alaska when the PDO is in positive phase, resulting in dramatic increases in salmon production (Mantua et al. 1997), and a reversal of demersal fish community dominance – from a community dominated by shrimps to one dominated by pollock (Anderson and Piatt, 1991). Associated changes to the California Current ecosystem include dramatic decreases in zooplankton (McGowan et al. 1998) and salmon (Pearcy 1991) when the PDO changed to positive phase in 1977. Recently the sign changes have occurred with a higher frequency: cool phase from 1999-2002 (Peterson and Schwing 2003) was interrupted by four year of warm phase (2003-2006). Zooplankton and salmon responded rapidly and positively to the switch to cool phase in 1999: the zooplankton changed to a cold-water community and salmon returns increased

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by nearly an order of magnitude. However, with the switch to warm phase in 2003, zooplankton and salmon populations collapsed (see http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm.

One of the most intriguing problems that GLOBEC programs in the Pacific investigated was that of understanding the causes of cycles in sardine and anchovy populations in the Pacific Ocean. There is also evidence that the large osciallations in abundances of sardine and anchovy populations are associated with PDO shifts, such that during positive (warm) phase, sardine stocks are favored but during negative (cool) phase, anchovy stocks dominate (e.g., Chavez et al. 2003).

**El Niño Events**. Another major driver of climate variability is the El Niño – Southern Oscillation (ENSO). The ENSO affects rainfall patterns in the South America and the Southeastern U.S. (causing droughts during La Niña events and excess rainfall during El Niño events). El Niño events also wreck havoc on zooplankton and fish stocks from Chile, north to Peru, then across the equator to Mexico, the United States, and Canada. Plankton and fish stocks collapse due to sudden warming of the waters (by 4 to 10°C), as well through poleward advection of tropical species into temperate zones. Impacts of ENSO activity is well-known and well-studied and is probably beyond the scope of this brief overview.

**Warming and acidification**. It has recently been noted that a general warming of the oceans is stressing coral reefs, particularly in the tropical Pacific; also, recent reports are suggesting that increases in $CO_2$ concentration are lower ocean pH, an additional stressor on coral reefs (Orr et al. 2005). Again, as with ENSO, this is a huge topic, that cannot be adequately reviewed here.

**Other climate-driven physical forces that affect marine ecosystems**. The following is only a listing of some of the problems that marine organisms are likely to face with continued global warming. The listing reflects processes that are likely to change significantly for waters of the northern California Current (off the Pacific Northwest), and is drawn from a document in preparation by the National Marine Fisheries Service that is summarizing potential impacts of global warming and climate change on the nation's fisheries of the US Exclusive Economic Zone (EEZ):

The California Current (CC) is designated by NOAA as one of eight "Large Marine Ecosystems" (LME) within the United States EEZ. However, one should not view the CCLME as a homogenous body of water, which contains one "large" ecosystem because the current is typified by latitudinal gradients in both physical forcing and biological response. The northern end of the current is dominated by strong seasonal variability in winds, temperature, upwelling, plankton production and the spawning times of many fishes, whereas the southern end of the current has much less seasonal variability in these parameters. For planktonic organisms and some fish species, the northern end of the Current is dominated by sub-arctic boreal fauna, whereas the southern end is dominated by tropical and sub-tropical species. Faunal boundaries, i.e., regions where rapid changes in species composition are observed, are known for the waters between Cape Blanco

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Oregon/Cape Mendocino California, and in the vicinity of Point Conception California. Higher trophic-level organisms often take advantage of the strong seasonal cycles of production in the north by migrating to northern waters during the summer to feed. Animals that exhibit this behavior include pelagic seabirds, such as black-footed albatross and sooty shearwaters, fishes such as Pacific whiting and sardines, and gray and humpback whales

Climate and ecosystem studies in the North Pacific have been assigned a high priority by NOAA because climate signals in this region are quite strong. During the past 10 years, the North Pacific has seen two El Niño events (1997/98 2002/03), one La Niña event (1999), a four-year climate regime shift to a cold phase from 1999 until late 2002, followed by a four-year shift to warm phase from 2002 until 2006. The response of ocean conditions, plankton and fish to these events is well documented in the scientific literature. The biological responses are often so strong that the animals themselves often give early warning of impending events and may be more capable of providing early indications of climate change than projections made purely from physical variables.

### 5.5.1 Observed and Projected Impacts

Based on long-term observation records, global climate models, regional climate models, and first principles, there is a general consensus on the following scenarios of climate change for the northern California Current:

- Snowpack & Rainfall – Warmer air temperatures will result in more precipitation and less snowpack per unit of precipitation. Potential changes in rainfall and snowpack, for example, are likely to increase winter and spring runoff but decrease summer runoff. The current system of hydropower generation and water storage will become less suitable to this changed pattern, but capital investments in the system can mitigate some of those effects. This may change the way the freshwater of the Columbia and Sacramento Rivers is managed, which in turn may affect the way salmon and estuarine-dependent species are managed.

- Increased Water Temperature – Warmer water temperatures will also affect freshwater salmon habitats, by reducing habitat opportunity on both spatial and seasonal time scales. In oceanic habitats, the southern boundaries of salmon habitat will likely shift northward.

- Water Column Stratification – Warmer air temperatures may lead to increased stratification of the coastal waters off the Pacific Northwest as well as the Gulf of Alaska; moreover, increased melting of glaciers in the Gulf of Alaska, coupled with warmer sea surface temperatures will result in increased stratification of the Gulf. Since some of the source waters that supply the northern California Current (NCC) originate in the Gulf of Alaska, more stratified source waters will contribute to increased stratification of coastal waters of the NCC.

- Freshwater Input – Climate models project the 21st century will feature greater

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annual precipitation in the Pacific Northwest, extreme winter precipitation events in California, and a more rapid spring melt leading to a shorter, more intense spring period of river flow and freshwater discharge. This will greatly alter coastal stratification, plume formation and evolution, and the transport of anadramous populations.

- Upwelling Winds – Coastal upwelling may become stronger due to greater contrasts between heating of the land (resulting in low atmospheric pressure) and heating of the ocean. That is, soils heat much faster than water thus we will have deeper lows over land in summer and higher highs over the ocean, resulting in higher wind speeds and the potential for more upwelling.

- Upwelling of Nutrient-rich Water – Even though northward winds that cause coastal upwelling are likely to increase in magnitude, we do not know if these winds will be able to over-ride increased water column stratification. That is, the winds may not be able to mix this light buoyant water or transport it offshore, resulting in the inability of the cold nutrient-rich water to be brought to the sea surface. Thus, phytoplankton blooms may not be as intense, and results will be transmittal of negative effects up the food chain.

- Shifts in Seasonal Cycles of Production – Should the increased-upwelling scenario prove to be true, then it is likely that the upwelling season will begin earlier and continue longer in each year. Animals that migrate within the California Current to take advantage of feeding opportunities associated with the seasonal cycle of production (such as whiting, sardines, shearwaters, loggerhead turtles, Grey Whales) may find that their migrations will have to be timed to an earlier arrival at the feeding grounds. Similarly, fish and sea birds whose spawning, breeding, or nesting coincides with peaks in seasonal cycles of production may have to make adjustments in the timing of such activities.

- Phytoplankton Species Composition – The long-term observations program in Monterey Bay is suggesting that as a result of increased stratification, the phytoplankton community is changing from one dominated by diatoms to one dominated by dinoflagellates. Although we do not know what impact this might have on zooplankton grazers, it is clear that diatoms are the primary source of lipids, which contribute to lipid- and energy-rich food chains. There is no similar information available from other regions of the California Current.

- Zooplankton Species Composition – Warm ocean conditions lead to a community of zooplankton that is subtropical in origin whereas cold water conditions result in a cold water community. The dominant cold-water zooplankton species are large lipid-rich species, which result in a food chain of higher bioenergetic content. The opposite case is also true – warm-water species are small and do not have high lipid reserves.

- Northward Shifts in Distribution – Generally warmer conditions will mean a

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northward shift in the distribution of most pelagic species, and possibly the creation of reproductive populations in new regions. The existing faunal boundaries are likely to remain as strong faunal boundaries, but their resiliency to shifts in ocean conditions due to global climate change is not known. However, there is considerable heterogeneity in factors such as upwelling and climate along coastal regions that can complicate this generalized response for benthic species.

- Lower Productivity – It is generally accepted that the future climate will be warmer, and the upper ocean will be on average more stratified. This will make upwelling more difficult and lower primary productivity in the CC. In the northernmost regions, areas where production is light limited may see higher productivity.

- Greater Atmospheric and Oceanic Variability – One of the likely consequences of global climate change will be a more volatile climate with greater extreme events on intraseasonal-to-interannual scales. For the CC, this will mean more frequent and severe winter storms, with greater wind mixing, higher waves, and coastal erosion, and more extreme precipitation events and years, which would impact coastal circulation and stratification.

- ENSO – Some global climate models predict a higher frequency of El Niño events. If true, primary and secondary production will be greatly reduced in the northern California Current, with negative effects transmitted up the food chain.

- Decadal Variability (Regime Shifts) – Most models project roughly the same timing and frequency of decadal variability in the North Pacific under the impacts of global warming. However, combined with the global warming trend, the CC is likely to experience a greater frequency of years consistent with historical periods of lower productivity (e.g., positive PDO values). We know from ongoing observations that a positive PDO and warmer ocean result in dominance of small, warm-water zooplankton (which are lipid-depleted), which may result in food chains with lower bioenergetic content. By about 2030, it is expected that the *minima* in decadal regimes will be *above* the historical mean of the 20th century (i.e., the greenhouse gas warming trend will be as large as natural variability).

- Impacts on Humans in Coastal Communities – Humans derive ecosystem goods and services from the California Current. Predicting the effects of global climate change on human communities is complicated by the ability of humans to adapt to and mitigate those changes. If global climate change affects the location of commercial and recreation marine resources, for example, communities with locational advantages today are likely to suffer while other communities may gain those locational advantages. If the overall level of those resources falls, coastal communities as a whole are likely to experience negative effects. Also, sea level rise, will clearly impact development of coastal communities, particularly land developed in low-lying areas, and dock facilities.

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- Surprises – All of the global climate models predict increased variability in physical forcing. That could translate into problems for living marine resources of the Pacific Northwest if the past three years are any guide. The summer of 2005 was characterized by a three-month delay to the start of the upwelling season resulting in a lack of significant plankton production until August (rather than the usual April-May time period). Thus, fish, birds, and mammals that relied upon plankton production occurring at the normal time experienced massive recruitment failure. In contrast, the summer of 2006 had some of the strongest upwelling winds on record, yet many species again experienced recruitment failure, in part because there was a one-month period of no winds (mid-May to mid-June) that occurred at the time when many bird and fish species are recruiting. The year 2007 experienced a very early transition to a summer state (February), but intense storms may have erased that signature. Regardless, the ocean has been very cold during the winter of 2006-2007, and plankton production this year could be very high. But will anomalous storms interrupt this potential? Are we in for another surprise this summer?

## *5.6 Particular Sensitive Systems*

### 5.6.1 Impacts of climate change on montane ecosystems

Temperate montane ecosystems are characterized by cooler temperatures and often increased precipitation compared to surrounding lowlands. Consequently, much of the precipitation falls in the form of snow, which serves to insulate the ground from freezing air temperatures, stores water that will be released as the snow melts during the following growing season, and triggers vertical migration by animal species that can’t survive in deep snow. Changes in historical patterns of snowfall and snowpack are predicted as a consequence of global climate change, in part due to changes in spatial patterns of precipitation, and in part due to the warming that will result in more precipitation falling as rain rather than snow (Beniston and Fox 1996; MacCracken et al. 2001). Areas that historically had most of their annual precipitation as snow are now seeing more of it as rain; documentation of this trend comes from the Sierra Mountains, where Johnson found from analysis of a 28-year dataset (Johnson 1998) that below 2400 meters, less snow is accumulating and it is melting earlier. Diaz et al. (2003) also reported that all the major continental mountain chains exhibit upward shifts in the height of the freezing level surface over the past three to five decades. Increased variation in precipitation and temperatures is also predicted by climate change models, and Johnson (1998) also found that “Higher elevations exhibit greater variability, with most stations accumulating more snow and melting earlier. This could be the result of warmer air masses having higher moisture contents."

In addition to the influences of global climate change, which could affect both precipitation and temperature, regional effects can be important. For example, in the

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Colorado Rocky Mountains there are significant effects of the ENSO and North Pacific Oscillation (PDO) on winter precipitation. ENSO has also been shown to cause changes in freezing level in the American Cordillera (Diaz et al. 2003). Of course, all downstream water flows from headwaters in mountain areas are also affected by the variation in both timing and quantity of snowmelt (e.g., Karamouz and Zahraie 2004).

These environmental changes are also resulting in the disappearance of glaciers in most montane areas around the world. The changes in patterns and abundance of melt water from these glaciers have significant implications for the sixth of the world's population that is dependent upon glaciers and melting snowpack for water supplies (Barnett et al. 2005). Plant and animal communities are also affected as glaciers recede, exposing new terrain for colonization in an ongoing process of succession (e.g., for spider communities, see (Gobbi et al. 2006)). One group of organisms whose reproductive phenology is closely tied to snowmelt is amphibians, for which this environmental cue is apparently more important than temperature (Corn 2003). Hibernating and migratory species that reproduce at high altitudes during the summer are also affected by the 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 (Inouye et al. 2000). Species such as deer, bighorn sheep, and elk, which move to lower altitudes for the winter, may also be affected by changing temporal patterns of snowpack formation and disappearance.

The annual disappearance of snowpack is the environmental cue that marks the beginning of the growing season in most montane environments. Thus it is not surprising that flowering phenology has been advancing in these habitats (Inouye and Wielgolaski 2003), as well as others at lower altitudes, mirroring what is going on at higher latitudes (Wielgolaski and Inouye 2003). There is a very strong correlation between the timing of snowmelt, which integrates snowpack depth and spring air temperatures, and the beginning of flowering by wildflowers in the Colorado Rocky Mountains (e.g., Inouye et al. 2002, 2003). And for some wildflowers, there is also a strong correlation between the depth of snowpack during the previous winter and the abundance of flowers produced (Inouye et al. 2002; Saavedra et al. 2003). The abundance of flowers can have effects on a variety of consumers, including pollinators (Inouye et al. 1991), herbivores, seed predators, and parasitoids, all of which are dependent on flowers, fruits, or seeds.

An unexpected consequence of earlier snowmelt in the Rocky Mountains has been the increased frequency of frost damage to montane plants, including the loss of new growth on conifer trees, of fruits on some plants such as *Erythronium grandiflorum* (glacier lilies), and of flower buds of other wildflowers (e.g., *Delphinium* spp., *Helianthella quinquenervis*, etc.) (Inouye 2007). Although most of these species are long-lived perennials, as the number of years in which frost damage has negative consequences on recruitment increases, significant demographic consequences may result. These and other responses to the changing montane environment are predicted to result in loss of some species at lower altitudes, and migration of others to higher altitudes. Evidence that this is already happening comes from studies in both North America (at least on a latitudinal scale, Lesica and McCune 2004) and Europe (Grabherr et al. 1994). It is predicted that

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some animal species may also respond by moving up in altitude, and preliminary evidence suggests that some bumble bee (*Bombus*) species in Colorado have moved as much as a couple of thousand feet over the past 30 years (J. Thomson, personal communication).

### 5.6.2 Polar bears in a changing climate

Approximately 150,000 to 250,000 years ago, a lineage of brown bears (*Ursus arctos*) diverged into the lineage that led to the brown bears found today in the Alexander Archipelago of southeastern Alaska, and another that led to the polar bear (*Ursus maritimus*) (Cronin et al. 1991; Talbot and Shields 1996; Waits et al. 1998). The latter form evolved rapidly after colonizing the sea ice environment of the Arctic Ocean, and had developed the distinctive morphology of modern polar bears by 20,000 to 40,000 years ago (Stanley 1979; Talbot and Shields 1996). The bears' invasion of this novel environment was stimulated by an abundance of seals, which had colonized the region earlier in the Pleistocene (Demẻrẻ et al. 2003; Lister 2004). Adapting to the sea ice environment and a dependence on seals – especially ringed seals (*Pusa hispida*) – exerted strong selection on the morphology, physiology, and behavior of polar bears.

Morphological adaptations to the sea ice environment include dense, white fur over most of the body (including between foot pads), with hollow guard hairs; short, highly curved claws; and dentition specialized for carnivory. Physiologically, polar bears are extremely well adapted to feed on a diet high in fat; store fat for later future energy needs; and enter and sustain periods of reduced metabolism whenever food is in short supply (Derocher et al. 1990; Atkinson and Ramsay 1995). Feeding success is strongly related to ice conditions; when stable ice is over productive shelf waters, polar bears can feed throughout the year on their primary prey, ringed seals (Stirling and McEwan 1975; Stirling and Smith 1975; Stirling and Archibald 1977; Amstrup and DeMaster 1988; Amstrup et al. 2000). Less frequently, they feed on other marine mammals (Smith 1980, 1985; Calvert and Stirling 1990) and even more rarely on terrestrial foods (Lunn and Stirling 1985; Derocher et al. 1993). Polar bears exhibit the behavioral plasticity typical of top-level predators, and they are adept at capturing seals from the ice (Stirling 1974; Stirling and Derocher 1993).

Today, an estimated 20,000 to 25,000 polar bears live in 19 apparently discrete populations distributed around the circumpolar Arctic (IUCN Polar Bear Specialists Group 2005). Their overall distribution largely matches that of ringed seals, which inhabit all seasonally ice-covered seas in the Northern Hemisphere (Scheffer 1958; King 1983), an area extending to approximately 15,000,000 km$^2$. Polar bears are not regularly found, however, in some of the marginal seas (e.g., the Okhotsk Sea) inhabited by ringed seals. The broad distribution of their seal prey is reflected in the home ranges of polar bears that, averaging over 125,000 km$^2$, are more than 200 times larger than the averages for terrestrial carnivores of similar size (Durner and Amstrup 1995; Ferguson et al. 1999). Most polar bear populations expand and contract their range seasonally with the distribution of sea ice, and they spend most of year on the ice (Stirling and Smith 1975;

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Garner et al. 1994). Most populations, however, retain their ancestral tie to the terrestrial environment for denning, although denning on the sea ice is common among the bears of the Beaufort and Chukchi seas (Harrington 1968; Stirling and Andriashek 1992; Amstrup and Durner 1994; Messeir et al. 1994; Durner et al. 2003). Dens on land and on ice are excavated in snow drifts, the stability and predictability of which are essential to cub survival (Blix and Lentfer 1979; Ramsay and Stirling 1988, 1990; Clarkson and Irish 1991).

The rapid rates of warming in the Arctic observed in recent decades and projected for at least the next century are dramatically reducing the snow and ice covers that provide denning and foraging habitat for polar bears (Roots 1989; Overpeck et al. 1997; Serreze et al. 2000; Stroeve et al. 2007). These changes to their environment will exert new, strong selection pressures on polar bears. Adaptive traits reflect selection by past environments, and the time needed to adapt to new environments depends on genetic diversity in populations, the intensity of selection, and the pace of change. Genetic diversity among polar bears is evident in the 19 putative populations, suggesting some scope for adaptation within the species as a whole even if some populations will be at greater risk than others. On the other hand, the nature of the environmental change affecting critical features of polar bears' breeding and foraging habitats, and the rapid pace of change relative to the bears' long generation time (circa 15 years) do not favor successful adaptation.

The most obvious change to breeding habitats is the reduction in the snow cover on which successful denning depends (Blix and Lenter 1979; Amstrup and Gardner 1994; Messier et al. 1994; Durner et al. 2003). Female polar bears hibernate for four to five months per year in snow dens in which they give birth to cubs, typically twins, each weighing just over 0.5 kg (Blix and Lentfer 1979). The small cubs depend on snow cover to maintain thermal neutrality. Whether it remains within the genetic scope of polar bears to revert to the ancestral habit of rearing in earthen dens is unknown.

Changes in the foraging habitat that will entail new selection pressures include seasonal mismatches between the energetic demands of reproduction and prey availability; changes in prey abundance; changes in access to prey; and changes in community structure.

Emergence of female and young polar bears from dens in the spring coincides with the ringed seal's birthing season, and the newly emerged bears depend on catching and consuming young seals to recover from months of fasting (Stirling and Øritsland 1995). That coincidence may be disrupted by changes in timing and duration of snow and ice cover. Such mismatches between reproductive cycles and food availability are increasingly recognized as a means by which animal populations are impacted by climate change (Stenseth and Mysterud 2002; Stenseth et al. 2002; Walther et al. 2002).

Recognized as the most abundant of northern seals, ringed seal populations also may decline as the sea ice habitat changes (Stirling and Derocher 1993; Kelly 2001). Like polar bears, ringed seals depend on snow caves for rearing their young, and increasingly

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early snow melts have led to high rates of seal mortality due to hypothermia and predation (Lydersen and Smith 1989; Kelly 2001; Stirling and Smith 2004). Walruses (*Odobenus* rosmarus) and bearded seals (*Erignathus barbatus*) can also be important prey of polar bears, and the ecology of these pinnipeds is also tightly coupled to the sea ice environment, such that their populations are vulnerable to reductions in ice cover (Tynan and DeMaster 1997; Kelly 2001; Grebmeier et al. 2006).

The polar bear's ability to capture seals depends on the presence of ice. In that habitat, bears take advantage of the fact that seals must surface to breathe in limited openings in the ice cover. In the open ocean, however, bears lack a hunting platform, seals are not restricted in where they can surface, and successful predation is exceedingly rare (Furnell and Oolooyuk 1980). Only in ice-covered waters are bears regularly successful at hunting seals. When restricted to shorelines, bears feed little if at all, and terrestrial foods are thought to be of little significance to polar bears (Lunn and Stirling 1985; Ramsay and Hobson 1991). Predation on reindeer observed in Svalbard, however, indicates that polar bears have some capacity to switch to alternate prey (Derocher et al. 2000).

Seal and other prey populations also will be impacted by fundamental changes in the fate of primary production. For example, in the Bering and Chukchi seas, the reduction in sea ice cover alters the physical oceanography in ways that diminish carbon flow to the benthos, and increase carbon recycling in pelagic communities (Grebmeier et al. 2006). The resultant shift in community structure will include higher trophic levels. The exact composition of future communities is not known, nor is it known how effectively polar bears might exploit those communities.

During previous climate warmings, polar bears apparently survived in some unknown refuges. Whether they can withstand the more-extreme warming ahead is doubtful (Stirling and Derocher 1993; Lunn and Stirling 2001). As snow and ice covers decline, polar bears may respond adaptively to the new selection pressures or they may become extinct. Extinction could result from mortality outpacing production, or from re-absorption into the brown bear genome. Crosses between polar bears and brown bears produce fertile offspring (a hybrid was recently document in the wild), and extinction through hybridization has been documented in other mammals (Rhymer and Simberloff 1996).

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## 5.7 Ecosystem Services and Expectations for Future Change

The Millennium Ecosystem Assessment (MA) (2006) is the most comprehensive scientific review of the status, trends, conditions, and potential futures for ecosystem services. It was international in coverage, although individual sections did focus on regions, ecosystem types, and particular ecosystem services. The MA categorized services as supporting, provisioning, regulating, and cultural (Figure 5.1). Some of these services are already traded in markets, e.g. provision of food, wood, and fiber from both managed and unmanaged ecosystems, or the cultural services of providing recreational activities that generate substantial revenue both within the United States and globally.

Other services, in particular many cultural services, regulating services, and supporting services are not priced, and therefore not traded in markets. A few, like provision of fresh water or carbon sequestration potential, are mostly not traded in markets, but could be, and especially for carbon, there are many developing markets.

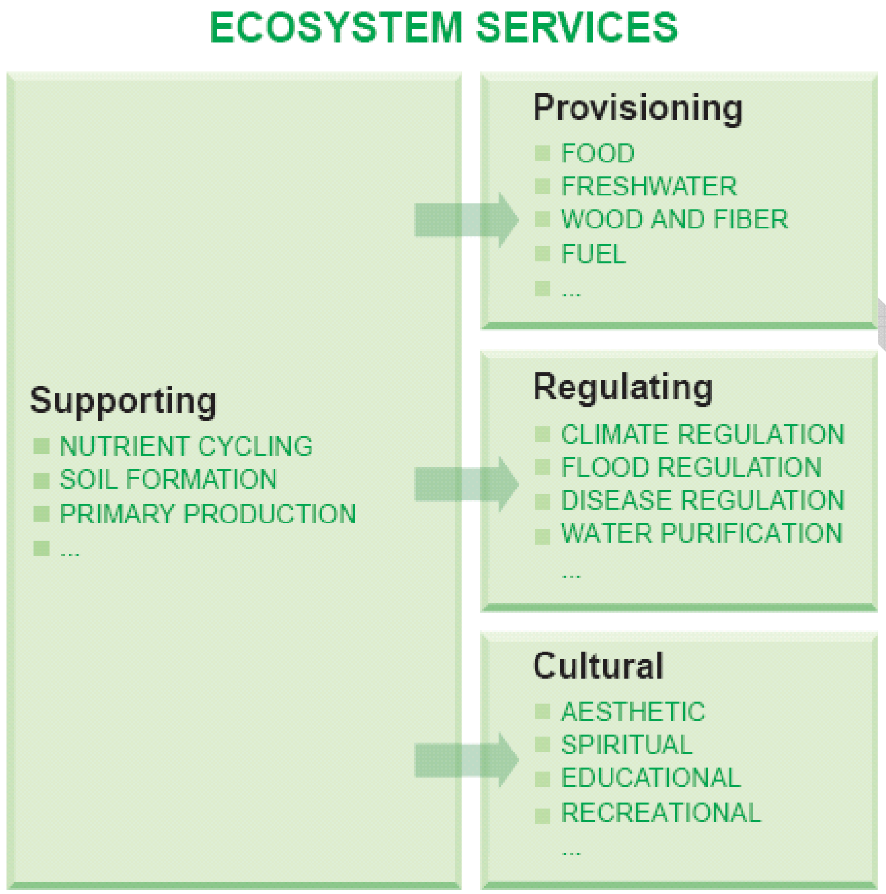
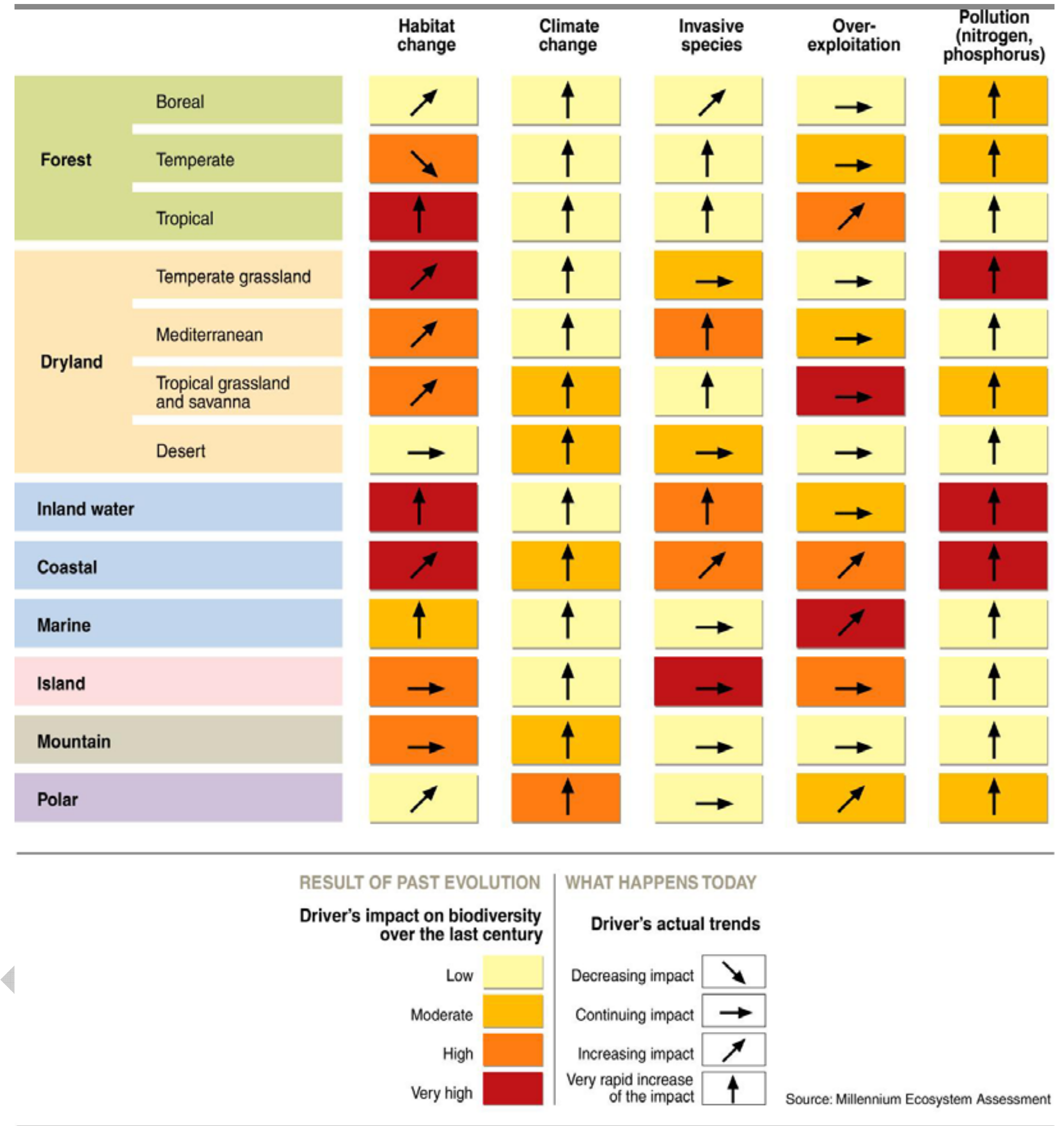


Figure 5.1

Biological diversity is recognized as providing an underpinning for all these services in a fundamental way. A major finding of the MA from a global perspective was that out of 24 different ecosystems services that were analyzed, 16 were being used in ultimately unsustainable ways. While this finding was not specific to U.S. ecosystems, it does set a context within which the changes that have been documented as a consequence of changes in the physical climate need to be considered.

A subsequent question is whether any such changes in services can be reasonably attributed to climate change. The MA evaluated the relative magnitudes and importance of a number of different direct drivers (Nelson et al. 2006) for changes in ecosystems, and whether the importance of those drivers was likely to increase, decrease, or stay about the same over the next several decades. The conclusion was that although climate change was not currently the most important driver of change in many ecosystems, it was one of the only drivers whose importance was likely to continue to increase in all ecosystems over the next several decades (Figure 5.2).



| | | Habitat change | Climate change | Invasive species | Over-exploitation | Pollution (nitrogen, phosphorus) |
|---|---|---|---|---|---|---|
| Forest | Boreal | 🟨 ↗ | 🟨 ↑ | 🟨 ↗ | 🟨 → | 🟡 ↑ |
| | Temperate | 🟧 ↘ | 🟨 ↑ | 🟨 ↑ | 🟡 → | 🟡 ↑ |
| | Tropical | 🟥 ↑ | 🟨 ↑ | 🟨 ↑ | 🟧 ↗ | 🟨 ↑ |
| Dryland | Temperate grassland | 🟥 ↗ | 🟨 ↑ | 🟡 → | 🟨 → | 🟥 ↑ |
| | Mediterranean | 🟧 ↗ | 🟨 ↑ | 🟧 ↑ | 🟡 → | 🟨 ↑ |
| | Tropical grassland and savanna | 🟧 ↗ | 🟡 ↑ | 🟨 ↑ | 🟥 → | 🟡 ↑ |
| | Desert | 🟨 → | 🟡 ↑ | 🟡 → | 🟨 → | 🟨 ↑ |
| Inland water | | 🟥 ↑ | 🟨 ↑ | 🟧 ↑ | 🟡 → | 🟥 ↑ |
| Coastal | | 🟥 ↗ | 🟡 ↑ | 🟧 ↗ | 🟧 ↗ | 🟥 ↑ |
| Marine | | 🟡 ↑ | 🟨 ↑ | 🟨 → | 🟥 ↗ | 🟨 ↑ |
| Island | | 🟧 → | 🟨 ↑ | 🟥 → | 🟧 → | 🟨 ↑ |
| Mountain | | 🟧 → | 🟡 ↑ | 🟨 → | 🟨 → | 🟨 ↑ |
| Polar | | 🟨 ↗ | 🟧 ↑ | 🟨 → | 🟡 ↗ | 🟡 ↑ |

| RESULT OF PAST EVOLUTION<br>Driver's impact on biodiversity over the last century | | WHAT HAPPENS TODAY<br>Driver's actual trends | |
|---|---|---|---|
| Low | 🟨 | Decreasing impact | ↘ |
| Moderate | 🟡 | Continuing impact | → |
| High | 🟧 | Increasing impact | ↗ |
| Very high | 🟥 | Very rapid increase of the impact | ↑ |

Source: Millennium Ecosystem Assessment

Figure 5.2

## 5.8 Adequacy of observing systems

One of the challenges for understanding changes in biological diversity related to variability and change in the physical climate system is the adequacy of the variety of monitoring programs that exist for documenting those changes.

It is useful to think about such programs as falling into three general categories. The first is the 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 particular ecosystems (e.g. Coral Reef Watch). These tend to have been established for very particular purposes, e.g. 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.

A second category of monitoring programs are those in which initial justification has been to investigate particular research problems, whether primarily oriented around biodiversity or not. So, for example, the existing LTER sites are important for monitoring and understanding trends in biodiversity in representative biomes in the United States, although their original justification was much more oriented around understanding ecosystem functioning. The yet-to-be established NEON network would also fall into this category, although the published design for site locations samples both climate variability and ecological variability within the United States in a much more systematic way than ever before for a long-term research network, so there are likely to be very powerful results that can potentially come from network-wide analyses.

The table below lists a large number of operational and research monitoring networks that fall into these first two categories.

A third category of monitoring systems are those that offer the extensive spatial and variable temporal resolution of remotely sensed information from Earth-orbiting satellites. These are not always thought of as being part of the nation's system for monitoring biological diversity, but in fact, they are an essential component of it. Remotely sensed data are the primary source of information on a national scale for documenting land-cover and land-cover change across the United States, for example, and thus they are essential for tracking changes in perhaps the biggest single driver of changes in biodiversity – i.e. changes in habitat. Over the 1990s and 2000s, the remarkable profusion of Earth observation satellites has provided global coverage of many critical environmental parameters, from variability and trends in the length of growing season, to NPP monitoring, to the occurrence of fires, to the collection of global imagery on 30-meter spatial resolution for more than a decade. Observational needs for biodiversity monitoring and research are recently reviewed by the International Global Observations of Land Panel, in a special report from a conference (IGOL 2006).

However, in recent years, the U.S. contribution to such measurements has waned, and new systems have been slow to be developed by NASA and NOAA. The National Research Council has recently released the first-ever Decadal Survey for Earth Science and Observations, which makes a comprehensive set of recommendations for future measurements and missions, which would simultaneously enhance scientific progress, preserve essential data sets, and benefit a wide variety of potential applications.

Are these existing monitoring systems 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

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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 that purpose, even if it means that the scientific community is attempting to use them for a purpose other than what they were originally designed for. 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.

## 5.8.1 Table: Existing monitoring systems

### *1.1.1.36 Bird Monitoring in North America*

Canadian Bird Checklist Program (http://www.oiseauxqc.org/feuillets/cbcp_can.html)
Project FeederWatch (http://www.birds.cornell.edu/PFW/)
Breeding Bird Survey (http://www.pwrc.usgs.gov/bbs/)
Breeding Bird Survey Summary and Analysis (http://www.mbr-pwrc.usgs.gov/bbs/bbs.html)
Christmas Bird Count (http://www.audubon.org/bird/cbc/index.html)
Point Count Database (http://www.pwrc.usgs.gov/point/)
Breeding Bird Census (http://www.pwrc.usgs.gov/birds/bbc.html)
Bird Banding Laboratory (http://www.pwrc.usgs.gov/bbl/)
Monitoring Avian Productivity and Survivorship (http://www.birdpop.org/maps.htm)
Migration Monitoring
Marsh Bird Monitoring (http://www.bsc-eoc.org/)
*Night Bird Monitoring*
*Winter Bird Survey*
Urban Birds (Birdscape Project) (http://www.pwrc.usgs.gov/birdscap/scapein.html)
Waterbird Monitoring Partnership (http://www.waterbirdconservation.org/)
International Shorebird Survey (http://www.pwrc.usgs.gov/iss/iss.html)
Waterfowl and Gamebird Surveys (http://www.fws.gov/migratorybirds/statsurv/mntrtbl.html#tbl)
Hawk Migration Monitoring (http://www.hawkmountain.org/default.shtml)
Forest Bird Monitoring (http://www.cwf-fcf.org/pages/wildresources/surveys/survey18.htm)
Project NestWatch Canada (http://www.bsc-eoc.org/national/nestwatch.html)
BioBlitz (http://www.pwrc.usgs.gov/blitz.html)

### *1.1.1.37 Amphibian Monitoring:*

North American Amphibian Monitoring Program (http://www.pwrc.usgs.gov/naamp/)
Northeast Amphibian Monitoring Program (http://www.pwrc.usgs.gov/nearmi/)

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#### *1.1.1.38 Mammal Monitoring in North America*

#### *1.1.1.39 Butterfly Monitoring in North America*

#### *1.1.1.40 General Biodiversity Monitoring:*

#### *1.1.1.41 Long-Term Ecological Research (LTER) sites*

The LTER Network is a collaborative effort involving more than 1800 scientists and students investigating ecological processes over long temporal and broad spatial scales. http://www.lternet.edu/

**National Ecological Observatory Network (NEON)**
http://www.neoninc.org/archive/2005/01/subscribe_to_th.html

**National Park Service Inventory and Monitoring Program**
Baseline inventories of basic biological and geophysical natural resources with long-term monitoring programs efficiently and effectively monitor ecosystem status and trends over time at various spatial scales.
http://www1.nature.nps.gov/protectingrestoring/IM/inventoryandmonitoring.htm

**NatureServe**
Documents the condition and distribution of species and ecosystems, with an emphasis on those of greatest conservation concern.
http://www.natureserve.org/projects/united_states.jsp

**Smithsonian Institution's Monitoring and Assessment of Biodiversity Program (MAB)** works internationally with governments, industries, academia, nongovernmental organizations, local communities, and others to assess and monitor the biodiversity in the tropical and temperate forests of Latin America, the Caribbean, North America, Africa, and Asia. http://nationalzoo.si.edu/ConservationAndScience/MAB/about/

**Strategic Plan for North American Cooperation in the Conservation of Biodiversity** seeks to enhance collaboration among Canada, Mexico, and the United States in furthering the conservation and sustainable use of biodiversity, in particular transboundary and migratory species.

**United Nation Environment Programme World Conservation Monitoring Centre (IUCN WCMC)** UNEP-WCMC, in collaboration with the UNESCO World Heritage Centre (WHC) and IUCN, has prepared a review of the World Heritage network in relation to global biogeography, biodiversity and habitats. The assessment is a contribution to the World Heritage Global Strategy. The Global Strategy adopted by the World Heritage Committee aims to achieve a balanced, representative and credible World Heritage List that reflects the world's diverse heritage
http://www.unep-wcmc.org/protected_areas/world_heritage/wh_review.htm

**United States Geological Survey**

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Natural Resources Canada and the U.S. Geological Survey have a high-tech satellite mapping initiative to better monitor changes in the combined land cover of the two nations.

**NOAA Coral Reef Watch**

## *5.9 Major Findings and Conclusions*

In this section, we list the major findings from each section of the chapter, by topic heading. We then draw some general conclusions about the observed and potential impacts of climate change on biological diversity, the relationships to ecosystem sevices, and the adequacy of existing monitoring systems to document continuing chang**e.**

### 5.9.1 Growing Season and Phenology

There is evidence indicating a significant lengthening of the growing season and higher NPP in the higher latitudes of North America, where temperature increases are relatively high.

Over the last 19 years, global satellite data indicates an earlier onset of spring across the temperate latitudes by 10 to 14 days (Myeni 2001; Lucht 2002), an increase in summer photosynthetic activity (NDVI satellite estimates, (Myeni 2001)), and an increase in the amplitude of annual $CO_2$ cycle (Keeling, 1996), all supported by climatological and field observations.

Forest productivity, in contrast, generally limited by low temperature and short growing seasons in the higher latitudes and elevations, has been slowly increasing at less than one percent per decade (Boisvenue 2006; Joos 2002; McKenzie 2001; Caspersen 2000).

The exception to this pattern is in forested regions that are subject to drought from climate warming, where growth rates have decreased since 1895 (McKenzie 2001. Recently, widespread mortality over 12,000 km$^2$ of lower elevational forest in the southwest U.S. demonstrate the impacts of increased temperature and the associated multiyear drought (Breshears 2005) even as productivity at treeline had increased previously (Swetnam, 1998).

Disturbances created from the interaction of drought, pests, diseases, and fire are projected to have increasing impacts on forests and their future distributions (IPPC FER SPM 2007). These changes in forests and other ecosystems will cascade through trophic webs, impacting other species.

### 5.9.2 Biogeographical and phenological shifts

Evidence from two meta-analyses (143 studies, (Root 2003); 1,700 species, (Parmesan 2003)) and a synthesis (866 studies, (Parmesan 2006)) on species from a broad array of taxa suggest that there is a significant impact of recent climatic warming in the form of long-term, large-scale alteration of animal and plant populations.

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Movement of species in regions of North America in response to climate warming is expected to result in shifts of species ranges poleward and upward, along elevational gradients (Parmesan 2006).

In an analysis of 866 peer-reviewed papers exploring the ecological consequences of climate change, nearly 60 percent of the 1,598 species studied exhibited shifts in their distributions and/or phenologies over the a 20 and 140 year time frame (Parmesan 2003).

Analyses of field-based phenological responses have reported shifts as great as 5.1 days per decade (Root 2003), with an average of 2.3 days per decade across all species (Parmesan 2003).

***Migratory Birds***

A climate change signature is apparent in the advancement of spring migration phenology (Root 2003), but the indirect effects may be more important than the direct effects of climate in determining the impact on species persistence and diversity.

***Butterflies***

The migration of butterflies in the spring is highly correlated with spring temperatures, and with early springs; researchers have documented many instances of earlier arrivals (26 of 35 species in the United Kingdom, (Roy 2000); 17 of 17 species in Spain, (Stefanescu 2004); 16 0f 23 species in central California, and (Forister 2003).

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

### 5.9.3 Coastal and Near Shore Systems

In the tropics there have been increasing coral bleaching and disease events and increasing storm intensity. In temperate regions there are demonstrated range shifts and possible alterations of ocean currents and upwelling sites. In the Arctic, there have been dramatic reductions in sea ice extent and thickness, as well as related coastal erosion. Marine species were the first to be listed due to the effects of climate change.

### 5.9.4 Corals

Corals and tropical regions where they live are experiencing increasing water temperatures, increasing storm intensity (Emmuel 2005), and a reduction in pH (Ravens et al. 2005), all while experiencing a host of other on-going challenges from

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development/tourism, fishing and pollution.

The major threats that motivated the listings of Elkhorn (*Acropora palmata*) and Staghorn (*A. cervicornis*) corals were disease, elevated sea surface temperatures and hurricanes – all of which relate to climate change.

### 5.9.5 Coastal Lands

Projections for sea level rise by 2100 vary from 0.18 to 0.59 meters (±0.1-0.2) (IPCC 2007), to 0.5 to 1.4 m (Rahmstorf 2007). It has been estimated that a one-meter increase in sea level would lead to the loss of 65 percent of the coastal marshlands and swamps in the contiguous United States (Park et al. 1989). In addition to overt loss of land, there will also be shifts in “quality” of habitat in these regions. Prior to being inundated, coastal watershed will become more saline due to saltwater intrusion into both surface and groundwater.

Climate change will also lead 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.

### 5.9.6 Arctic

Changes in the Arctic are resulting in substantial shifts in habitat, especially for sea ice-dependent species, where it is literally melting away. The sea ice, which provides habitat both below and above the ocean, has been in retreat for at least 30 years (Stroeve et al. 2005; Rothrock et al. 2003). It is estimated that a summer-ice-free Arctic Ocean is likely by the end of the century (Overpeck et al. 2005), with some models suggesting it could be as soon as 2040 (Holland et al. 2006).

Ice loss to date is already causing measurable changes in polar bear and ringed seal populations and fitness (Derocher et al. 2004; Ferguson et al. 2005; Stirling et al. 1999). There are also shifts in species ranges in the Arctic, both on land and in the water, and changes in phenology.

### 5.9.7 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 world-wide, and decimating amphibian populations. A recent study by Pounds and colleagues (2006) showed that widespread amphibian extinction in the mountains of Costa Rica is positively linked to global climate change.

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To date, geographic range expansion of pathogens related to warming temperatures have been the most easily detected (Harvell et al. 2002), perhaps most readily for arthropod-borne infectious disease (Daszak et al.). 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.

### 5.9.8 Invasive Plants

Projected increases in $CO_2$ are expected 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 $CO_2$, but definitive evidence of a general benefit of $CO_2$ enrichment to invasive plants over natives has not emerged (Dukes and Mooney 1999).

Nonetheless, in general, invasive plants 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 (Vila et al. *In Press*).

Finally, it is critical to recognize that other elements of climate change (e.g., nitrogen deposition, land conversion) will play a significant role in the success of invasive plants in the future, either alone or under elevated $CO_2$ (Vila et. al. *In Press*).

### 5.9.9 Marine Fisheries

Large basin-scale atmospheric pressure systems that drive basin-scale winds can suddenly shift their location and intensity at decadal time scales, with dramatic impacts on winds and ocean circulation patterns. Perhaps the greatest discovery of the past 10 years is that these shifts have dramatic impacts on marine ecosystems.

Examples include increased flow of oceanic water into the English Channel and North Sea, resulting in a northward shift in the distribution of zooplankton such that the zooplankton community became dominated by warm water species (Beaugrand 2004), with concomitant changes in fish communities from one dominated by whiting (hake) to one dominated by sprat (similar to a herring).

Similar (and drastic) ecosystem changes are known for the Baltic Sea (Kenny and Mollman 2006), where dramatic changes in both zooplankton and fish communities were observed. Cod were replaced by sprat and dominance in zooplankton switched from lipid-rich (and high bioenergetic content) species to lipid-poor species.

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Linkages between the NAO, zooplankton, and fisheries have also been described for the Northwest Atlantic, waters off eastern Canada and the United States: Pershing and Green (2007) report a decrease in salinity, and an increase in biomass of small copepods (zooplankton). They suggest that the recovery of the codfish populations, which collapsed in the early 1990s (presumably as a result of overfishing), may continue to be difficult due to negative changes in food chain structure of their forage base, the zooplankton.

### 5.9.10 Particular Sensitive Systems

Plant and animal communities are also affected as glaciers recede, exposing new terrain for colonization in an ongoing process of succession. One group of organisms whose reproductive phenology is closely tied to snowmelt is amphibians, for which this environmental cue is apparently more important than temperature.

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, may also be affected by changing temporal patterns of snowpack formation and disappearance.

The annual disappearance of snowpack is the environmental cue that marks the beginning of the growing season in most montane environments. Thus it is not surprising that flowering phenology has been advancing in these habitats, as well as others at lower altitudes, mirroring what is going on at higher latitudes.

There is a very strong correlation between the timing of snowmelt, which integrates snowpack depth and spring air temperatures, and the beginning of flowering by wildflowers in the Colorado Rocky Mountains.

For some wildflowers there is also a strong correlation between the depth of snowpack during the previous winter and the abundance of flowers produced.

An unexpected consequence of earlier snowmelt in the Rocky Mountains has been the increased frequency of frost damage to montane plants, including loss of new growth on conifer trees, of fruits on some plants such as *Erythronium grandiflorum* (glacier lilies), and of flower buds of other wildflowers (e.g., *Delphinium* spp., *Helianthella quinquenervis*, etc.). Although most of these species are long-lived perennials, as the number of years in which frost damage has negative consequences on recruitment increases, significant demographic consequences may result.

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### 5.9.11 Polar Bears

Today, an estimated 20,000 to 25,000 polar bears live in 19, apparently discrete populations distributed around the circumpolar Arctic (IUCN Polar Bear Specialists Group 2005). Their overall distribution largely matches that of ringed seals, which inhabit all seasonally ice-covered seas in the northern hemisphere (Scheffer 1958; King 1983), an area extending to approximately 15,000,000 km$^2$.

Most polar bear populations expand and contract their range seasonally with the distribution of sea ice, and they spend most of the year on the ice (Stirling and Smith 1975; Garner et al. 1994).

The rapid rates of warming in the Arctic observed in recent decades and projected for at least the next century are causing dramatic reduction of snow and ice cover, which provide denning and foraging habitat for polar bears (Roots 1989; Overpeck et al. 1997; Serreze et al. 2000; Stroeve et al. 2007).

During previous climate warmings, polar bears apparently survived in some unknown refuges. Whether they can withstand the continued loss of sea ice from the more extreme warming ahead is doubtful (Stirling and Derocher 1993; Lunn and Stirling 2001).

## *Conclusions*

Terrestrial systems are already being demonstrably impacted by climate change. There are observable impacts of climate change on terrestrial ecosystems in North America including changes in the timing of growing season and its 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) states, for ecosystems and biological resources around the world.

There are a family 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 specifically related to changes in biological diversity in the United States. The MA (2005) is the most recent, and most comprehensive scientific assessment of the state of ecosystem services around the world, the drivers of changes in both ecosystems and services, the inherent tradeoffs among different types of ecosystem services, and what the prospects are for sustainable use of ecological resources. The MA concludes that climate change is likely to increase in

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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 Unitd States as a consequence of changes in climate or other drivers of change has not been done.

We can think of the monitoring systems that have been used to evaluate the relationship between changes in the physical climate system and biological diversity as having three components. There is a plethora of species-specific or ecosystem-specific monitoring systems, variously sponsored by 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 that make routine measurements 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.

The third components are spatially extensive observations derived from remotely sensed data. These are primarily focus on land-cover, and thus are a good indicator of the major, single drivers of changes in biodiversity patterns, or on estimating ecosystem functioning – such as producing estimates of NPP and changes in the growing season – 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 NRC (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.

# 6 Synthesis

**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.

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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

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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).

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**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

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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.

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**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

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- 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, 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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**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 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

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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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# Appendix A. Acronym List and Glossary

## Acronym Glossary

| | |
|---|---|
| **AET** | Apparent equivalent temperature |
| **ANPP** | Aboveground net primary productivity |
| **AOGCM** | Atmosphere-ocean general circulation models |
| **BT** | Body temperature |
| **CCSM** | Community Climate System Model |
| **CCSP** | U.S. Climate Change Science Program |
| **CGC** | Canadian Global Coupled Model |
| **DOY** | Day of year |
| **ET** | Evapotranspiration |
| **ENSO** | El Niño-Southern Oscillation |
| **FACE** | Free-Air $CO_2$ Enrichment |
| **GCM** | General Circulation Model |
| **GFDL** | Geophysical Fluid Dynamics Laboratory |
| **HadCM2** | Hadley Centre for Climate Prediction and Research's Climate Model 2 |
| **HCN** | Historical Climatology Network |
| **HI** | Harvest index |
| **HLI** | Heat load index |
| **IBP** | International Biome Project |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IPCC AR4** | Intergovernmental Panel on Climate Change 4th Assessment Report |
| **IPCC TAR** | Intergovernmental Panel on Climate Change 3rd Assessment Report |
| **IPM** | Integrated pest management |

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|---|---|
| **LAI** | Leaf area index |
| **LTER** | Long Term Ecological Research |
| **LWSI** | Livestock weather safety index |
| **NCAR** | National Center for Atmospheric Research |
| **NEON** | National Ecological Observatory Network |
| **NPP** | Net primary productivity |
| **NRCS** | Natural Resources Conservation Service |
| **NRCS SCAN** | Natural Resources Conservation Service Soil Climate and Analysis Network |
| **NRC** | National Research Council |
| **NWS COOP** | National Weather Service Cooperative Observer Program |
| **PCMDI** | (Lawrence Livermore National Laboratory's) Program for Climate Model Diagnosis and Intercomparison |
| **PDO** | Pacific Decadal Oscillation |
| **PE** | Potential evaporation |
| **ppb** | Parts per billion |
| **ppm** | Parts per million |
| **RH** | Relative humidity |
| **RMSE** | Root mean square error |
| **RR** | Respiration rate |
| **SOM** | Soil organic matter |
| **SRAD** | Solar radiation |
| **SRES** | Special Report on Emissions Scenarios |
| **SWE** | Snow water equivalent |
| **TBCA** | Total carbon allocation belowground |
| **THI** | Temperature-humidity index |
| **USDA** | United States Department of Agriculture |
| **USGS** | United States Geological Survey |
| **USGS HCDN** | United States Geological Survey Hydro-Climatic Data Network |
| **VFI** | Voluntary feed intake |

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| | |
|---|---|
| **VIC** | Variable Infiltration Capacity |
| **VOC** | Volatile organic compound |
| **VPD** | Vapor pressure deficit |
| **WS** | Wind speed |
| **WUE** | Water use efficiency |

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# Glossary

**Anthesis**
The period during which a flower is fully open and functional.

**Boll**
The seed-bearing capsule of certain plants, especially cotton and flax.

**C3 species**
Almost all plant life on Earth can be broken into two categories based on the way they assimilate carbon dioxide into their systems. During the first steps in $CO_2$ assimilation, C3 plants form a pair of three carbon-atom molecules. C3 species continue to increase photosynthesis with rising $CO_2$. C3 plants include more than 95 percent of the plant species on Earth.

**C4 species**
C4 plants initially form four carbon-atom molecules. C4 plants include such crop plants as sugar cane and corn. They are the second most prevalent photosynthetic type, and do not assimilate $CO_2$ as well as C3 plants.

**Carbon sink.**
A carbon reservoir. Carbon sinks include the oceans, and plants and other organisms that remove carbon from the atmosphere via photosynthetic processes.

**Carbon source**
The term describing processes that add carbon dioxide to the atmosphere.

**Carbon sequestration**
The term describing processes that remove carbon dioxide from the atmosphere.

**$CO_2$ enrichment**
Addition of $CO_2$ to the atmosphere.

**Coefficient of variation of annual runoff**
A measure of the variability of runoff

**Complementary hypothesis**
This hypothesis states that trends in actual evaporation and pan evaporation should be in opposite directions.

**Cucurbits**
Any of various mostly climbing or trailing plants of the family Cucurbitaceae, which includes the squash, pumpkin, cucumber, gourd, watermelon, and cantaloupe.

**Endophyte**
A plant living within another plant, usually as a parasite.

**Evaporation paradox**
Temperature, precipitation, stream flow and cloud cover records indicate that warmer, rainier weather is now more common in many regions of the world. However, pan evaporation readings, taken at weather stations, indicate that less moisture has been rising back into the air from these pans.

**Evapotranspiration**

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The sum of evaporation and plant transpiration. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and water bodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves.

**Free-Air $CO_2$ Enrichment (FACE)**

FACE is a method and infrastructure used to experimentally enrich the atmosphere enveloping portions of a terrestrial ecosystem with controlled amounts of carbon dioxide (and in some cases, other gases), without using chambers or walls.

**Forb**

A broad-leaved herb (not a grass), especially one growing in a field, prairie, or meadow.

**Global dimming**

The gradual reduction in the amount of global direct irradiance at the Earth's surface that was observed for several decades after the start of systematic measurements in 1950s

**Herbivores**

Animals that feed chiefly on plants.

**Homeostasis**

The scientific study of periodic biological phenomena, such as flowering, breeding, and migration, in relation to climatic conditions.

**Instream flow**

The term used to identify a specific stream flow (typically measured in cubic feet per second, or cfs) at a specific location for a defined time, and typically following seasonal variations. Instream flows are usually defined as the stream flows needed to protect and preserve instream resources and values, such as fish, wildlife and recreation. Instream flows are most often described and established in a formal legal document, typically an adopted state rule.

**Irrigation Modes**

***Drip*** irrigation allows water to drip slowly to the roots of plants through a network of valves, pipes, tubing, and emitters.

***Flood*** irrigation pumps water onto the fields. The water then flows freely along the ground among the crops.

***Spray*** irrigation relies on machinery to spray water in all directions.

**Latent heat**

The heat required to change the phase of a substance, for example a solid to vapor (sublimation), liquid to vapor (vaporization) or solid to liquid (melting); the temperature does not change during these processes. Heat is released for the reverse processes, for example vapor to solid (frost), liquid to solid (freezing), or vapor to liquid (condensation).

**Leaf area index (LAI)**

The ratio of total upper leaf surface of a crop divided by the surface area of the land on which the crop grows.

**Lignin**

An organic substance that, with cellulose, forms the chief part of woody tissue.

**Lysimeter**

A device for collecting water from the pore spaces of soils, and for determining the soluble constituents removed in the drainage.

**Mutualistic relationship**

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A positive, reciprocal relationship between two species. Through this relationship, both species enhance their survival, growth or fitness.

**Net primary productivity (NPP)**
The ratio of all biomass accumulation and biomass losses in units of carbon, weight or energy, per land surface unit, over a set time interval (usually a year).

**Pan evaporation**
Pans used to determine the quantity of evaporation at a given location. These are generally located in agricultural areas, and have been used as an index to potential evaporation.

**Panicle**
The complete assembly of spikelets on a rice plant.

**Phenology**
The study of periodic biological phenomena (flowering of plants, breeding, and species migration) in relation to climatic conditions.

**Potential Evapotranspiration**
A representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapor from the ground up into the lower atmosphere.

**Runoff ration**
The total amount of runoff divided by the total moisture that falls during a precipitation event.

**Ruminant**
Even-toed, cud-chewing, hoofed mammals of the suborder *Ruminantia*, such as domestic cattle.

**Sensible heat**
Heat that can be measured by a thermometer.

**Spikelet**
The individual places on a rice plant where a grain develops.

**Stomatal**
One of the minute pores in the epidermis of a leaf or stem through which gases and water vapor pass.

**Tiller**
New shoots that develop at the base of the plant.

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# Appendix B. References

## Introduction

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