environment

Observed Impacts of global **climate change** in the U.S.

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Observed Impacts of global climate change in the U.S.

Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

For over a century, scientists have documented the important role that that the climate plays in the geographic distribution of the world's ecosystems and the wildlife they support. Yet, it is now quite evident that the climate these species depend upon is changing. Global temperatures increased by over 1°F during the past century and are projected to increase 2.5-10.4°F by 2100 as a result of human emissions of greenhouse gases. Given the reliance of plants and animals on their natural environment, they are often early barometers of the effects of climate change.

"Observed Impacts of Global Climate Change in the U.S." is the twelfth in a series of Pew Center reports examining the impacts of climate change on the U.S. environment. While past Pew Center reports have reviewed the potential impacts of future climate change, this report provides compelling evidence that ecosystems are already responding to climate change and provides insights into what we can expect from future changes in the Earth's climate. Looking specifically at the United States, report authors, Drs. Camille Parmesan and Hector Galbraith find:

A number of ecological changes have already occurred in the United States over the past century in concert with increases in average U.S. temperature and changes in precipitation. Warmer temperatures have resulted in longer growing seasons at the national level, altered carbon cycling and storage in the Alaskan tundra, and increased the frequency of fires and other disturbances in U.S. forests. Individual species such as Edith's checkerspot butterfly and the red fox have shifted north or to higher altitudes. Other species including Mexican jays and tree swallows have experienced changes in the timing of reproduction, as have plants such as forest phlox and butterfly weed. While these changes illustrate efforts by species to adapt to a warming climate, these responses may alter competition and predator-prey relationships and have other unforeseen consequences.

These observed changes have been linked to human-induced warming of the global climate. There is increasingly strong evidence that the observed global climate change, particularly that of the past 50 years, is primarily the result of human emissions of greenhouse gases. Changes in U.S. climate have also been linked with human activities.

Changes in natural systems will continue and become even more apparent in the future, resulting in the degradation and loss of U.S. biodiversity. With continued and more severe changes in the climate, the ability of U.S. wildlife to adapt through migration and physiological change will be increasingly limited. Furthermore, because of adaptive migration, species such as the red fox are now competing for habitat previously dominated by the arctic fox, threatening the arctic fox's long-term survival. The challenge is even greater when considered along with the broad range of other environmental threats currently affecting wildlife, such as habitat loss, environmental contamination, and invasive species.

Efforts to reduce greenhouse gas emissions, protect U.S. ecosystems and wildlife, and provide refuge for sensitive species are all necessary to limit the future ecological consequences of climate change. Curbing greenhouse gas emissions can reduce the rate and magnitude of future climate change, consequently reducing the severity of, but not preventing, climatic stresses to wildlife. Meanwhile, the expansion of nature reserves and habitat conservation efforts can alleviate some non-climate stresses and enable species to adapt better to the effects of climate change.

The authors and the Pew Center gratefully acknowledge the input of Drs. Lou Pitelka and Walter Oechel on this report. The Pew Center would also like to thank Joel Smith of Stratus Consulting for his assistance in the management of this Environmental Impacts Series.

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Executive Summary

One of the major, most well-documented, and robust findings in ecology over the past century has been the crucial role of climate in determining the geographical distribution of species and ecological communities. Climate variability and change can affect plants and animals in a number of ways, including their distributions, population sizes, and even physical structure, metabolism, and behavior. These ecological responses to changes in climate have important implications, given the historical and continuing increases in atmospheric concentrations of greenhouse gases associated with human activities. Future human-induced changes in the global climate will directly affect regional conditions, such as geographic patterns of temperature and precipitation. Previous reports by the Pew Center on Global Climate Change have identified a range of future adverse effects that could occur in U.S. marine and freshwater systems, forests, and ecosystem processes due to greenhouse gas-induced global climate change.

The effect of climate change, however, is not relegated to future decades. Scientists have already documented changes in temperature and precipitation patterns in the United States and around the world. Average U.S. temperatures increased by approximately 0.6°C (1°F) over the past century, while precipatation increased by 5-10 percent. The magnitude of warming, however, has varied among different regions within the United States. Alaska, for example, has experienced an average temperature increase of 2-4°C (4-7°F) in just the past 50 years. These climatic changes have altered the environmental contexts within which many species live in the United States, causing physical, behavioral and location changes as the species respond to their changing environments. In addition to being biological indicators of global warming, these changes may have direct adverse effects on U.S. biodiversity and ecosystem stability, resilience, and goods and services.

This report assesses the scientific evidence compiled to date on the observed ecological effects of climate change in the United States and their consequences. It evaluates the strength of that evidence and the relationships between observed biological changes and human activities. Although many species and ecological systems of interest have yet to be studied (often due to inherent limitations of available data) and the attribution of ecological changes to a particular cause remains challenging, a number of robust findings emerge from this report.

1) Sufficient studies now exist to conclude that the consequences of climate change are already detectable within U.S. ecosystems. This report reviews more than 40 studies that associate climate change with observed ecological impacts in the United States, and, using objective evaluation criteria, finds that more than half provide strong evidence of a direct link. These studies span a broad range of plant and animal species from various regions of the United States. Yet, despite the diversity among studies, the observed ecological responses are consistent with one another, as well as with the changes that one would expect based on the nature of U.S. climate change observed to date.

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2) The timing of important ecological events, including the flowering of plants and the breeding times of animals, has shifted, and these changes have occurred in conjunction with changes in U.S. climate. If these timing shifts are synchronous across species that normally interact with each other (for example, if adult butterflies and the flowers they depend on for nectar both emerge two weeks earlier), then these species' interactions are preserved, and the system may remain healthy. On the other hand, if responses to temperature increases vary across species (for example, if butterflies emerge before the flowers they depend on for survival), then species' interactions may become out of synchrony and could lead to population declines. Both types of situations have been documented.

3) Geographic ranges of some plants and animals have shifted northward and upward in elevation, and in some cases, contracted. One of the most detailed and best-studied examples is the Edith's checkerspot butterfly in the western United States. As temperatures have increased over the last century, many southern and lower-elevation populations of this species have disappeared entirely. The effect of this shift has been a contraction of the species' range to the north (i.e., it is disappearing from Mexico but thriving in Canada). The red fox, another example, has shifted northward and is now encroaching on the arctic fox's range, threatening its survival. Similar range shifts within the United States have also been observed in organisms as diverse as birds, mammals, intertidal invertebrates, and plants. Such major shifts in species' locations alter species' interactions and potentially threaten U.S. biodiversity.

4) Species composition within communities has changed in concert with local temperature rise. As species within a community change abundances or, ultimately, are added or lost, the relationships among species also change. In particular, such shifts in composition are likely to alter important competitive and predatory/prey relationships, which can reduce local or regional biodiversity. A particularly compelling example of this is the change observed over more than 60 years in the intertidal communities of Monterey, California, where a community previously dominated by northern colder-water species has been "infiltrated" by southern warmer-water species in response to oceanic warming. Similar changes have also been observed in nearby offshore marine fish communities. Thus, many protected lands, such as the marine reserve in Monterey Bay, are experiencing a shift in the communities that they protect.

5) Ecosystem processes such as carbon cycling and storage have been altered by climate change. The lengthening of the growing season has altered the annual cycle of carbon-dioxide (CO_2) levels in the atmosphere, because plants are a major intermediary for carbon flow through ecosystems. The Alaskan tundra has switched from being a net sink of CO_2 (absorbing and storing more carbon from the atmosphere than is released) to being a net source of CO_2 (releasing more carbon than is stored), because warmer winters have allowed dead plant matter previously stored in the soil to decompose and release CO_2. Like the tundra, boreal forests have become carbon sources because of reduced growth due to climate-mediated increases in water stress, pest outbreaks, and wildfires. Conversely, many of the forests of the lower 48 states have switched in the opposite direction—becoming carbon sinks in recent decades. This transition is attributed to regrowth of forests following logging and abandonment of agricultural fields. However, it is expected to stop as soon as the forests mature.

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6) The findings that climate change is affecting U.S. biological systems are consistent across different geographic scales and a variety of species, and these U.S. impacts reflect global trends. Even against a background of apparently dominating forces such as direct human-driven habitat destruction and alteration, a climate "fingerprint" is discernible in natural systems. The most rigorous studies within the United States provide strong evidence that climate change has affected the timing of biological events in at least three taxa (i.e., groups of related species). They also provide strong evidence that at least three taxa have shifted their ranges in response to climate change and that climate change has altered ecological communities and processes. Further, very few instances of biotic change run completely counter to climate-change predictions, and the findings of many of the U.S. studies are mirrored by studies elsewhere around the world. Climate change has the potential to degrade ecosystem functions vital to global health. If the observed biological changes are merely one phase in a cyclical pattern of warming and cooling periods, then they may not represent a threat to long-term species and ecosystem health. If, however, they are linked to anthropogenic climate change, they will continue along the same path. Thus, it is essential to address the extent to which the U.S. climate change responsible for observed ecological responses can be attributed to global emissions of anthropogenic greenhouse gases.

7) There is an emerging link between observed changes in wild plants and animals across the United States and human-driven global increases in greenhouse gases. In 2001, the Intergovernmental Panel on Climate Change concluded that the global rise in average yearly temperature over the past 50 years was primarily due to increased concentrations of anthropogenic greenhouse gases. U.S. climate trends are consistent with global climate trends. Global biological trends are predicted by (and match) observed climate trends, indicating that anthropogenic global climate change has affected natural systems. Recent research focusing on North America has also shown a significant greenhouse gas signal in North American climate trends over the past 50 years. The combination of strong consistency across climate and biological studies and across scales (from regional to global), coupled with new climate analyses specific to the United States, links U.S. biological changes to anthropogenic climate change. The implications of this link are that current biological trends will continue over future decades as greenhouse gas emissions continue to rise.

8) The addition of climate change to the mix of stressors already affecting valued habitats and endangered species will present a major challenge to future conservation of U.S. ecological resources. Many if not most of the ecosystems and organisms in the United States are already suffering from other anthropogenic stressors such as habitat destruction or fragmentation, introduction of invasive species, and contamination. As yet, scientists do not have a clear idea how climate change might affect this already fragile situation. It is likely, however, that in many cases climate change may exacerbate current conditions, further stressing wild species and their associated ecosystems. There is a growing consensus within the scientific community that climate change will compound existing threats and lead to an acceleration of the rate at which biodiversity is lost.

9) In the future, range contractions are more likely than simple northward or upslope shifts. During historic glacial cycles, range shifts of hundreds to thousands of miles were common, and species extinction was rare. However, achieving such massive relocation is much more problematic across the human-dominated, artificially fragmented landscapes of today. The large reduction in the areas of natural habitats and the growth of barriers to species' dispersal (urban and agricultural zones) make simple range shifts unlikely. Species that are not adapted to urban and agricultural environments are likely to be confined to smaller total geographic areas as climate causes them to contract from their southern and lower boundaries. Already rare or endangered species, or those living only on high mountaintops, are likely to have the highest risk of extinction.

10) Reducing the adverse effects of climate change on U.S. ecosystems can be facilitated through a broad range of strategies, including adaptive management, promotion of transitional habitat in nonpreserved areas, and the alleviation of nonclimate stressors. The protection of transitional habitat that links natural areas might assist in enabling species migration in response to climate change. Meanwhile, promoting dynamic design and management plans for nature reserves may enable managers to facilitate the adjustment of wild species to changing climate conditions (e.g., through active relocation programs). Also, because climate change may be particularly dangerous to natural systems when superimposed on already existing stressors, alleviation of the stress due to these other anthropogenic factors may help reduce their combined effects with climate change.

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I. Introduction

A. Overview

One of the major and most robust findings of ecology in the past 100 years is the crucial role of climate in determining geographical distribution patterns of major biomes or vegetation communities. In turn, the distributions of the animals associated with and dependent on these vegetation communities are also a function of climate (Andrewartha and Birch, 1954; Woodward, 1987, Parmesan et al., in press). For example, the distribution of arctic tundra and its plant and animal communities is largely confined to a band circling the Arctic between about 60°N and 75°N latitude (Larsen, 1980; Barbour and Billings, 1988). North of this band, tundra is replaced by permanent ice or snow, or by polar desert, while to the south tundra merges into boreal forest. These vegetation zones are largely a result of north-to-south variation in temperature and precipitation. Temperature, in particular, has a strong effect on the length of the growing season in these far northern systems. Variation in precipitation across the Arctic interacts with the variation in temperature to produce the different plant communities. In the farthest northern lands, precipitation is not sufficient to support vegetation growth (hence the polar desert). Precipitation increases to the south, resulting in the grass, forb, and shrub communities that comprise the tundra. Only in the southernmost areas of the Arctic does the combination of higher temperatures, longer growing seasons, and adequate precipitation allow the development of forest communities. Variation in soils and fire history also plays a minor role, but the large-scale north/south pattern seen in major biomes is largely a function of climate.

The influence of climate on vegetation communities and their associated organisms is also important across elevations. An observer climbing from the high plains in the western United States to the summits of the Rocky Mountains would notice a well-marked altitudinal succession, with short grass prairie at the lowest elevations (about 5,000 feet) being replaced in succession by montane conifer forest, subalpine conifer forest, tundra, and, at the highest altitudes (above 13,000 feet), unvegetated rock and snow. These life zones are largely a function of colder temperatures at higher elevation (temperature decreases by about 1°C [2°F] for every 400-foot increase in elevation; Holdridge, 1967). The high plains

and Rocky Mountains of the United States support about five or six succeeding life zones.

Animals are directly and indirectly sensitive to climatic patterns, which ultimately limit their geographic distributions. Climate limitation on animal distributions may result from direct effects of climate on individuals. For example, individual organisms are physically adapted to specific tolerance zones or "climate envelopes." If the local climate changes (e.g., by warming a few degrees on average), such an organism may be unable to persist in the new climate. Animals may also feel the effects of climate indirectly through specific climate-dependent habitat requirements (such as requiring certain plants as part of their diet). Climate-induced alteration of habitat, in turn, affects the distribution and abundance of the associated animals.

Empirical studies of effects of weather and climate at the population level fill the 20th century biological literature (Uvarov, 1931; Singer, 1972; Precht et al., 1973; Weiser, 1973; Weiss et al., 1988; Hoffmann and Parsons, 1997). It is well documented that a gradual change in climate, as well as local or regional climate characteristics, can affect population abundance (Singer and Thomas, 1996; Martin, 1998), species' distribution (Andrewartha and Birch, 1954; Woodward, 1987; Root, 1988; Davis and Zabinski, 1992; Coope, 1995; Parmesan, 1996), morphology (Hadly, 1997), and behavior (Rubenstein, 1992), ultimately also impacting community structure (Pickett and White, 1985).

Climate-induced energetic constraints also influence plants and animals. Many biological processes undergo sudden shifts at particular temperature or precipitation thresholds (Precht et al., 1973; Weiser, 1973; Hoffman and Parsons, 1997). Sensitivity to frost and to low levels of precipitation often determines plant and animal range boundaries (Andrewartha and Birch, 1954; Woodward, 1987; Root, 1988). In addition, single extreme temperature events can alter physical characteristics. An example of this comes from environmental sex-determination in reptiles. In some species, an individual's sex is determined by the maximum temperature experienced during a critical phase of embryonic development (Bull, 1980). Studies predict that increases in daily maximum temperature should alter population sex ratios in turtles (Janzen, 1994). Changes in weather patterns can be as important as maxima and minima. For example, in the Dulzura kangaroo rat *(Dipodomys simulans),* body size is related to yearly climatic variability; individuals are smaller in habitats with pronounced seasonality (Sullivan and Best, 1997). Similarly, changes in the proportion of days exceeding species-specific temperature thresholds, or changes in the frequency of droughts or extreme seasonal precipitation, are expected to lead to physical

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and behavioral changes in a few species and to dramatic changes in the distributions of many other species (Parmesan et al., 2000).

B. Global Climate Change Patterns

Because of the tight relationships among species, ecosystem processes, and climate, human-induced global warming has the potential to severely exacerbate the outcomes of already high levels of stress on ecosystems. The most recent Intergovernmental Panel on Climate Change (IPCC) report confirms a significant warming trend in the past century and strengthens the causal link between increasing greenhouse gases and global warming trends. Globally, temperatures have risen by about 0.6°C (1.1°F), and are expected to rise by a further 1.4-5.8°C (2.5-10.4°F) over the next century (IPCC, 2001a). During the 20th century, the United

Figure 1

| Temperature Trends | in the Contiguous United States
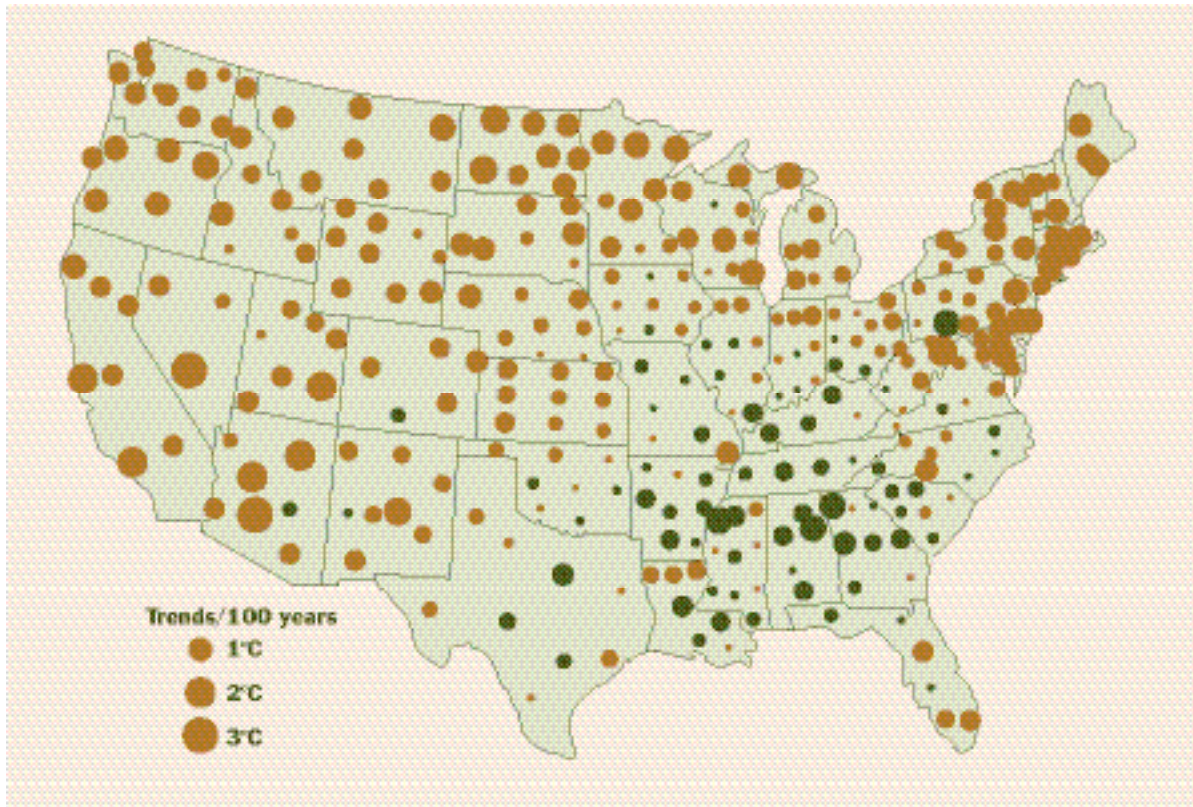
Notes: The above figure representing observed temperature trends in the contiguous United States (1901 to 1998) indicates that much of the country is warming. Data are from more than 1,200 individual climate stations; circles show average trends from groups of near-by stations, with the size of the circle representing the magnitude of the trend (positive or negative). Brown circles indicate warming, green circles indicate cooling. All stations/trends are displayed, regardless of statistical significance.

Source: National Environmental Satellite, Data and Information Service, National Climatic Data Center, National Oceanographic and Atmospheric Administration

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States warmed, overall, by 0.8°C (1.4°F; Figure 1). The greatest temperature increases have occurred at higher latitudes (as predicted by the climate models). In some parts of Alaska, average annual temperatures have increased by 2-4°C (4-7°F) since 1900, a much greater increase than in most areas of the contiguous United States (Oechel et al., 1993; IPCC, 2001a). In addition, sea level has been rising globally since the end of the last glaciation. The current rate, however, is expected to accelerate under climate change to a global projection of 8-88 cm (3-35 in) by 2100 (IPCC, 2001a).

Precipitation patterns are also changing (Meehl et al., 2000a,b; Easterling et al., 2000a,b). Total precipitation has increased by 5-10 percent in the United States, and rain and snow are falling in fewer, more extreme, events (Figure 2; Karl et al., 1996; Groisman et al., 1999, 2001). Snowpack has increased in the Great Lakes Region, while other U.S. regions such as the Southwest are becoming drier

Figure 2

Precipitation Trends in the Contiguous United States
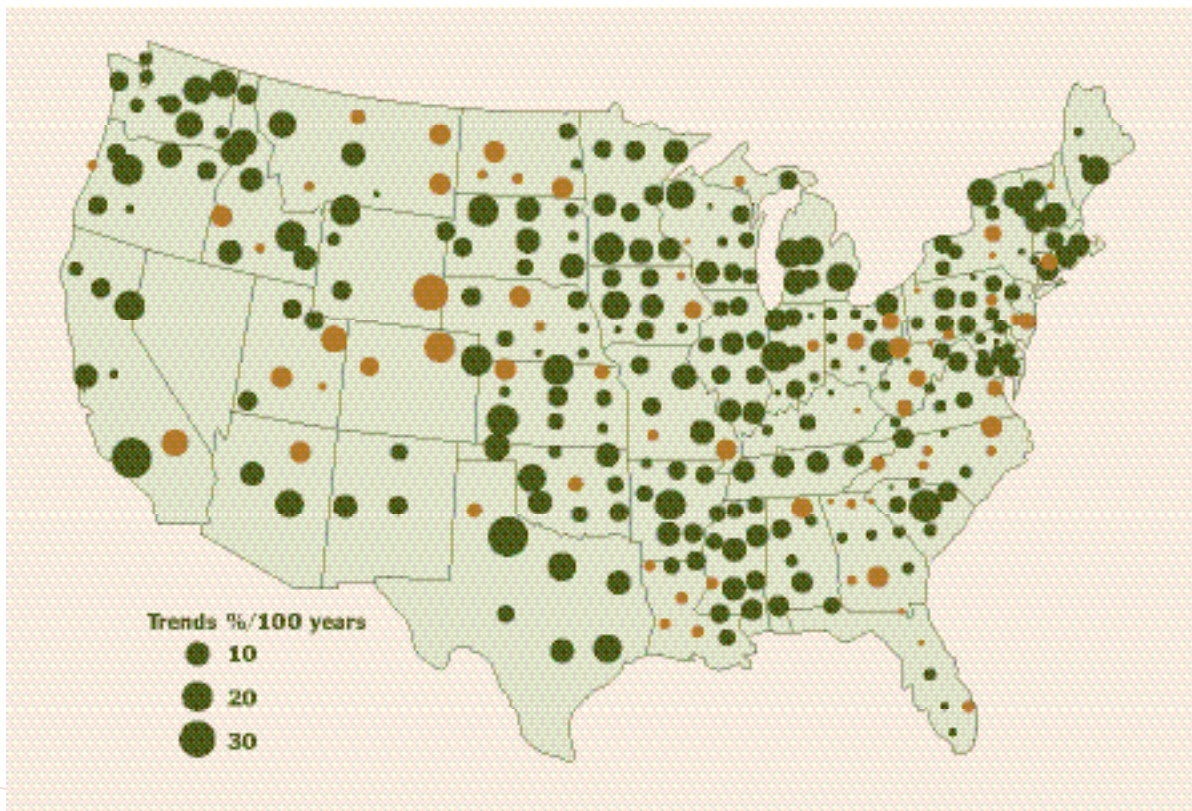
Notes: The above figure represents observed precipitation trends in the contiguous United States (1901 to 1998), which indicate that much of the country has experienced increased precipitation. Data are from more than 1,200 individual climate stations; circles show average trends from groups of nearby stations, with the size of the circle representing the magnitude of the trend (positive or negative). Green circles indicate increased precipitation, brown circles indicate decreased precipitation. All stations/trends are displayed, regardless of statistical significance.

Source: National Environmental Satellite, Data and Information Service, National Climatic Data Center, National Oceanographic and Atmospheric Administration

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(IPCC, 2001a). El Niño events have increased in frequency and intensity, and some models predict that the "normal" state by 2050 may resemble "El Niño-like conditions" (Meehl et al., 2000b).

According to climate models, the future frequencies of extreme temperature events may increase. This change could result in an increase in the number of days falling outside of temperature thresholds set by basic physiological tolerances for each species (Easterling et al., 2000a,b; Meehl et al., 2000a; Parmesan et al., 2000). For instance, at northern latitudes, the trend has been toward fewer days and nights below freezing in wintertime, and more days surpassing a given heat index in summer (Changnon et al., 2000). These extreme events may in some cases simply reflect the same level of variation, but around a changed average, but it is possible that yearly temperatures might become more variable in an absolute sense.

C. Biological Responses to 20th Century Climate Change

This report both reviews and assesses the strength of evidence that 20th century climate change has caused important biological changes, particularly shifts in the timing of events in, or distributions of, wild species. The basic relationships among climate, ecological systems, and potential climate change impacts have been reviewed and discussed in previous Pew Center reports: terrestrial ecosystems and biodiversity (Malcolm and Pitelka, 2000), inland freshwater and coastal wetland ecosystems (Poff et al., 2002), and marine and estuarine ecosystems (Kennedy et al., 2002).

A number of recently published reviews and synthetic analyses present convincing evidence that climate change has already caused measurable impacts on natural systems globally (Hughes, 2000; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003). This paper reviews studies pertaining to the United States; in addition, some global syntheses across studies are included to provide support and context for the U.S. observations. The potential implications of the observed changes for the conservation of ecological resources and biodiversity are also discussed.

II. Potential Effects of Climate Change on Wild Plants, Animals, and Ecological Processes

Predictions of how ecological systems and species may behave in response to climate change come from snapshot analyses of current relationships between climate contours and species' distributions, from manipulative laboratory studies on plant and animal physiologies with respect to temperature and precipitation tolerances, and from analyses of the fossil record. This information forms the bases for a variety of models that produce expected outcomes of different climate scenarios on particular plants or animals.

Strict freeze and precipitation tolerances are known for many plants and animals. For example, trees grow only where annual precipitation is more than 30 cm (12 inches). Tropical trees are killed by low temperatures ranging from 0 to 10°C (32 to 50°F), whereas temperate broadleaved deciduous trees can survive temperatures as low as -40°C (-40°F), and many boreal species appear to be able to survive any extreme low temperature (Woodward, 1987). Mammals are also relatively well studied with respect to climatic limitations mediated by physiological processes. For instance, the nine-banded armadillo *(Dasypus novemcinctus)* requires more than 38 cm (15 in) of annual precipitation and is further restricted to latitudes with fewer than 20 to 24 days below freezing throughout winter, and they cannot tolerate more than 9 consecutive days below freezing (Taulman and Robbins, 1996).

Consequences of drought have also been well studied. For example, a widespread drought in 1987-88 caused simultaneous crashes of insect populations across the United States, affecting diverse taxa from butterflies to sawflies to grasshoppers (Hawkins and Holyoak, 1998). Conversely, drought can be related to population booms in other insects (e.g., certain beetles, aphids, and moths; Mattson and Haack, 1987). Heat and cold stresses are also implicated in population crashes, even in aquatic systems. For instance, heat stroke has been known to cause large losses of salmon in Canadian streams (Huntsman, 1942). In a Michigan lake, 76 percent of fish species were severely affected by a single hot day in which water temperatures reached 38°C (100°F; Bailey, 1955). Thus, from basic ecological and

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physiological research, increases in extreme weather events and extreme climate years are predicted to cause responses in wild species.

Findings in the biological literature can be grouped into six major types of potential climate-change effects on biological systems. These responses include evolutionary changes, physical and physiological changes, phenological changes, range shifts, community changes, and ecosystem process changes. Each of these types of responses is discussed further below.

A. Evolutionary Changes

Over the past several glacial cycles, there is little evidence to suggest that dramatic climatic changes caused major evolution at the species level. That is, most species appeared to shift their distributions as though tracking the changing climate, rather than staying stationary and evolving new forms (Huntley and Birks, 1983; Huntley, 1991; Davis and Zabinski, 1992; Coope, 1995). Within a species, there may be significant variation among individuals in their climate tolerances, which could result in the evolution of new phenotypes (i.e., observable characteristics) within a particular population. However, the fact that species' ranges shifted with past major global climate changes indicates that all species have climatic limitations beyond which they cannot survive.

A hypothetical animal may illustrate the point best. Imagine a small mouse-like animal called a "thwartle," which is distributed across the western United States. In the northern-most populations (in Idaho), thwartles die if temperatures exceed 95°F for more than half an hour. In the southern-most populations (in Arizona), thwartles can survive temperatures up to 110°F for half an hour. If the whole of the western United States warmed up by 5°F, the Idaho populations might evolve to survive up to 100°F for a half hour, because this is within the realm of phenotypes in existence for this species. But the Arizona populations are already at the upper limit for temperature tolerance, and so they may not have the genetic variation necessary to evolve to tolerate the even more extreme high temperatures. This is the scenario indicated by the paleological data (evolution within populations but not major evolution of a species from one "type" to a new distinct "type").

B. Physical and Physiological Changes

Body shape, size, and other physical traits may change to provide better adaptation to local climate. The average body trait for any given population may be genetically based, representing an evolutionary adaptation to the prevailing climatic conditions (through, for example,

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the relationship of body size to heat conservation or loss), but variation in the body trait of an individual animal can also be caused by variation in the environment experienced by the animal as it develops. A trait that can change rapidly within an animal's lifetime to adjust to a changing environment is called a "plastic" trait. Physical characteristics that are sensitive to climate include body size, hairiness, length of limbs, and skin or hair color. In most cases, scientists do not know whether these traits are principally plastic or genetic, but many appear to have been affected by past climate changes.

Changes in body size of small mammals, lizards, and zooplankton have been documented under historical (natural) climate shifts (Morgan et al., 1995; Hadly, 1997; Sullivan and Best, 1997; Badgley, 1998; Smith et al., 1998). Bodies tend to become smaller with general warming and larger with cooling, a phenonomenon first associated with latitudinal trends in temperature, now known as "Bergmann's rule" (Bergmann 1847). In fact, temporal fluctuations of body size in woodrats are so precise that Smith and Betancourt (1998) called these animals "paleothermometers" because changes in temperature can be gauged from changes in their body sizes. Even freshwater zooplankton become smaller in response to warmer water temperatures (Schindler, 1997). Exceptions to Bergmann's rule do exist, but are rare (e.g., the Dulzura kangaroo rat, *Dipodomys simulans;* Sullivan and Best, 1997).

C. Phenological Changes

The phenology (timing) of many of the important events in an organism's life cycle may be affected by climate. For example, the onset of spring growth in both plants and animals is frequently triggered by environmental conditions that exceed critical temperature or precipitation thresholds. Similarly, the timing of migration and breeding is often driven, or modulated, by temperature and precipitation patterns. Consequently, if temperature regimes change, the timing of seasonal events may also change. In addition, some species that may not depend on temperature cues have strong interactions with other species that do. For example, insectivorous birds often rely on spring insect emergence for food, and insects frequently specialize on one species of host plant. If the interacting species use different cues to time their emergence and breeding events, then a mismatch may occur between predator and prey or parasite and host, which could cause major species declines (Andrewartha and Birch, 1954; Crick et al., 1997). One such alternative timing cue is day length, which for many species is a major driver of phenological events. The overall impacts of climate change will depend on the extent to which climate or day length is the predominant trigger of events for different species.

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D. Range Shifts

Changes in the distributions of plants and animals in North America during and after the last glaciation provide unambiguous examples of climate-driven range shifts. When the glaciers were at their maximum extent 15,000 years ago, plants and animals that are now confined to high latitudes (e.g., dwarf birch, caribou, and musk ox) were found far south of their current ranges in what is now the Midwest. As the temperature warmed and glaciers retreated, species shifted their ranges to follow their major habitat and climatic optima (Graham, 1992). Thus, shifts of species ranges of 1,000 to 2,000 km occurred with global temperature changes of 4-6°C (7-11°F; Huntley, 1991; Coope, 1995).

E. Community Changes

As an area is affected by climate change and becomes less suitable for different organisms, representation of species within communities may shift. Ecological communities comprise associations of different plant and animal species, each of which has its own specific climatic requirements. The abilities of these species to shift in response to changing climate are likely to be very different. For example, a Townsend warbler that every year can migrate many thousands of miles is much more mobile than the seeds of the Douglas fir forest that comprises its breeding habitat. As climate changes, the composition of communities may be altered as species track their climatic tolerances by moving out of and into an area (or become extinct). Such community shifts could involve relatively subtle changes in species composition (e.g., a grassland becoming dominated by a different suite of grass species), or major switches as one habitat type (e.g., grassland) is replaced by another (e.g., shrubland).

F. Ecosystem Process Changes

Underpinning all ecosystem processes are chemical reactions, and these reactions depend on specific temperature conditions. For example, the breakdown of dead organic material in the nutrient cycling process hinges on the ability of bacteria to chemically degrade and assimilate the material. The rates at which these chemical changes occur are affected by temperature and water regimes. Climatic changes that modify these limiting factors can, in turn, accelerate or decelerate the rates at which the ecosystem processes occur. For a complete discussion of ecosystem processes and climate change, see the Pew Center report by Malcolm and Pitelka (2000).

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G. Complications of Multiple Stressors

The changes identified above are based on purely biological considerations as applied to natural systems, but a variety of other anthropogenic forces are simultaneously stressing natural systems. The Earth's natural systems are increasingly under stress from human exploitation. Habitat destruction, overexploitation, contamination, and the introduction of exotic species into sensitive ecosystems have altered the planetary support systems and continue to take their toll. Primarily because of habitat destruction and overharvesting, 25 percent of the world's remaining mammals and 11 percent of its birds are at significant risk of extinction (IUCN, 1996). Eighty percent of the forests that once existed have been cleared or degraded, and mining, logging, and other developments threaten almost 40 percent of remaining areas (UNEP, 1999). Aquatic habitats are no better off. In North America alone, 70 percent of mollusks and 37 percent of fish are at risk of extinction (Master, 1990). The net result of these pressures is that biological systems may already be in the early stages of a major extinction event that could result in the global loss of one-third of all species by 2100 (Soule, 1991; Thomas et al 2004). Realistic long-term predictions of climate effects are difficult to make because it is within this already stressed environment that climate change will exert its effects.

III. Scope of Review and Evaluation Criteria for Studies

This report attempts to provide information on the strength of the evidence provided by each study individually, and by syntheses across studies, that climate change is already affecting ecological systems or species in the United States. More than 40 peer-reviewed published papers that address observed impacts in the United States were identified and included in this report. Four main criteria were considered in assessing a study's evidence:

Adequacy of design and analyses While most studies incorporate adequate sampling methods and appropriate statistical analyses, data are sometimes anecdotal or have not been statistically analyzed for a significant trend. Also, study systems for which climate had been analyzed as well as organisms' responses were regarded as providing stronger evidence than those that reported only responses.

Extent to which alternative hypotheses were addressed Often, a number of potential factors could have caused an ecological response. For example, either climate change or land-use changes could result in shifts in the distributions of plant communities. Studies that evaluated the potential contributions of all realistic cause/effect mechanisms, rather than focusing exclusively on climate change, were regarded as providing stronger evidence.

Temporal and spatial scale of data Studies with large spatial or long temporal scales provide more conclusive evidence of long-term impacts than small-scale, short-term studies. At a local level, many different local stressors could cause similar changes. As the spatial scale of a study expands, it becomes less likely that any one particular local stressor will coincide exactly with regional climatic change, making it easier to distinguish responses to climate change from responses to other potential stressors. Likewise, studies that take place over long time scales (i.e., decades rather than years) are more likely to distinguish between long-term climate change effects and yearly fluctuations.

Theoretical support and experimental corroboration The degree to which the trajectory of ecological change was consistent with expectations from the scientific community's understanding of climate and

ecology relationships and from prior studies is variable. For some species, a great deal is known about the relationship between climate and the species' ecological response. This information comes from previous empirical work on physiological tolerances to climate extremes as well as from field and laboratory manipulations of temperature and precipitation. Furthermore, long-term studies have provided an opportunity to witness responses to "natural" experiments in which extreme weather and climate years are followed by dramatic changes in the study population. Studies reporting results consistent with those reported in other independent studies are considered to provide stronger evidence.

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IV. Current Observed Climate Change Impacts

Global ecological responses to climate change provide the perspective of a larger context from which to view U.S. climate changes, and they assist in the evaluation of causality and consistency across the strictly U.S. studies that comprise the bulk of this report's analysis. Underlying all observational studies of climate change in the natural world are the issues of how well science can detect true trends among noisy biological data, and, once a trend is detected, whether it is possible to attribute that change to a response to climate change. Although this report focuses on U.S. systems, the following brief review of global studies facilitates attribution to climate change by providing context and corroboration for U.S. responses. These issues of detection and attribution are complex (Parmesan, 2001b), and are more fully described in Box 1.

Box 1

Detection and Attribution in the Biological Realm

This report brings together evidence from many individual studies as well as synthetic worldwide analyses to conclude that global results provide convincing evidence that 20th century anthropogenic global warming has already affected the Earth's biota. However, this seemingly simple statement glosses over the enormous difficulties biologists have encountered in tackling the question of climate change impacts (Parmesan, 2001b). Issues of detection and attribution in the biological realm parallel those in the climate realm. For both disciplines, the challenge lies in deciphering the causes of 20th century trends from correlated data. For both disciplines, conclusions come from more inferential methods of scientific inquiry, rather than from direct experimental manipulation. Further, detecting significant trends in long-term datasets is particularly difficult when data are often patchy in quantity and quality, and when natural yearly fluctuations are typically noisy. Once a change has been detected, attribution requires consideration of multiple non-climatic factors that may confound the effects of climate. It is no surprise, then, that detection and attribution of a climate "signal" in natural systems has been a challenge for climate-change biologists. The final step, attributing these changes to anthropogenic climate change has only been possible with recent global-scale analyses (see discussion in text).

Lines of evidence

Biologists rely on three main lines of evidence to ascribe biotic changes to local or regional climate changes:

- A large body of theory that links known regional climate changes to observed biotic changes (from paleological studies, biogeographic theory, biogeographic models);

- Known fundamental mechanistic links between thermal/precipitation tolerances and the study species (from physiological studies and laboratory and field experimental manipulations);

- Direct observations of climate effects (from long-term field research).

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Issues of scale

Studies of climate-change impacts vary considerably along axes of time, space, and replication (e.g., numbers of populations, numbers of species). Few distributional studies meet the ideal of long-term data collection (more than 50 years), measured at yearly intervals, and across a species' natural range. Because of data limitations, many studies extrapolate range shifts from small-scale range boundary studies. Potential problems arise with this technique, because changes along one part of a species' range may not reflect trends over the whole range (see below).

Issues of confounding factors

Many wild species have shifted their ranges in concert with regional climate shifts. However, the leap from correlation to causation is a particularly difficult phenomenon to document, because land-use changes have strongly affected the distributions of many wild species over the 20th century. It is important, then, to consider the complicating influences of urbanization, conversion of land to agriculture, contamination, naturally occurring pathogens, over-grazing, and invasion by exotic species. The influence of these other factors may never be completely separated out; however, they can be minimized to the extent that any signal due to climatic factors can be discerned.

At larger spatial scales, the effects of many of these non-climate factors may be more easily teased out from the effects of climate change. For many species with ranges that span much of North America, the destruction of habitat by urbanization, for example, might cause localized loss of populations in and near cities, creating a patchwork of "holes" in a species' range. In contrast, increased temperatures would be expected to cause a general northward shift in that range (or more locally, an elevational shift uphill). Thus, observations of northward and uphill range shifts over large scales indicate a response to general warming.

Interpretation of **Species Range Changes**

Notes: The above figure depicting hypothetical scenarios for three imaginary species, demonstrates the risk of drawing conclusions from studies of species conducted at the edge of their ranges. The green squares represent generic continental land masses, each containing a species whose range spans the bulk of the continent. (a) Species "a" is disappearing from its southern range and expanding along its northern range edge. (b) Species "b" is expanding along all range edges in all directions. (c) Species "c" is disappearing from parts of its southern edge as well as parts of its northern edge, and it is expanding along only one portion of its northern edge. (d) A blow-up of the northwestern corner of all species' ranges shows that they are all expanding along that part of the northern range edge.

Source: Parmesan (2001b)

Observed Impacts of global climate change in the U.S.

Positive publishing bias

As with any phenomenon, there is less incentive to research or to publish a "non-result" (i.e., documentation of no response to climate change) than there is to publish an observed response. This bias is perhaps most evident in the few studies of evolutionary responses to climate change. Inevitably, these studies are of individual species with a high probability that only positive results have been written up in the context of climate change. For other types of response, however, studies are increasingly being published that examine multi-species assemblages (e.g., birds of Monteverde Preserve; Pounds et al., 1999), or even more complex, multi-community ecosystems (e.g., coral reefs; Hoegh-Guldberg, 1999). Such studies, by incorporating data across species, result in publication of data showing species/systems that are and are not responsive to climate change. These multi-species studies allow an estimate to be made of the proportion of wild species that have responded to recent climate change (Parmesan and Yohe, 2003).

Scientific rigor through large-scale syntheses

The issues of scaling, confounding factors, and publishing bias are real but not insurmountable. These issues are minimal when large-scale syntheses are conducted that assess impacts over many hundreds of species and regions. Sufficient individual studies have been published to allow for such global analyses and each of these has found a clear climate-change signal in observed biological changes worldwide (IPCC, 2001b; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003).

A. Globally Coherent Signals of Climate Change Impacts

Global results provide convincing evidence that 20th century anthropogenic global warming has already affected the Earth's biota. These changes have been reviewed in several recent scientific publications (Hughes, 2000; IPCC, 2001b; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003, Parmesan in press). One meta-study synthesizes the results of many independent studies that describe long-term observations of almost 1,600 species across the globe (Parmesan and Yohe, 2003). This synthesis focuses on multi-species studies; hence, species that have not responded to recent climate change were documented along with those that have responded, allowing for an estimation of the overall impact of climate change. The analysis showed that about half of the species studied exhibited significant changes in their phenologies and/or distributions over the past 20 to 140 years. These changes are not random; rather they are systematically in the direction expected from regional changes in the climate. The species' responses have been occurring in diverse ecosystems (from temperate terrestrial grasslands to marine intertidal zones to tropical cloud forests), and in a wide variety of organisms including birds, butterflies, sea urchins, trees, and mountain flowers (Table 1).

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Table 1

A **Global Summary** of Observed Changes

Climate change prediction	Changed as predicted	Changed opposite to prediction	Statistical likelihood of obtaining pattern by chance
Earlier timing of spring events	87%	13%	Less than one in a billion[1]
Extension of species' range poleward or upward shift in elevation	81%	19%	Less than one in a billion[1]
Community abundance: cold-adapted species declining and warm-adapted species increasing	85%	15%	Less than one in a billion[1]

Notes: A global summary of observed changes from more than 30 studies shows a systematic change in the direction predicted by regional climate change. Data available for 1,598 individual species show that 944 (59 percent) detectably changed, mainly (80-90 percent) in the direction predicted by regional climate change.

[1] Binomial test ($P < 0.1 \times 10^{-12}$)

Source: Adapted from Parmesan and Yohe (2003)

Important diagnostic patterns specific to climate change impacts helped to "finger" global warming as the driver of the observed changes in natural systems (Parmesan and Yohe, 2003). These patterns include differential responses of cold-adapted and warm-adapted species at the same location, and species' tracking of decadal temperature swings, such as shifting southward during cool periods and northward during warm periods. Such diagnostic "sign-switching" responses were observed in 294 species spread across the globe, ranging from oceanic fish to tropical birds to European butterflies.

At the global level, climate scientists have attributed the majority of warming in the past 50 years to the human-caused increase in greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and certain industrial gases. The warming influence of these greenhouse gases has been estimated to be more than six times as powerful as solar influences (IPCC, 2001a). At the global scale, then, it is possible to relate greenhouse gas-driven climate change to biological change. The syntheses of recently published studies on worldwide changes in plants and wildlife provide convincing evidence that recent anthropogenic global climate change has affected natural systems.

Linking global trends to regional or local changes is not entirely straightforward, however. The larger the study area, the smoother the climate signal and the greater the ease in detecting an anthropogenic finger-print (IPCC, 2001a). As one focuses on smaller geographic areas, yearly climatic variation becomes strong enough to mask the types of anthropogenic signals that climate scientists use to link recent warming to human-induced increases in atmospheric CO_2. Thus, no single weather event, or even long-term trends in a single location, can be unambiguously linked to "anthropogenic climate change." Therefore, changes in plants and animals at single locations also cannot be unambiguously linked to anthropogenic climate change. However, over large regions some signals of an anthropogenic greenhouse gas influence have been detected.

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Observed Impacts of global climate change in the U.S.

At the scale of the entire United States, certain patterns of change in climate suggest the influence of greenhouse gases (Karl et al., 1996; Easterling et al., 1997; Groisman et al., 1999; Kunkel et al., 1999):

- Average yearly precipitation has increased overall

- Precipitation has occurred in fewer, more extreme events

- Average temperature has risen in rural sites, mainly due to increased nighttime temperatures rather than increased daytime temperatures

- Winters have warmed more than summers

- Warming has been more extreme at high latitudes (Alaska) than at lower latitudes (the contiguous United States)

Finally, several modeling studies indicate that a greenhouse gas influence is detectable in U.S. climate trends of the past 50 years (Karoly et al., 2003; Stott, 2003; Zwiers and Zhang, 2003). Thus, the same types of biological changes observed at a global scale can be expected to be replicated within the United States. The next section of this report evaluates the extent to which this has actually happened.

B. Observed Changes in the United States

Physical and Physiological Changes

Studies of small mammals in the southwestern United States provide excellent documentation of physical changes in response to both historical and current climate change. Not enough is understood about the biology of these animals, however, to know whether these physical changes involved genetic evolution or merely an immediate, plastic response to a changing environment. Small mammals have exhibited relatively slight range shifts since the last glacial maximum compared with insects and plants. This might give the impression that they are little affected by climatic regime. On the contrary, paleological and modern studies show that they are quite sensitive. An eight-year study of body size of white-throated wood rats in New Mexico shows that these small mammals responded to warmer winters and hotter summers by shrinking in body size by 16 percent (Smith and Betancourt, 1998). This study was able to pinpoint a 2-3°C (4-5°F) rise in temperature as the driver of the size change, simultaneously demonstrating that change in precipitation was not correlated with size change. The reasons for this size change are unknown, but being smaller may reduce overheating in the summer, warmer winters may favor the survival of the smallest individuals, or size may reflect a response to changes in vegetation, and therefore in the wood rat's diet.

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Phenological Changes

Phenological Changes in the United States

Studies across the United States provide evidence that global climate change has already changed the timing of biological events. Results from studies of breeding birds comprise the first—and strongest—U.S. evidence of phenological change. Brown et al. (1999) studied Mexican jays *(Aphelocoma ultramarina)* in the Chiricuahua Mountains of southern Arizona. The researchers found that between 1971 and 1998, the breeding season of the birds advanced by an average of 10 days. The laying date of first clutches was significantly correlated with spring monthly temperatures, which increased over the duration of the study (e.g., April monthly minimum temperatures increased by about 2.5°C [4.5°F]). No consistent trends in precipitation were recorded. This study benefits from its long time period, its methodology of following individually marked birds throughout their lives, and the tight correla-tion between climate change and ecological response. One limitation is that it was confined to a relatively small geographic scale, and may not represent responses of the species as a whole.

In another avian study, Dunn and Winkler (1999) eliminated the problem of small spatial scale by adopting the whole of North America as their study area. Using more than 3,400 nest records from 1959 to 1991, the authors studied the timing of the initiation of breeding in tree swallows *(Tachycineta bicolor)* throughout their range in the contiguous United States and Canada. The authors showed that the average date of laying advanced by nine days (Figure 3). They

Figure 3

Observed Changes in the

Average Laying Date for Tree Swallows
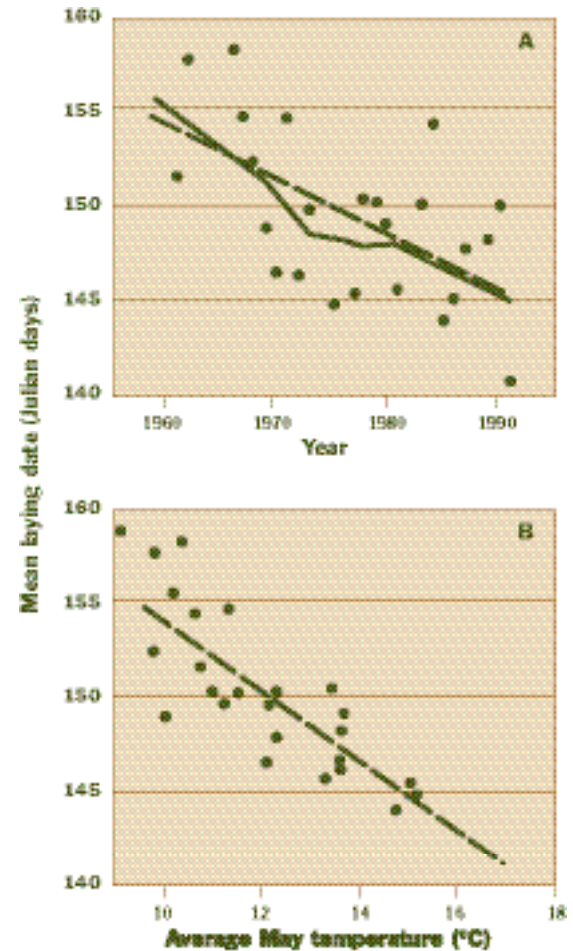
Notes: Figure A represents observed changes in the average egg-laying date for tree swallows (in Julian days; i.e., days of the year) from 1959 to 1991. Over this time period, the average laying date advanced by 9 days (from Julian dates 145 to 154), a change that is statistically significant.[1] Figure B depicts the relationship between average May temperature (°C) and the laying date over a 30-year period, indicating that laying dates occur significantly earlier as May temperatures increase.[2] Dashed lines represent linear regression, and the solid curve in Figure A is from a LOWESS (locally weighted scatter plot smoothing; Wilkinson, 1992).

[1] $r^2=0.41$, n=32, p=0.0001
[1] $r^2=0.75$, p<0.0001
[3] tension=0.05

Source: Dunn and Winkler (1999)

Observed Impacts of global climate change in the U.S.

also found that the timing of laying throughout the study period was significantly correlated with the average May temperature.

Inouye et al. (2000) report results of almost 25 years of monitoring (between 1975 and 1999) at Rocky Mountain Biological Laboratory in Colorado. The annual date of snowmelt and plant flowering did not change during this time. However, yellow-bellied marmots *(Marmota flaviventris)* are emerging approximately 23 days earlier from hibernation than they did in the 1970s, and there is a slight (non-significant) trend toward the earlier spring arrival of American robins *(Turdus migratorius)*. Temperatures have risen significantly in the Rocky Mountain region during the study period, and there has been a (non-significant) 1.4°C (2.5°F) rise in temperature at a station near this site.

Most phenological studies take place over a relatively short time span—fewer than 30 years. However, Bradley et al. (1999) were able to take advantage of observations on the timing of spring events made by Aldo Leopold on a Wisconsin farm in the 1930s and 1940s. Comparing Leopold's data on birds and native flowers to their own surveys in the 1980s and 1990s enabled them to look for long-term trends over a 61-year period. They found that the more recent surveys indicated that spring events for many species are taking place substantially earlier than in Leopold's time; for example, northern cardinals sing 22 days earlier, forest phlox blooms 15 days earlier, and butterfly weed blooms 18 days earlier. Of 55 species studied, 18 (35 percent) show advancement of spring events, while the rest show no change in timing (with the exception of cowbirds arriving later). On average, spring events occur 7.3 days earlier in the 1990s, coinciding with March temperatures being 2.8°C (5.0°F) warmer.

One other long-term (100-year) study focused on frogs in Ithaca, New York. Gibbs and Breisch (2001) compared recent records (1990-1999) with a turn-of-the-century study (1900-1912). They found that males in four out of six species begin courtship calling 10-13 days earlier than they did in the early 1900s (the other two species showed no change). Maximum temperatures in the study area have increased by 1.0-2.3°C (1.8-4.1°F) during five of the eight months critical for the frogs' reproductive cycle. Other studies of frogs show that reproduction is closely linked to both nighttime and daytime temperatures (Beebee, 1995).

With the exception of the tree swallow study, most of the U.S. studies mentioned so far have the limitation of being small in geographical scale—often encompassing only a single population. Thus, a concern is that these studies might not address what is happening throughout the bulk of a species' range. They have also tended to be near the northern limit of a species' range, which one might expect to

be most limited by spring temperatures, and thus may be more likely to show a stronger response than populations further south in the species' range.

Satellite Imagery and Geographic Analysis

Satellite imagery has allowed for very large-scale geographic analyses. Using satellite images from northern latitudes for the period 1981-1999, Myneni et al. (1997) and Zhou et al. (2001) show that the growing season has lengthened by about 12 days. Lucht et al. (2002) demonstrate that changes in growing season followed yearly temperature swings, reducing the likelihood that these patterns are due to CO_2 fertilization (i.e., the enhancement of vegetation productivity in response to higher atmospheric CO_2 concentrations). These studies have the advantage of being very large scale—covering thousands of square miles from the northern United States to the North Pole and down into Siberia and northern Europe. On the other hand, these studies extend over only 18 years, making it difficult to tease apart small cycles from true long-term trends.

Urban Heat Islands and Interpretation of Phenological Trends

The studies reviewed above link biological responses to local or regional climate trends, but to what extent are these local trends tied to anthropogenic global climate change? In urban areas, the answer is complicated by a suite of human activities that alter climate locally. High buildings decrease airflow, concrete and asphalt radiate heat, and natural vegetation, which would normally cool the surroundings by evapotranspiration, is removed. These and other alterations create an "urban warming" effect, which, while also anthropogenic in origin, is separate from greenhouse gas warming. Urban warming effects have been documented in U.S. climate records, and they account for about 0.06°C (0.1°F) of the warming from 1901 to 1984 (Karl et al., 1988).

For biological systems, trends toward earlier spring events in cities are quite clear (Zhang et al., 2004). Because of the interest of amateur naturalists in recording the "signs of spring," quite a few datasets cover the onset of flowering and the first singing of birds in American cities. An impressive dataset covering the past 30 years of first-flowering records for more than 600 plant species was assembled by a group of amateur naturalists and scientists in the Washington, D.C., area (Abu-Asab et al., 2001). An analysis of the 100 species with the best records showed that 89 species were flowering earlier (by 4.5 days) at the end of the period, and only 11 species were flowering later.

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The overall average advancement of flowering of 2.5 days was statistically related to a local increase in nighttime temperatures of 0.2-1.2°C (0.4-2.1°F). A similar study was conducted in Edmonton, Alberta (Canada), which incorporated records dating back to 1901 (e.g., for poplars), and it found that overall spring flowering events have advanced by 8 days over the past 60 years (Beaubien and Freeland, 2000). Most surprisingly, a significant link was found between yearly flowering dates in Edmonton and sea-surface temperatures in the Pacific Ocean, nearly 600 miles away.

As found in the above studies, background climate warming effects in cities are exacerbated because of additional impacts of urban warming. Wildlife and plants in cities experience higher temperatures than their countryside counterparts. The complexity of climate drivers in urban areas therefore makes it difficult to use these extensive datasets to look for impacts of CO_2-induced climate change. A European study (Roetzer et al., 2000) explicitly quantified these different effects by comparing phenological trends between urban and rural sites. Analyzing records from 1951 to 1995, they found that the urban sites showed significantly stronger shifts toward earlier spring timing than nearby rural sites—by 2-4 days. An analysis of "greening" in the United States via satellite imagery also concluded that urban areas have experienced an earlier onset of spring compared with rural areas (White et al., 2002). Thus, spring events are occurring earlier in cities because of increases in local temperatures, but, as Roetzer et al. (2000) show, any urban study should be cautiously interpreted with respect to global greenhouse warming. For these reasons, this report does not consider results from urban studies in forming its conclusions on general impacts of greenhouse gas-driven climate change.

Global Phenological Changes

Observed phenological trends in the United States are mirrored in other parts of the world. In the United Kingdom, Crick et al. (1997), analyzing more than 74,000 nest records from 65 bird species between 1971 and 1995, found that the average laying dates of first clutches for 20 species have advanced by an average of about 9 days, similar to the findings of the U.S. studies. Butterflies in Europe show similar correlations between dates of first appearance and spring temperatures, and 26 out of 35 species are appearing earlier in spring (Roy and Sparks, 2000). In Great Britain, the red admiral *(Vanessa atalanta)* is appearing more than a month earlier than it did 20 years ago. Amphibian breeding has advanced by 1-3 weeks per decade in England (Beebee, 1995). Throughout Europe, trees are leafing out earlier, shrubs and herbs are flowering earlier, and fall colors are coming later, leading to an overall lengthening of the vegetative growing season by nearly 11 days since 1960 (Menzel and Fabian, 1999; Menzel 2000).

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Table 2

Reported **Changes in Phenological Events** Induced by Climate Change

Organism	Study period (years)	Spatial scale	Phenological event	Phenological shift	Reference
Mexican jay	1971-1998	Mountain range in southern Arizona	Egg laying	10 days earlier	Brown et al., 1999
Tree swallow	1959-1991	North America	Egg laying	9 days earlier	Dunn and Winkler, 1999
Various	1930-1990s	One farm in Wisconsin	Breeding, migration, flowering	7.3 days earlier	Bradley et al., 1999
Amphibians	Early 1900s vs. 1990s	One city in New York state	Breeding	10-13 days earlier	Gibbs and Breisch, 2001
Plants	1981-1999	Boreal region	Greening period	12 days longer	Myneni et al., 1997; Zhou et al., 2001; Lucht et al., 2002
Flowering plants	30-year period	Washington, D.C.	Flowering	4.5 days earlier	Abu-Asab et al., 2001

In summary, several studies across the United States provide strong evidence on their own that the timing of certain ecological events has changed over the 20th century and that the probable cause is long-term climate change (Table 2). When placed in the context of results from elsewhere in the Northern Hemisphere, the cumulative evidence strengthens this causal link.

Range Shifts

Many wild species have shifted their ranges in concert with regional climate shifts (Parmesan and Yohe, 2003; Parmesan, in press). A range shift is a particularly difficult phenomenon to document, because land-use and other changes also have strongly affected the distribution of many species over the 20th century. Any study of climate change must, therefore, attempt to rule out the complicating influences of urbanization, conversion of land to agriculture, contaminants, naturally occurring pathogens, and invasion by exotic species. The influence of these other factors may never be completely ruled out; however, they can be minimized to the extent that any signal due to climatic factors becomes detectable.

At larger spatial scales, the effects of many of these confounding factors may be distinguished from the effects of climate change. For example, many species have ranges that span much of North America. The destruction of habitat by urbanization (for example) might cause localized losses of species in and near cities, creating a patchwork of "holes" in a species' range. In contrast, increased tempera-tures would be expected to cause a general northward shift in that range (or more locally, an elevational shift uphill). Such shifts may provide the best evidence of climate-change effects.
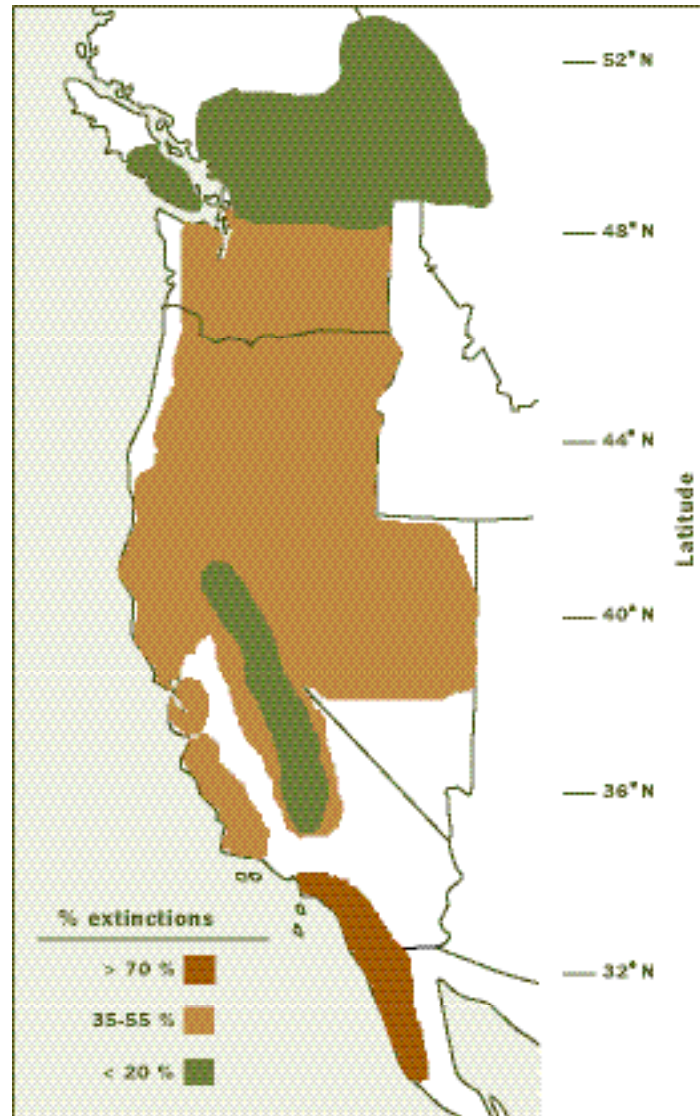
Edith's Checkerspot Butterfly

Edith's checkerspot butterfly (*Euphydryas editha*), which lives in western North America from Mexico to Canada, has demonstrated a clear range shift both northward and upward in elevation in response to warming temperatures (about a 0.7°C or 1.3°F rise; Parmesan, 1996, 2003). This range shift was driven by very high numbers of extinctions among southern and low elevation populations. In this study the problem of teasing out the effects of habitat degradation on population extinctions from the effects of climate change were addressed directly by only including sites in which the habitat was still suitable, defined by an abundance of host plants (species within the snap-dragon family) and good nectar resources (Parmesan, 1996). Further, the basic biology of this butterfly is well understood, having been intensively studied for more than 40 years.

In particular, it is well documented that populations are strongly influenced by climate, and that severe weather events cause population declines and even extinctions. Other factors that could also affect population extinctions, such as parasitic wasps, have been shown not to be important drivers of yearly changes in population size (Moore, 1989).

Population Extinctions of Edith's Checkerspot Butterfly

Notes: This map of western North America depicts the current status of Edith's checkerspot butterfly (*Euphydryas editha*) populations throughout the species' range, based on a census conducted from 1993 to 1996. The current range was compared to historical records dating from 1860 to 1983. In areas shaded green, fewer than 20 percent of the populations had become extinct (northern or high altitude areas); in areas shaded beige, about 40 percent of the populations had become extinct; in the area shaded brown, nearly 80 percent of the populations had become extinct. At all sites, the habitat remained apparently suitable, indicating climate as the likely driver of observed changes. The brown area is approximately the range of the endangered subspecies, Quino Checkerspot (*Euphydryas editha quino*).

Source: Parmesan (1996)

Observed Impacts of global climate change in the U.S.

The study's 1993-1996 census documented that nearly 80 percent of historical populations had become extinct in the southern part of Edith's checkerspot's range (Parmesan, 1996). These populations represent the known range of an endangered subspecies of Edith's checkerspot butterfly, the Quino butterfly (E. editha quino). Its entire range occurs in southern California (United States) and northern Baja California (Mexico), an area which has not only experienced significant warming, but drying as well (Karl et al., 1996). Previous field and laboratory work on a similar subspecies, the Bay checkerspot (E. editha bayensis), showed that with warmer temperatures or drier conditions, the host plants tend to dry up before the caterpillars can fully develop (Singer, 1972; Singer and Ehrlich, 1979; Weiss et al., 1988).

A climate-driven mismatch between the caterpillar growth and the timing of the plants drying up at the end of the season is the likely mechanism for the very high population extinction rates along this southern-most range edge of Edith's checkerspot. This process was visible during the most recent census (1993-1996), where there were many instances of eggs hatching on plants that were already half-dry. The tiny 1-2 day-old caterpillars were unable to walk the inch or more to nearby plants (and those often were in no better condition), and thus starved to death (Parmesan, personal observation).

In contrast, populations of Edith's checkerspot are doing well at their northernmost range boundary (in Canada) and at the highest elevations (in the Sierra Nevada). The population extinction rate in Canada is less than 20 percent, and in the high mountains it is less than 15 percent (Figure 4). This asymmetrical trend in extinctions at the range edges has shifted the butterfly's range northward by 55 miles and upward by 409 feet. The individual butterflies have not actually moved, but rather the populations at the southern end of the range and at lower elevations have become extinct much faster than populations at the northern end of the range and at high elevations (Parmesan, 1996).
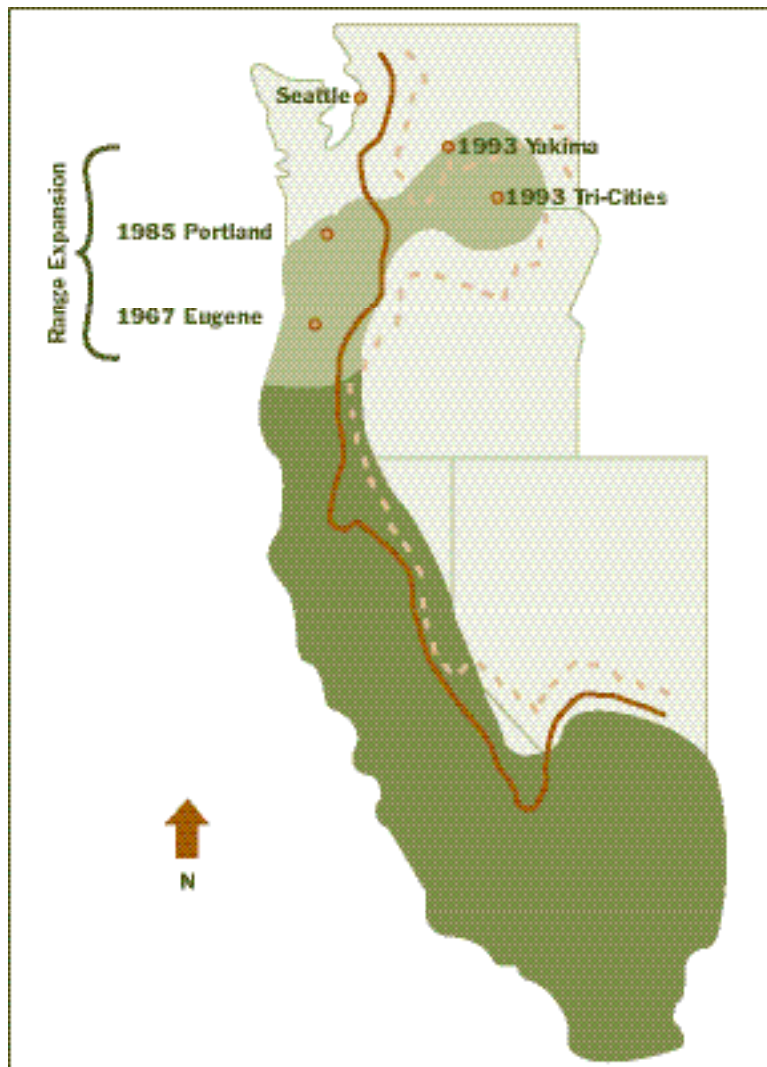
Edith's checkerspot also provides a good example of how the effects of land-use change give different expected patterns of population extinction than do the effects of temperature rise. Urbanization and agricultural growth in the western United States have caused loss of populations in the areas in and around Seattle, San Francisco Bay, Los Angeles, and San Diego, as well as in the agricultural valleys throughout central Washington, Oregon, and California. These areas of high habitat destruction coincide with the ranges of three federally listed endangered subspecies of Edith's checkerspot: the Bay checkerspot, Taylor's checkerspot, and Quino checkerspot. In spite of this, however, the species as a whole has shifted its range northward away from Mexico and toward Canada. Sufficient suitable habitat remained outside of these large areas of destruction to allow for the detection of a large-scale range shift for this species.

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Sachem Skipper Butterfly

Figure 5

The range of the sachem skipper butterfly *(Atalopedes campestris)* has expanded 420 miles from California to Washington State in just 35 years (Crozier, 2003; Figure 5). It has expanded northward into areas where winters were previously too cold for it to survive. During the warmest year on record (1998), it expanded its range north by 75 miles. Initial transplant experiments, which artificially placed young caterpillars north of where they naturally lived, gave puzzling results, because they seemed to indicate that this butterfly wasn't limited by climate, since it initially thrived in these colder habitats. However, longer-term censuses that look at year-round dynamics of natural populations at that range edge show very high overwinter death rates. Laboratory experi-

| **Overwintering Range** of the Sachem Skipper Butterfly |

Notes: The above figure depicts the overwintering range of the sachem skipper butterfly, which includes Washington, Oregon, California, and Nevada. The historical range is shaded green. Range expansion over the past three decades is shown in light green shading. Colonization dates of A. campestris in four cities in Oregon and Washington show the chronology of the range expansion. Contour lines represent the January average minimum 4°C (39°F) isotherm from 1950 to 1959 (solid) and 1990 to 1998 (dotted).

Source: Adapted from Crozier (2003)

ments on temperature tolerance show that this species is easily killed by a single short exposure to extreme low temperatures (-10°C or 14°F), or by repeated exposure to temperatures around -4°C (25°F). Many northern insects hibernate in winter, placing themselves in a low-energy state that allows them to survive the extremes of northern winters. The sachem skipper butterfly, on the other hand, is a southern species, and it stays active all winter long. By remaining active, it is vulnerable to being killed by sudden frost, which is the likely force determining how far north the species can successfully breed.

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Red Fox

The red fox *(Vulpes vulpes)* has shifted its range north, which appears to have caused retreat of its competitor, the arctic fox *(Alopex lagopus)*. The red fox occupies much of North America and Eurasia, whereas the arctic fox is generally confined to the arctic regions. The red fox has physical attributes that make it less well adapted to cold conditions than the arctic fox (e.g., longer ears and limbs, which increase rates of heat loss). When the two species are artificially placed together, the red fox is competitively dominant over the arctic fox. That is, the red fox is more aggressive, is much larger in body size, and wins in direct fights with the arctic fox (Hersteinsson and Macdonald, 1992). Recent studies, together with historical records, suggest that these two species cannot coexist. The arctic fox is thought to be unable to extend its range farther south because of the presence of the aggressive red fox. On the other hand, the red fox has hitherto been unable to live farther north because of the low temperatures. During the 20th century warming of about 2°C (4°F) that occurred in northern Canada, however, the red fox expanded northward (Hersteinsson and Macdonald, 1992). The northward shift was least in areas where temperatures rapidly drop off to the north, and greatest in areas where the temperatures decrease gradually to the north, bolstering the conclusion that the red fox is responding to temperature shifts. On Baffin Island, the red fox expanded northward more than 600 miles over a 30-year period. As the red fox advanced northward, the arctic fox retreated northward (either due to competition with the red fox or to the warming trend, or both). If these shifts continue, the range of the arctic fox will be further diminished.

Southern Latitude Species Range Shifts

Warming trends in the United States are perhaps most telling by the movements of southern latitude species into more temperate areas. The rufous hummingbird has undergone a dramatic shift in its winter range (Hill et al., 1998). Thirty years ago, it wintered mainly in Mexico, and between 1900 and 1990 there were never more than 30 winter sightings per year (usually far fewer) in the United States. In the early 1990s, the sightings increased to more than 100 per year. The numbers of sightings have increased steadily since then—up to 1,643 by 1996, with some evidence that further northward extension has occurred since 1996 (Howell, 2002). Over this same time period, winter temperatures in the Gulf Coast States have risen by about 1°C (2°F; IPCC, 2001a). Also, in Florida, two new species of tropical dragonfly established themselves in 2000, an apparently natural invasion from Cuba and the Bahamas (Paulson, 2001).

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Altitude Changes

Evidence for other wildlife moving up mountains is beginning to emerge. Researchers are beginning to replicate the type of study conducted with Edith's checkerspot butterfly by recensusing historically documented populations and looking for non-random patterns of population extinctions which would indicate elevational shifts. A 1990s recensus of 25 historic sites for pikas (*Ochotona princeps*) on mountains in the Great Basin, Nevada revealed that seven populations have become extinct since the 1930s (Beever et al., 2003). Extinct populations were at significantly lower elevations than those still present (Mann-Whitney U test, $P<0.005$, done by Parmesan). However, the extinct populations were also geographically clumped, making it impossible to rule out co-occurring human disturbance factors such as a common response to overgrazing or other local habitat changes (Figure 6). But for this particular species, human disturbance is likely to be minimal, because all pika habitat is on high-elevation talus (scree) slopes, which are generally not suitable for ranching or recreational activities.

Figure 6

Changes in Pika Populations in the Southwest United States
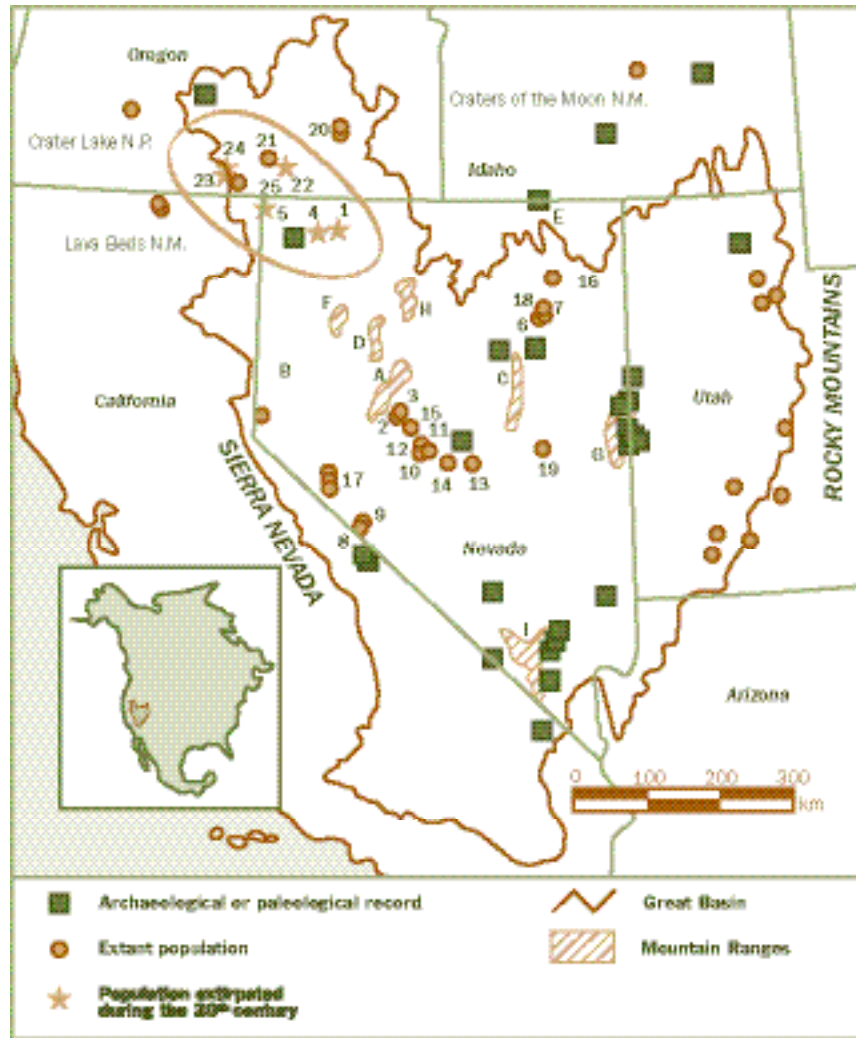
Notes: The above figure represents a map of pika populations from historical records and results of a modern re-census (numbered) showing which populations are still present (circles) and which have gone extinct (stars). Ancient sites that have not been occupied in modern times are shown by squares. Lettered mountain ranges possess appropriate talus habitat at suitably high elevations, but researchers found no pikas there during exploratory searches. Sites on the eastern slope of the Sierra Nevada Mountains were too numerous to include with clarity. Note that extinct pika populations are clumped in the northwest corner of the study area (circled in light brown).

Source: Adapted from Beever et al. (2003)

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Range Shifts in Response to Changes in Rainfall

Significant changes in rainfall have occurred in the past century, which may be more important than temperature for some species. The United States has experienced an overall increase in precipitation since 1910, particularly in the western part of the country (Karl et al., 1996; Groisman et al., 1999, 2001). This increase in precipitation has led, for example, to more snow falling in the highest elevations of the Sierra Nevada (Johnson et al., 1999), but an overall decline in snowpack in this mountain range, likely due to warmer temperatures causing an upward shift in the snowline (Johnson et al., 1999). Several physiological and ecological studies indicate that the breeding or overwintering distributions of many birds are restricted by some threshold climatic conditions (Root, 1988; Mehlman, 1997).

Johnson (1994) concentrated on North American Breeding Bird Survey (BBS) data for the western United States and noticed a striking pattern. Twenty-four species had shifted their ranges over the previous three decades. A significant tendency toward northward shifts was seen, with 14 out of 24 species showing either the northward expansion of subtropical species or the contraction of the southern range edge of north-temperate species (i.e., those with the bulk of their distribution in Canada). Only four species showed opposite movements.

However, the detailed pattern of change is more complex than this. For many species, the dry areas of the Great Basin region (most of Arizona, Nevada and Utah, western Colorado) represent a barrier. Thus, some species with the bulk of their range in Mexico only reach as far north as southern Arizona, eastern species extend only as far west as the Rocky Mountains, western species are found only in the Pacific coastal states, and north-temperate species reside mostly in Canada, with their southern boundaries just extending into Idaho or northern Nevada. The Great Basin has historically been unoccupied by these species. However, in the past 30 years, many have extended their breeding ranges into previously unoccupied Great Basin areas. Thus, southward, eastward, and westward shifts have been seen along with northward shifts. Johnson attributes these changes to increases in rainfall, and, indeed, the vegetation of the southwestern United States shows signs of changing toward woody species and away from succulent and herbaceous species. At least part of this increased "woodiness" is believed to be due to increased rainfall (see discussion of vegetation changes under "Community Changes" to follow).

Data from the BBS are not perfect, because the survey is conducted largely by volunteer amateurs with varying degrees of adherence to survey protocols and varying levels of expertise. Further,

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levels of survey intensity seem to be concentrated around population centers, rather than around the locations of birds. Nevertheless, the BBS represents a large set of fairly good quality data that has at least some coverage over the entire United States and southern Canada (and high coverage in the northeastern United States) and spans more than 30 years. Further analyses of BBS data, such as Johnson's, will continue to be useful.

Shifts in High Latitude Tree Lines

Multiple studies of tree lines at high latitudes in the Northern Hemisphere show upward and poleward shifts in the 20th century. Changes in tree line have been monitored directly by following the distribution of seedlings and indirectly by measurements of the width of annual growth rings—shifts in tree line show up as increased tree ring growth for mature trees at northern or upper boundaries, and as decreased growth at southern or lower boundaries (Grace et al., 2002). In the temperate latitudes (40-70°N), in which the greater part of North America lies, tree line roughly coincides with elevations in which the average July temperature is 10°C (50°F; Tuhkanen, 1993; Körner, 1998). However, the precise elevation and latitude of tree lines results from a complex response to temperature, precipitation, fire regimes, herbivory, and outbreaks of pathogens (Luckman and Kavanagh, 2000; Grace et al., 2002). Mechanistically, patterns of variability in temperature and precipitation are considered to be far more important than simple isotherm averages (Swetnam and Betancourt, 1998).

Globally, several studies show poleward and upward movement of tree lines in certain localities (Kullman, 2001; Moiseev and Shiyatov, 2003). Within North America, general upward movement of tree line has occurred in the Canadian Rocky Mountains as temperatures have risen by 1.5°C (2.7°F; Luckman and Kavanagh, 2000). However, given the complex nature of the interacting factors determining tree line, interpretation of 20th century trends has typically not been so straightforward. One puzzling pattern seen in many studies is a strong response to warming in the late 1930s and 1940s at some sites, but a weaker (or absent) response in recent warm decades (1970s to the present; Innes, 1991; Jacoby and D'Arrigo, 1995; Lescop-Sinclair and Payette, 1995; Briffa et al., 1998a,b). The explanation for different responses may lie in differences in rainfall during the two warm periods. At sites in Alaska, recent decades have been relatively dry, which may have prevented trees from responding to current warming as they did before (Briffa et al., 1998b; Barber et al., 2000). In contrast, tree lines in the arid Southwest have shown unprecedented increased tree ring growth at high elevations—this area has experienced not only warmer temperatures but also increased rainfall (Swetnam and Betancourt, 1998).

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Sea-Level Rise

Sea-level rise has caused some contraction in the distribution of coastal species. Globally, an 8-10-inch rise in sea level has been observed since 1901, due primarily to thermal expansion as the oceans have warmed by 0.6°C (1.1°F; IPCC, 2001a). The pine forest barrens in the Florida Keys have been steadily eliminated from the lowest-lying areas because of increased ground water salinity caused by sea-level rise (Ross et al., 1994). They are now restricted to the hillier areas, which has resulted in habitat loss for species that depend on the pine barrens.

Since the 1940s, a salt marsh on Barn Island, Rhode Island, has undergone large changes in its vegetation community composition, with increases in cover of low-marsh species such as smooth cordgrass *(Spartina alterniflora)*, forbs, and grasses, at the expense of the high-marsh communities (dominated by saltmeadow cordgrass *[Spartina patens]* and saltmarsh rush *[Juncus gerardii]*; Warren and Niering, 1993). This example indicates that responses to rising sea level are not likely to be simple landward shifts of individual species. The entire marsh community appears to be shifting towards low-marsh species. Warren and Niering (1993) suggest that sea-level rise has been faster than the rate of new accumulation of marsh substrate, leading to less habitat for high-marsh species. At the site with the most vegetation change this may be linked to excessive human manipulations (e.g., ditching) affecting water flow and reducing sediment input. However, in recent years other marshes in the same system have been showing (less-pronounced) vegetation changes in the same directions. Loss of low marsh species where human impact has been minimal indicates that even relatively undisturbed sites may suffer similar problems to their more urban counterparts. Simply shifting inland as the sea level rises appears unlikely regardless of the degree of coastal development—the rates of change differ, but the ultimate result may not.

Community Changes

Changes in the structure of local plant and animal communities at some sites indicate that warm-adapted species are flourishing, while cold-adapted species are declining. This trend has been particularly well documented in the Californian coastal waters of the Pacific Ocean, which have experienced a 60-year period of significant warming in nearshore sea temperatures (Figure 7; Barry et al., 1995; Holbrook et al., 1997; Sagarin et al., 1999).
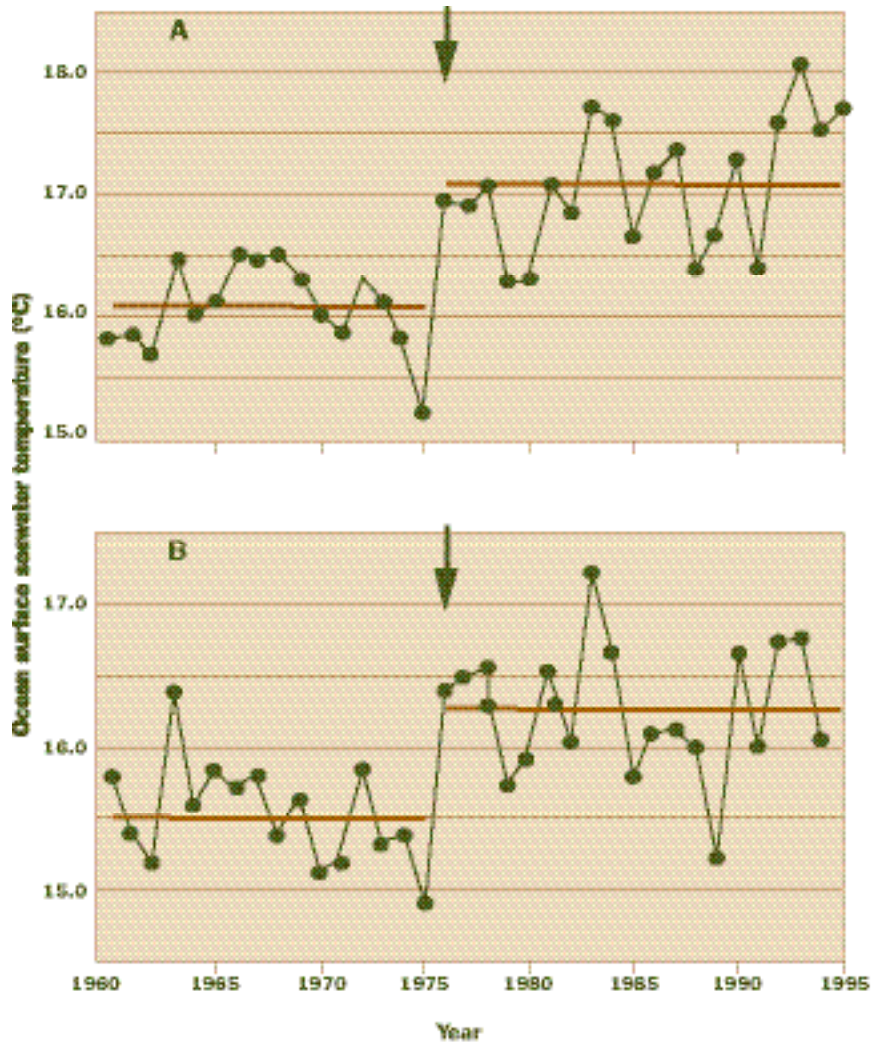
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Figure 7

Changes in **Average Ocean Surface Temperature**

Notes: Average annual ocean surface seawater temperatures off the California coast (1960–1995) show a warming trend at (A) Scripps Pier and (B) Santa Barbara. Horizontal lines indicate long-term average temperatures for the periods 1960-1975 and 1976-1995. Arrows indicate a regime shift from cooler to warmer waters during 1976-1977.

Source: Holbrook et al. (1997)

A marine sanctuary in Monterey Bay has provided a valuable, relatively undisturbed environment to look for responses to the rise in ocean temperatures. In addition, Monterey Bay is an interesting example because it is located in a small region of overlap between northern species (with ranges extending as far north as Alaska), and southern species (with ranges extending as far south as Mexico). Fixed plots were installed in intertidal areas and characterized in 1931. Researchers in the 1990s were able to locate and resurvey these plots. Compared with the earlier survey, abundances of nearly all southern species had increased significantly while abundances of nearly all northern species had decreased (Barry et al., 1995; Sagarin et al., 1999). Thus, the composition of this intertidal community has shifted markedly in response to water temperature change. Holbrook et al. (1997) found similar shifts over the past 25 years in kelp forest fish communities off the southern California coast (Figure 8). Southern fish species have greatly increased their proportionate dominance in the community composition, at the expense of more northern species. Farther offshore, Roemmich and McGowan (1995) show that the population abundance of plankton species also greatly

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decreased over a 43-year period (1951-1993) during which the oceanic temperature increased. Taken as a whole, this body of work in the California Current and associated intertidal areas has demonstrated clear effects of warming sea temperatures on vertebrate and invertebrate communities.

Some plant communities in North America have shown an increase in woody species relative to grasses and forbs. In experimental manipulations, multiple individual factors (increased temperature, increased water availability, and increased CO_2) have all resulted in the increased abundance of woody species in plant communities (Chapin et al., 1995; Harte and Shaw, 1995). Large-scale trends in a direction favoring woody species appear to be occurring in diverse landscapes, from Alaskan tundra (Chapin et al., 1995; Sturm et al., 2001) to the desert Southwest (McPherson and Wright, 1990; Turner, 1990; Brown et al., 1997). Although overgrazing is partially responsible in given locales, experimental results suggest that the general phenomenon also stems from the joint effects of increases in all three of these factors (temperature, water, CO_2) in these regions (Archer, 1995).

Grassland communities have been relatively understudied with respect to climate change, although they have a high economic importance as rangelands. One study in Colorado documented changes in the vegetation structure of a protected short-grass prairie site between 1970 and 1992, a time during which nighttime temperatures rose by 1.3°C (2.4°F) and precipitation significantly increased by 6 mm/year. Since 1983, the density of the dominant grass (Bouteloua) significantly declined by more than one third, while exotic forb density significantly increased (Alward et al., 1999). Conversely, short-

Figure 8

Interpretation of **Species Range Changes**
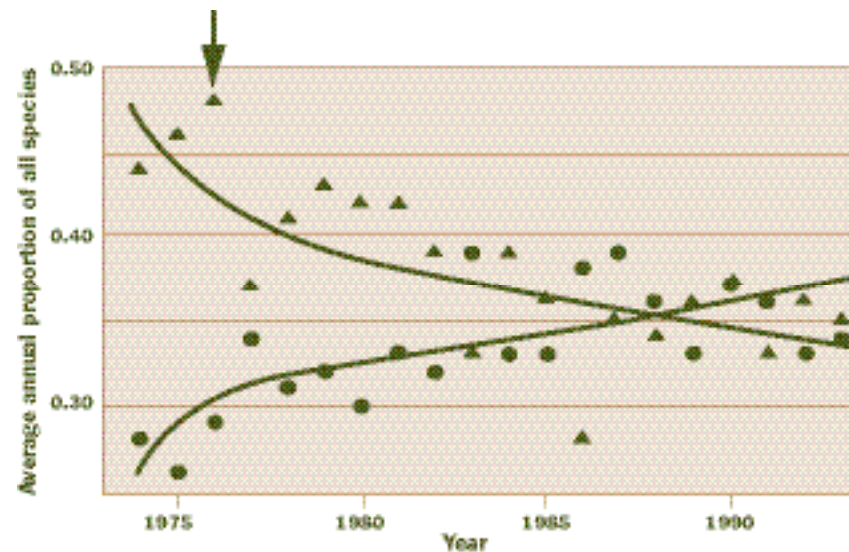
Notes: The above figure depicts changes in proportions of the total annual species off the southern California coast as reflected in census data from 1974 to 1995. The number of northern species (triangles) has decreased, while representation by southern species (circles) has increased. The arrow indicates a regime shift from cooler to warmer waters during 1976-1977.

Source: Holbrook et al. (1997)

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term experimental manipulations at a protected coastal California grassland site showed no change in grass diversity but a significant decline in native forb diversity with warming treatments over a three-year period (Zavaleta et al., 2003). Such discrepancies highlight the need for more long-term research (both observational and experimental) in important ecosystems.

Ecosystem process changes

Are scientists detecting changes in the flows of energy and nutrients in the biosphere? These processes, termed "ecosystem functions," are difficult to assess, even in the absence of environmental change. Rather than tackle that question directly, it is easier to detect changes in specific components of ecosystem flows and processes. The satellite analyses discussed earlier reveal an increase in the length of the growing season (Myneni et al., 1997; Zhou et al., 2001; Lucht et al., 2002). Because plants are a major intermediary for carbon flow through ecosystems, this lengthening of the growing season has altered the annual cycle of CO_2 levels in the atmosphere (Keeling et al., 1996).

The Alaskan tundra has historically been a CO_2 sink, but its status has changed in recent decades. Historically, when tundra plants die, they quickly become part of a seasonally or permanently frozen layer of organic matter. Even in midsummer, only the very upper surface of this layer defrosts. When the dead matter becomes part of a permanently frozen layer or a water-logged seasonally frozen layer, the rates of decomposition are greatly slowed. The soil organisms that break down dead plant matter are able to function only if conditions are relatively dry and above freezing. The warmer it is, the faster the decomposition works. Thus, as climates warm, carbon storage decreases. The Alaskan tundra has already experienced much stronger warming trends than the rest of the United States. At some point, as deeper layers remain above freezing, the rate of decomposition of dead matter will exceed the rate of plant growth, and the tundra will turn from a net sink to a net source of CO_2.

This switch from net sink to net source has already occurred in some tundra areas. Oechel et al. (1993) found that during 1983-1987 and 1990, the tundra across the North Slope of Alaska was acting as a source of CO_2 to the atmosphere, instead of the sink it had been in the historic and recent geologic past. This switch was associated with long-term atmospheric and soil temperature increases, soil drying, and increased depth to the water table. By 1998, moderate acclimation resulted in a return to the tundra acting as a sink in summertime (Oechel et al., 2000). However, warmer winters continue to cause an overall net loss of carbon. Tundra near Prudhoe Bay is estimated to be the source of 40 grams of carbon per square meter each year (released as CO_2 to the atmosphere; Oechel et al., 2000).

Less-direct methods of measuring carbon flow—a combination of satellite data on "greenness" (measured as the NDVI—normalized difference vegetation index), atmospheric measurements of CO_2, data on land-use change, and ecosystem process models—also indicate substantial changes in carbon uptake in the northern latitudes (Fan et al., 1998; Schimel et al., 2000, 2001; Myneni et al., 2001; Hicke et al., 2002). Although estimates of the magnitude and detailed spatial patterns of change vary across studies, they are consistent in their major message: over the past two decades, temperate forests of the contiguous United States have become carbon sinks, while much of the boreal forests of northern Canada and Alaska have become carbon sources (Myneni et al., 2001).

The lengthening of the growing season discussed earlier would be expected to generally increase carbon uptake simply by allowing more time for biomass accumulation. Indeed, net primary production has increased both across North America (Hicke et al., 2002) and globally (Nemani et al., 2003) and is ascribed to ameliorating climatic conditions. However, additional evidence suggests that the recent increased carbon storage in the eastern United States stems largely from regrowth of trees on previously logged mature forest and abandoned agricultural land (Fan et al., 1998; Shimel et al., 2000). Other factors, such as CO_2 fertilization, nitrogen fertilization (from air pollution and agricultural run-off), and regional climate change were considered, but the consensus of these studies is that the other factors contributed far less to the CO_2 sink than did forest regrowth. In contrast, the switch across boreal forests to becoming carbon sources is believed to stem directly and indirectly from regional climate change. The warming and drying trends in the boreal regions of North American have been linked to reduced tree growth due to water stress (Barber et al., 2000), increased pest outbreaks, and increased incidences of wildfire (Kurz and Apps, 1999).

These trends are not likely to be stable, as the underlying processes are dynamic and, to some extent, unpredictable. Once the regrowth occurring in the eastern United States becomes mature forest, the rate of carbon uptake will taper off substantially. It could also reverse if the areas are again logged or cleared for urban development. Likewise, fertilization effects of increased CO_2 and nitrogen are short term, having a positive effect only until some other resource becomes limiting to plant growth.

The impacts of climate change on community structure (discussed earlier) are also likely to influence ecosystem functioning. Different vegetation communities have very different carbon-cycling and storage properties (open tundra differs from spruce forest, for example). Therefore, current patterns of carbon uptake and emission from terrestrial vegetation are likely to change considerably over the next few decades as local communities undergo major shifts in vegetation type.

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V. Strength of Evidence that Climate Change is Already Affecting Natural Systems

Evidence that climate change is already affecting U.S. ecological resources is strong. Evaluating the strength of evidence provided by each reviewed study involved assessing the extent to which each study satisfies the criteria listed in section III. This evaluation is akin to using a "weight of evidence" approach (Moss and Schneider, 2000; Box 2). The important considerations in this evaluation are consistency of results across studies, rather than strength of results within any one study. Of the more than 40 studies initially reviewed, 28 were considered to adequately meet the above criteria to the extent that they provide strong evidence of responses to recent climate change (Table 3).

Box 2

Weight of Evidence Approach to Assessing Confidence in a Conclusion

In assessing the degree to which climate has changed and the cause of change and its impacts, the well-known method of hypothesis testing through experiments cannot be used. That is, it is not possible to construct replicate Earths, subject some to high levels of greenhouse gases and others to low levels, and then observe the outcome. Instead, researchers must use scientific inference to draw conclusions. Properly applied, scientific inference is just as rigorous as experimental methods. Inference relies on synthesizing data from a wide variety of sources and comparing that suite of data to a set of theoretical predictions based on known mechanisms.

Moss and Schneider (2000) suggested a qualitative approach to assessing confidence be used when results are not precise, statistical analyses are not possible, or exact conclusions are not possible given the available data (see below). This qualitative approach compares the amount of evidence to the level of agreement among scientists in interpretation of that evidence. One measure of amount of evidence would be the number of published papers in scientific journals. A well-established conclusion would be one for which many independent published studies, each using different approaches or datasets, came to the same conclusion, resulting in consensus within the scientific community.

Level of Agreement/ Consensus		
High	Established but Incomplete	Well Established
	Speculative	Compelling Explanations
Low		
	Low — Amount of Evidence (observations, model output, theory, etc.) — High	

The term "confidence" denotes the "degree of belief in the validity of a conclusion, based on collective expert judgment of observational evidence, modeling results, and theory" (Moss and Schneider, 2000).

Adapted from IPCC (2001b), Box 1.

Table 3

Papers Reporting Long-Term **Ecological Changes** in the United States

Taxon	Reference	Total number (n) of species (or species groups)	Spatial scale L	R	C	Time scale (maximum number of years)
Phenological changes						
Forbs, birds	Bradley et al., 1999	n=54 spp.	X			63
Bird (Mexican jay)	Brown et al., 1999	n=1 sp.	X			27
Bird (tree swallow)	DunnandWinkler, 1999	n=1 sp.		X		32
Amphibians	Gibbs and Breisch, 2001	n= 6 spp.	X			99
Distributional/abundance changes						
Tree line	Ross et al., 1994	5 groups (n=many spp.)	X			70
Shrubs	Sturm et al., 2001	n=4 spp.	X			50
Shrubs, mosses, grasses	Chapin et al., 1995	—	X			9
Cactus, shrubs	Turner, 1990	n=9 spp.	X			170
Coastal marsh plants	Warren and Niering, 1993	n>3 spp.	X			55
Birds	Johnson, 1994	Northern spp. (n=4 spp.)		X		36
		Southern spp. (n=14 spp.)		X		36
Mammals	Hersteinsson and MacDonald, 1992	n=2 spp.			X	52
Insects	Crozier, 2003	n= 1 sp.	X			35
Insects	Parmesan, 1996, 2003	n=1 sp.			X	137
Amphibians	Kiesecker et al, 2001	n=1 sp.	X			10
Fish	Holbrook et al., 1997	4 biogeographic groups (n=83 spp.)	X			25
Marine invertebrates	Sagarin et al., 1999; Barry et al., 1995	Northern spp. (n=7 spp.)	X			66
		Southern spp. (n=11 spp.)	X			66
		Cosmopolatin spp. (n=28 spp.)	X			66
Marine zooplankton	Roemmich and McGowan, 1995	n=many spp.	X			43
Physical changes						
Mammals	Smith et al., 1998	n=1 sp.	X			9
Ecosystem-level changes						
Boreal plants (satellite data)	Lucht et al., 2002; Zhou et al., 2001; Myneni et al., 1997; Keeling et al., 1996	All plant spp.			X	19
North American plants (satellite data)	Hicke et al, 2002	All plant spp.			X	16
Tundra plants	Oechel et al., 1993, 2000	All plant spp.		X		34+

Notes: The above table presents attributes (scope and scale) of recent major papers reporting phenological changes, distributional changes, physical changes, and ecosystem changes that provide strong evidence of responses to recent climate change. L=local scale; R=regional scale; C=continental scale. The time scale refers to the number of years over which changes were observed.

Source: Adapted from Parmesan and Yohe (2003)

The studies in Table 3 show that it is more likely than not that scientists are already observing impacts of a changing climate on U.S. natural biological systems. For example, the studies provide strong evidence that climate change has affected the phenologies of at least three taxa (species groups, e.g., birds are one taxon). They also provide strong evidence that at least three taxa have shifted their ranges in response to climate change, and that climate change has altered the abundance and composition of species in at least eight communities, and ecosystem processes in at least two instances.

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Very few instances of biotic change run completely counter to climate change predictions, and the findings of many of the U.S. studies are being mirrored by studies elsewhere on the planet and among different taxa (e.g., similar changes in the reproductive phenologies of birds in the United States and Europe). This consistency across scales of study and encompassing diverse taxa supports a conclusion that it is now "well-established" (Moss and Schneider, 2000; IPCC, 2001a) that 20th century climate change has already affected wild plants and animals in North America (Box 1).

There are two considerations regarding the attribution of biological changes within the United States to anthropogenic climate change. The first is the attribution of trends in biological systems to North American climate change (discussed above). The second is attribution of North American climate change to global rises in greenhouse gases (i.e., anthropogenic climate change). The IPCC concludes that global rises in average yearly temperature over the past 50 years are primarily due to global rises in anthropogenic greenhouse gases (Crowley, 2000; IPCC, 2001a; Karl and Trenberth, 2003; Stott, 2003). A 20th century average rise in ocean sea-surface temperatures of 0.4-0.8°C (0.7-1.4°F), an associated 10-20 cm (4-8 in) rise in sea-level, and regional alterations of sea-level pressure have also been linked to the influence of increased atmospheric greenhouse gases (Barnett et al., 2001; IPCC, 2001a; Levitus et al., 2001; Reichert et al., 2002; Gillett et al., 2003). The warming influence of these greenhouse gases since the 1950s has been estimated to be more than six times as powerful as solar influences (IPCC, 2001a).

Recent studies have found that U.S. climate trends of the past 50 years are also primarily anthropogenic in origin (Karoly et al., 2003; Stott, 2003; Zwiers and Zhang, 2003). Because the United States spans a very large geographic area, many global patterns are also manifest within U.S. data. Specifically, certain climate patterns indicate a "fingerprint" of greenhouse gas impacts. This fingerprint has been detected globally and is mirrored by U.S. trends. They include trends toward increased overall temperatures, greater increases in nighttime temperatures than in daytime temperatures, increased cloudiness, increased precipitation (most strongly reflected in the heaviest precipitation events), and strongest warming trends at the higher latitudes and during the winter months (Karl et al., 1996; Easterling et al., 1997; Groisman et al., 2001; IPCC, 2001a).

The consistency in both biological and climate trends across studies and across scales indicates a link between U.S. biological changes and anthropogenic climate change. The implications of this link are that current biological trends will continue into the next 100 years, as greenhouse gas emissions continue to rise.

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VI. Ecological Implications

A. Is there Reason for Concern?

Strong evidence supports the conclusion that wild plant and animal species in the United States have been affected by 20th century climate change, but what does this change mean in terms of preservation of biodiversity, conservation of endangered species, provision of ecosystem goods and services, and preservation of critical habitat? Humans have been altering species' distributions and influencing local population abundances for hundreds (perhaps thousands) of years. Hunting pressures and habitat alteration have frequently caused species to disappear locally, often as a prelude to global extinction. Given the magnitude of these and other human effects, even when it is possible to detect an influence of climate change on plants and wildlife, should society be concerned? What is the relative impact of climate change with respect to other anthropogenic stressors? If the impact of climate change is relatively weak and often buried within a general framework of human-mediated habitat deterioration, is climate change in itself important? Addressing these questions is essential for determining the conservation implications of climate change.

It is possible that some degree of climate change might benefit some species. Certain high-latitude countries may experience an overall increase in diversity of birds and butterflies as temperate species move northward. However, the long-term effects on species confined to polar regions is unclear, and in many cases such benefits may apply to species that society does not wish to encourage in natural ecosystems. For example, invasive species generally thrive in stressed conditions such as those brought about by climate change. By altering the competitive balance to favor invasive species, climate change may further disrupt ecological systems (Dukes and Mooney, 1999).

Analyses of fossil records indicate that past major climate fluctuations caused huge shifts in the global distributions of species, but they resulted in relatively few species extinctions (Coope, 1995). Modern human-dominated landscapes, however, have altered the potential for similar dynamics to occur

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under current and future climatic changes (Parmesan, 2001a). Natural ecosystems increasingly are confined to smaller and more isolated fragments, and population sizes of wild native species have generally declined (Groombridge, 1992). These constrictions have limited the options available to natural systems to contend with the predicted rapid changes in climatic extremes or in the frequency and intensity of disturbances. Reduced population sizes often result in diminished genetic variation, which could limit potential for local adaptation. The increased separation between natural habitat fragments decreases successful dispersal, thereby hindering simple shifts in species' distributions. Increased fragmentation also lowers the probability of successful recolonization of devastated areas after catastrophic disturbances because colonists not only have farther to travel, but they are coming from smaller source populations within impoverished communities. Consequently, modern ecological systems have lowered resiliency to the types of nonlinear climate dynamics predicted by scenarios of global climate change (Schneider and Root, 1996; Easterling et al., 2000a,b; Meehl et al., 2000a,b; Parmesan et al., 2000; Alley et al., 2003).

Similarly, coastal industry and urbanization limit the potential for rising sea levels to simply result in the inshore movement of intertidal habitats (e.g., salt marshes). Also, aquifer depletion by growing human communities and its associated land compaction amplify the rate and extent of sea-level rise. In some cases these effects may greatly exacerbate the ecological impacts associated with climate change (Galbraith et al., 2002).

The types of changes that have been reviewed in this study may presage further events of major ecological, economic, and societal importance. A recent study modeled the potential impacts of climate change on species extinction risks for sample regions across the globe and found that under mid-range climate warming scenarios between 15 percent and 37 percent will be headed for extinction by the year 2050 (Thomas, et al., 2004). Such extinction rates are unprecedented in historical times. Thomas et al. (2004) contend that if these results are valid, the planet would be entering a major climate change-induced extinction event. The resulting effects on ecosystem goods and services upon which human communities depend could be of fundamental societal and economic importance. It behooves us, therefore, to view the effects reported by the scientific community with a degree of concern. There are a number of reasons why we should do so:

> **1. Small, persistent changes are important in the long term.** The biological trends discussed in this report may appear small compared to the massive changes in species distributions caused by

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habitat loss and land-use modifications, but that does not mean they are unimportant. As argued elsewhere, weak but persistent forces will have a major impact on long-term trajectories, perhaps eclipsing the (apparent) importance of strong but short-lived forces (Parmesan and Yohe, 2003).

2. The estimate that one-half of all wild species studied have been affected by recent climate change is a conservative estimate (see Box 3). It will be important for predictive biological scenarios to eventually determine what proportion of the apparently non-responsive cases are truly stable systems.

Box 3

Determining the "Cause" of Non-Responsiveness

Species or systems that appear non-responsive to climate change do not represent a single "result," because their apparent stability could arise from many possible situations that may differ among species:

- The species' phenology, abundance, or distribution is not driven by climatic factors;

- The species is actually changing, but poor data resolution could not detect small changes; or

- The species' phenology, abundance, or distribution is driven by climatic factors but is failing to respond to current climate change.

Such a failure to respond to climate change could stem from a number of possible factors. For example, it could be due to a lag in response time. Lags are expected when limited dispersal capabilities retard poleward/upward colonization (Warren et al., 2001), or when a necessary resource has slower response time than the focal species (Parmesan et al., 1999). For example, ranges of many butterfly species in northern Europe are limited by the distributions of their host plants, and range limits of plants appear to change more slowly than those of butterflies (Grabherr et al., 1994; Parmesan et al., 1999). Natural or anthropogenic barriers to dispersal (e.g., habitat fragmentation) could also result in a lag in response time. Finally, a lag could arise because of an inability to respond due to genetic or physiological constraints. This outcome could be important in populations that have been recently reduced in size due to human activities—these artificially small populations could suffer reduced genetic variation, thereby restricting capacity for an evolutionary response.

If barriers are so large that dispersal is impossible, or if populations have effectively no genetic variation (as is the case with some endangered species), then species could fail to respond at all to climate change, even when local climate change is stressing the population.

For example, a recent analysis by Parmesan and Yohe (2003) showing that approximately 40 percent of wild species in large studies have shown no response to 20th century climate change is likely to include climate-sensitive as well as truly stable species. Therefore, the 59 percent of species that have shown significant response represents a minimum estimate of the true response to recent climate change.

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3. Climate change adds yet another factor that must be considered in the preservation of biodiversity. Many if not most of the ecosystems and organisms in the United States are already suffering from other anthropogenic stressors such as habitat destruction, habitat fragmentation, introduction of invasive species, and contamination. As yet, scientists do not have a clear idea how climate change might affect this already fragile situation. It is likely, however, that in many

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cases climate change may exacerbate current conditions, further stressing wild species and the ecosystems within which they are embedded. The result could be an acceleration of the rate at which biodiversity is being lost.

4. Carbon uptake is one of the many services performed by intact, healthy ecosystems (see Malcolm and Pitelka, 2000). The rate of carbon uptake and carbon storage capacity among different types of ecosystems has received considerable global attention from the policy community. Carbon uptake by plants is one of the few means of storing large amounts of CO_2 from the atmosphere. Large research programs are devoted to measuring which types of ecosystems act as net sinks of CO_2, and which types are net sources. Results indicate that climate plays a large role in determining whether a particular ecosystem is a CO_2 source or sink. Therefore, climate change may alter these source-sink dynamics. The relative numbers of source habitats versus sink habitats will directly influence future atmospheric CO_2 concentrations and therefore future climate change. Preliminary observational data indicate that some ecosystems have switched from being sinks to sources under recent climate change.

5. Climate change may jeopardize other goods and services provided by ecosystems, resulting in economic losses. Healthy ecosystems provide a number of economically valuable goods and services; for example, pollination of farmed crops, pest control by predators, water purification, and soil renewal. However, the ability of ecosystems to provide these essential services may be compromised by the biological effects of climate change. For example, if warming results in insectivorous birds shifting their ranges north faster than their forest habitats can move, their populations will crash, and the controls they exert on pest outbreaks may be lost.

B. General Recommendations for Conservation

A major future challenge is to achieve a better understanding of which systems or species are most or least susceptible to projected climate change. Such understanding is necessary to evaluate options to help mitigate potential adverse effects on the more sensitive species or ecosystems. However, the development of such vulnerability assessment tools and methods has begun only relatively recently (Galbraith and Price, in press). If future conservation of resources is to be effective, it is vital that these first steps be rapidly carried further.

Specific steps could also be taken to minimize the negative impacts of future climate change. With a stable climate, extensions of standard conservation approaches (e.g., protection of fixed areas, protection of rare species, habitat restoration/creation) may be sufficient to preserve biological systems. Alternatively, climate change may affect the viability of many of society's standard conservation "tools." This has some immediate implications for conservation planners and managers. A number of actions could be taken to mitigate climate change impacts:

1. Reassess species and habitat classifications to evaluate their relative vulnerabilities to climate change. A species' or habitat's level of endangerment and vulnerability may differ under a stable climate as compared with a changing climate. Reassessment might include placing higher value on populations at the northern range boundary and at the upper elevational limits, because these populations are expected to be least vulnerable to warmer conditions.

2. Design new reserves that allow for shifts in the distributions of target species. Reserve design could include protecting corridors or placing more value on areas with high topographic and elevational diversity.

3. Promote native habitat corridors between reserves. Native corridors, such as those along fence-lines, ditches, streams and other minimally used land, could aid the redistribution of wild species between preserved areas.

4. Practice dynamic rather than static habitat conservation planning. Dynamic habitat planning is particularly important because current climate scenario models do not work well at the small (local) scales on which most plans are based. Thus, empirical adaptive management is likely to be as useful (if not more useful) than detailed scenario modeling.

5. Alleviate the effects of other stressors. Climate change is occurring along with already existing anthropogenic stressors. The fate of a species lies in the net effect of all stressors combined. In some cases, it may be easiest to reduce the overall stress on a species by mitigating some of the non-climate stressors. For example, if both climate change and invasive species threaten a valued resource, it may be most cost-effective to focus attention on reducing the incursions of the invasive species.

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VII. Conclusions

1) Sufficient studies now exist to conclude that the consequences of climate change are already detectable within U.S. ecosystems. This report reviews more than 40 studies that associate climate change with observed ecological impacts in the United States, and, using objective evaluation criteria, finds that more than half provide strong evidence of a direct link. These studies span a broad range of plant and animal species from various regions of the United States. Yet, despite the diversity among studies, the observed ecological responses are consistent with one another, as well as with the changes that one would expect based on the nature of U.S. climate change observed to date.

2) The timing of important ecological events, including the flowering of plants and the breeding times of animals, has shifted, and these changes have occurred in conjunction with changes in U.S. climate. If these timing shifts are synchronous across species that normally interact with each other (for example, if adult butterflies and the flowers they depend on for nectar both emerge two weeks earlier), then these species' interactions are preserved, and the system may remain healthy. On the other hand, if responses to temperature increases vary across species (for example, if butterflies emerge before the flowers they depend on for survival), then species' interactions may become out of synchrony and could lead to population declines. Both types of situations have been documented.

3) Geographic ranges of some plants and animals have shifted northward and upward in elevation, and in some cases, contracted. One of the most detailed and best-studied examples is the Edith's checkerspot butterfly in the western United States. As temperatures have increased over the last century, many southern and lower-elevation populations of this species have disappeared entirely. The effect of this shift has been a contraction of the species' range to the north (i.e., it is disappearing from Mexico but thriving in Canada). The red fox, another example, has shifted northward and is now encroaching on the arctic fox's range, threatening its survival. Similar range shifts within the United States have also been observed in organisms as diverse as birds, mammals, intertidal invertebrates, and plants. Such major shifts alter species' interactions and potentially threaten U.S. biodiversity.

4) Species composition within communities has changed in concert with local temperature rise. As species within a community change abundances or, ultimately, are added or lost, the relationships among species also change. In particular, such shifts in composition are likely to alter important competitive and predatory/prey relationships, which can reduce local or regional biodiversity. A particularly compelling example of this is the change observed over more than 60 years in the intertidal communities of Monterey, California, where a community previously dominated by northern colder-water species has been "infiltrated" by southern warmer-water species in response to oceanic warming. Similar changes have also been observed in nearby offshore marine fish communities. Thus, many protected lands, such as the marine reserve in Monterey Bay, are experiencing a shift in the communities that they protect.

5) Ecosystem processes such as carbon cycling and storage have been altered by climate change. The lengthening of the growing season has altered the annual cycle of carbon-dioxide (CO_2) levels in the atmosphere, because plants are a major intermediary for carbon flow through ecosystems. The Alaskan tundra has switched from being a net sink of CO_2 (absorbing and storing more carbon from the atmosphere than is released) to being a net source of CO_2 (releasing more carbon than is stored), because warmer winters have allowed previously stored dead plant matter in the soil to decompose and release CO_2. Like the tundra, boreal forests have become carbon sources because of reduced growth due to climate-mediated increases in water stress, pest outbreaks, and wildfires. Conversely, many of the forests of the lower 48 states have switched in the opposite direction—becoming carbon sinks in recent decades. This transition is attributed to regrowth of forests following logging and abandonment of agricultural fields, however it is expected to stop as soon as the forests mature.

6) The findings that climate change is affecting U.S. biological systems are consistent across different geographic scales and a variety of species, and these U.S. impacts reflect global trends. Even against a background of apparently dominating forces such as direct human-driven habitat destruction and alteration, a climate "fingerprint" is discernible in natural systems. The most rigorous studies within the United States provide strong evidence that climate change has affected the timing of biological events in at least three taxa (i.e., groups of related species). They also provide strong evidence that at least three taxa have shifted their ranges in response to climate change and that climate change has altered ecological communities and processes. Further, very few instances of biotic change run completely counter to climate-change

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predictions, and the findings of many of the U.S. studies are mirrored by studies elsewhere around the world. Climate change has the potential to degrade ecosystem functions vital to global health. If the observed biological changes are merely one phase in a cyclical pattern of warming and cooling periods, then they may not represent a threat to long-term species and ecosystem health. If, however, they are linked to anthropogenic climate change, they will continue along the same path. Thus, it is essential to address the extent to which the U.S. climate change responsible for observed ecological responses can be attributed to global emissions of anthropogenic greenhouse gases.

7) There is an emerging link between observed changes in wild plants and animals across the U.S. and human-driven global increases in greenhouse gases. In 2001, the Intergovernmental Panel on Climate Change concluded that the global rise in average yearly temperature over the past 50 years was primarily due to increased concentrations of anthropogenic greenhouse gases. U.S. climate trends are consistent with global climate trends. Global biological trends are predicted by (and match) observed climate trends, indicating that anthropogenic global climate change has affected natural systems. Recent research focusing on North America has also shown a significant greenhouse gas signal in North American climate trends over the past 50 years. The combination of strong consistency across climate and biological studies and across scales (from regional to global), coupled with new climate analyses specific to the United States, links U.S. biological changes to anthropogenic climate change. The implications of this link are that current biological trends will continue over future decades as greenhouse gas emissions continue to rise.

8) The addition of climate change to the mix of stressors already affecting valued habitats and endangered species will present a major challenge to future conservation of U.S. ecological resources. Many if not most of the ecosystems and organisms in the United States are already suffering from other anthropogenic stressors such as habitat destruction or fragmentation, introduction of invasive species, and contamination. As yet, scientists do not have a clear idea how climate change might affect this already fragile situation. It is likely, however, that in many cases climate change may exacerbate current conditions, further stressing wild species and their associated ecosystems. There is a growing consensus within the scientific community that climate change will compound existing threats and lead to an acceleration of the rate at which biodiversity is lost.

9) Range contractions are more likely than simple northward or upslope shifts. During historic glacial cycles, range shifts of hundreds to thousands of miles were common, and species extinction was rare. However, achieving such massive relocation is much more problematic across the human-dominated, artificially fragmented landscapes of today. The large reduction in the areas of natural habitats and the growth of barriers to species' dispersal (urban and agricultural zones) make simple range shifts unlikely. Species that are not adapted to urban and agricultural environments are likely to be confined to smaller total geographic areas as climate causes them to contract from their southern and lower boundaries. Already rare or endangered species, or those living only on high mountaintops, are likely to have the highest risk of extinction.

10) Reducing the adverse effects of climate change on U.S. ecosystems can be facilitated through a broad range of strategies, including adaptive management, promotion of transitional habitat in nonpreserved areas, and the alleviation of nonclimate stressors. The protection of transitional habitat that links natural areas might assist in enabling species migration in response to climate change. Meanwhile, promoting dynamic design and management plans for nature reserves may enable managers to facilitate the adjustment of wild species to changing climate conditions (e.g., through active relocation programs). Also, because climate change may be particularly dangerous to natural systems when superimposed on already existing stressors, alleviation of the stress due to these other anthropogenic factors may help reduce their combined effects with climate change.

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notes

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