Biological Impacts of Climate Change

Introductory article

John P McCarty, *University of Nebraska at Omaha, Omaha, NE, USA*
L LaReesa Wolfenbarger, *University of Nebraska at Omaha, Omaha, NE, USA*
James A Wilson, *University of Nebraska at Omaha, Omaha, NE, USA*

Article Contents

Climate has far reaching impacts on biological systems. Survival and reproduction depend on how well adapted individuals are to local climate patterns. Climate change can disrupt the match between organisms and their local environment, reducing survival and reproduction and causing subsequent impacts on populations or species' distributions across geographic regions. Climate change may benefit some species and cause extinction for others. Cumulatively, it will alter biological communities and the functioning of ecosystems. The Earth is already experiencing sufficient climate change to affect biological systems; well-documented changes in plant and animal populations are related to recent climate change. Predicting future biological impacts of climate change remains a formidable challenge for science.

Introduction

One of the fundamental lessons from the science of ecology is that patterns of climate strongly influence the distribution and abundances of living organisms. Climate describes weather patterns for a given location over an extended period of time (e.g. 10+ years). Climate is not just the average conditions of temperature and precipitation but also the seasonal and annual weather variation, including the frequency and severity of extreme events such as storms or drought. The Earth's climatic patterns are now changing and there is increasing concern about how human activities are contributing to climate changes. The types of impacts climate change will have on living systems have far reaching consequences for natural ecosystems and the people who depend on the goods and services ecosystems provide. **See also**: Ecosystem Concepts: Introduction

The distribution of the general types of plants and animals or biomes around the world can be predicted with some accuracy from climate patterns. General climate patterns are in turn generated by atmospheric circulation patterns caused by differential heating of the Earth's surface, which determine the temperature and precipitation patterns in a given area. Relatively minor changes in the overall heat balance of the Earth can change atmospheric circulation and result in local climate change more dramatically than indicated by the degree of average warming. For example, a 1°C increase in the world's average temperature could result in some geographic regions experiencing much greater than 1°C warming, while other regions show little or no warming. Climate changes of this magnitude have been observed to impact species and entire biological communities.

One of the great challenges for biology today is to try to understand how future changes in climate will impact biological systems. Progress towards this goal depends on understanding how species respond to changes in climate, examining biological responses to recent climate changes and integrating this information in experiments and models to try to understand how complex biological systems will interact under future changing climate conditions.

ELS subject area: Ecology

How to cite:
McCarty, John P; Wolfenbarger, L LaReesa; and, Wilson, James A (March 2009) Biological Impacts of Climate Change. In: Encyclopedia of Life Sciences (ELS). John Wiley & Sons, Ltd: Chichester.
DOI: 10.1002/9780470015902.a0020480

How Climate Impacts Life

The basic components of climate – temperature and moisture – have pervasive impacts on organisms. Physiological processes define life, and at the most basic level these are chemical reactions. As such, they are subject to the unavoidable relationship between temperature and the speed of chemical reactions. Whereas the rates of simple chemical reactions increases as temperature increases, physiological processes respond in a more complex manner. This typically involves a thermal optima where the reaction proceeds most quickly. Physiological processes proceed more slowly at temperatures above or below the thermal optimum. Most physiological processes are also water-based. All organisms face a major challenge: maintain an appropriate water balance and temperature range for life-sustaining physiological processes while living in environments that are too wet/dry and too cold/warm.

The climate where an organism lives dictates the specifics of this challenge, and organisms have evolved numerous adaptations to cope with hostile environments. Organisms are exposed to not just the average temperature and moisture conditions but also the variability associated with seasons and with extreme events. Plants and animals cope with variation in the environment in many ways. Some animals move to different geographic areas to avoid severe conditions (e.g. migration). Both plants and animals can reduce activity when conditions are too severe: torpor in animals and senescence in plants. **See also**: Ecology of Water Relations and Thermoregulation; Ecology of Water Relations in Plants

Climate and individuals

The physiologic health or condition of individuals acts as the link between the habitat and population dynamics. Individuals poorly suited for their habitat may not obtain enough energy to maintain themselves in good condition and may forego reproduction completely or until conditions in the habitat improve.

Climate can impact survival and reproduction for animals that are able to regulate their body temperature within a narrow range even as surrounding air temperature varies, including endotherms such as birds and mammals. As the temperature of the environment decreases relative to body temperature, the individual needs to expend energy to stay warm and may eventually reach the point where it can no longer generate enough heat to maintain body temperature. If the individual cannot move to a warmer environment or obtain needed energy, it may die. At the other extreme, as environmental temperature rises above body temperature, individuals need to expend energy and often significant amounts of water, to stay cool. Once again if surrounding temperatures rise too high, the individual will no longer be able to regulate its body temperature and it could die. Even if environmental temperatures do not reach the extremes that cause death, the energy required to maintain internal conditions is no longer available for other important activities such as reproduction.

Climate also has profound effects on the survival and reproduction of ectotherms; animals such as amphibians, reptiles and insects that are unable to regulate their body temperature independently of the surrounding temperature of the environment. For these species, the rate of physiological processes determined by body temperature depends upon ambient temperature. As ambient temperature rises the rate of physiological processes increases in a nonlinear fashion and increases more rapidly when initial temperatures are low. For example a rate may triple across a temperature of 10–20°C but may only double from 20°C to 30°C. Although ectotherms have a limited ability to avoid the physiological consequences of changing environmental temperature, they have evolved a broad assortment of strategies for coping with a broad range of climate conditions. **See also**: Thermoregulation in Vertebrates; Vertebrate Metabolic Variation

As an adaptation to harsh environmental conditions, especially cold temperatures, some ectotherms become inactive during unfavourable seasons of years, and climate change will significantly alter the energy expenditures and body condition of these organisms. Body condition in ectotherms is tightly bound to reproductive output, timing to maturity and survival during inactive periods. Unlike hibernation in mammals, where individuals can regulate body temperature independent of ambient temperature, ectotherms cannot. Because their hibernating metabolic rate is dependent on ambient temperature, warmer winters will cause ectotherms to utilize more energy during hibernation than colder winters. Common toads (*Bufo bufo*) have shown a decline in body condition associated with increasing temperatures which is also associated with decreased annual survival. In addition, when ectotherms use more energy to hibernate during warming winter, they emerge from hibernation in poorer condition which reduces reproduction. **See also**: Hibernation: Endotherms; Hibernation: Poikilotherms; Thermoregulation in Vertebrates: Acclimation, Acclimatization and Adaptation

Plant physiology is also sensitive to temperature range and moisture balance. Temperature and moisture interact to determine the rate of photosynthesis, the physiological process in which plants meet their energy needs and use the sun's energy to synthesize carbohydrates from carbon dioxide and water. Because plants have limited ability to regulate internal temperatures or to avoid temperature extremes, many species become inactive during seasons when conditions are unfavourable. Therefore, climate determines the length of the growing season and the nongrowing season when plants lack the necessary moisture for photosynthesis or when temperatures drop below the freezing point of water. **See also**: Ecology of Water Relations in Plants; Photosynthesis: Ecology; Plant Physiological Responses to Climate and Environmental Change

Climate and populations

A population consists of a collection of individuals, and population size changes due to reproduction, immigration, mortality and emigration of these individuals. As such, a population can only grow when net individual reproduction and/or immigration is greater than mortality and/or emigration, and decreases when the opposite occurs. Population size is influenced by a complex interaction of direct and indirect factors that change the energy budget of individuals living in a population. Simply put, direct factors are those that are abiotic and reflect changes to a population due to thermal stress, extreme weather or changes in precipitation. Indirect factors represent changes to the biotic environment, typically manifested as changes in biotic interactions due to resource availability, community composition and structure and predation pressure.

Most species have solved the challenges associated with a specific range of climate conditions, and the occurrence of these conditions constrains the geographic range of a species. Outside of this range, factors driving populations down – mortality and emigration will overwhelm reproduction and immigration, and populations will die out. In some cases the correlation between specific climate conditions and the limits of geographic range can be quite close. For example, the northern limit of the wild madder plant (*Rubia peregrina*) in Europe corresponds closely to where January temperatures remain approximately 4.5°C. In North America, the combination of temperature and precipitation explains the distributions of many bird species, such as Northern Bobwhite (*Colinus virginianus*; **Figure 1**).

Although unfavourable climate can eliminate populations, favourable climate is not a guarantee that populations will occur or persist. Additional environmental conditions besides climate may be unfavourable, or geographic barriers may exist that prevent members of the population from ever reaching a given geographic region. **See also**: Range Limits

Climate and interactions among species

Individuals interact with members of other species in a variety of ways. These include interactions among parasites, disease organisms, predators and prey and competition over common resources as well as mutually beneficial interactions such as flowering plants producing nectar for the animals that pollinate their flowers. Through these interactions species may influence the population size and even geographic range of other species. Interactions among species in a community can produce indirect links between a population and climate. For example, rush moths (*Coleophora alticolella*) in England tolerate the direct effects of climate associated with high elevations sites, but the plants on which the caterpillars feed do not produce enough seeds at high elevation, thereby limiting the range of the moth to low elevation sites with abundant food for caterpillars. Differences among species in their abilities to cope with changes in climate can shift the balance between competitors or allow new predators, pathogens or parasites to invade a species range. **See also**: Coexistence; Community Ecology: An Introduction; Interspecific Competition; Interspecific Interaction; Predation (Including Parasites and Disease) and Herbivory

Climate and communities and ecosystems

The community of plants and animals in a given area emerges from the responses of individual species to climate and other physical factors. The species-specific nature of the factors limiting ranges means that biological communities do not respond to climate as cohesive units but rather are assemblages that reflect the tolerances of their component species. These assemblages of species are both familiar and have emergent properties such as diversity and productivity. As climate changes it is probable that assemblages of species that are now familiar will be broken up as species respond to new environmental conditions in different ways. New assemblages will then emerge with their own characteristics and properties.

Communities in turn are linked with the nonliving environment in ecosystems. Within an ecosystem, the flow of energy and matter among organisms is constrained by the ability of plants to capture the sun's energy in a form that can be used by other organisms. In this way, energy balance forms the link between individual condition, population dynamics and ecosystem functioning. Likewise, these higher-level processes that emerge from ecosystems have far-reaching implications for humans through their impacts on nutrient, air and water cycles. **See also**: Ecosystem Concepts: Introduction; Photosynthesis: Ecology

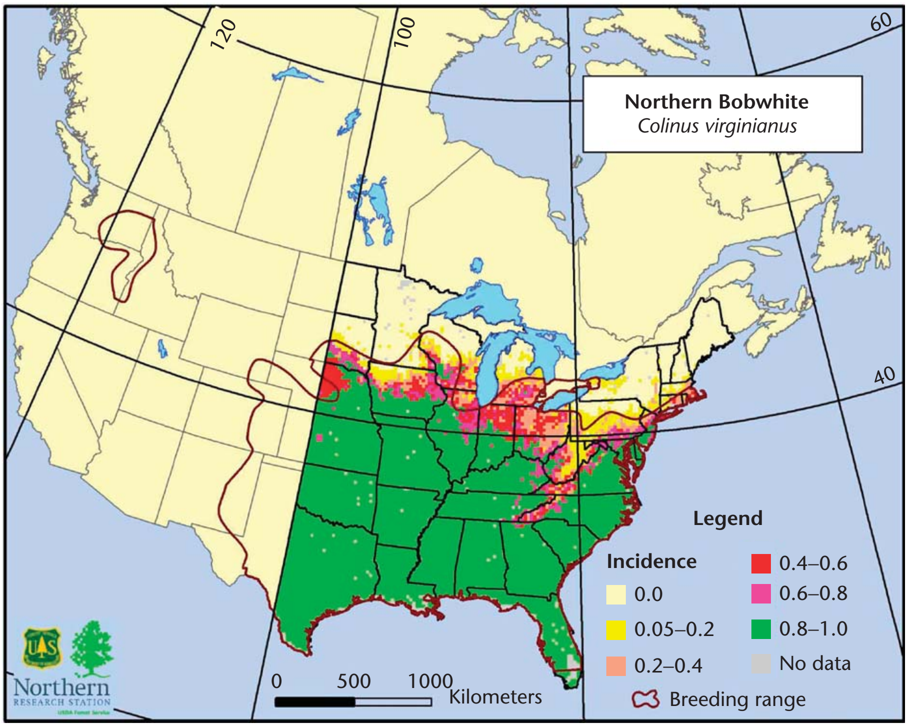
Observations of the Biological Impacts of Climate Change

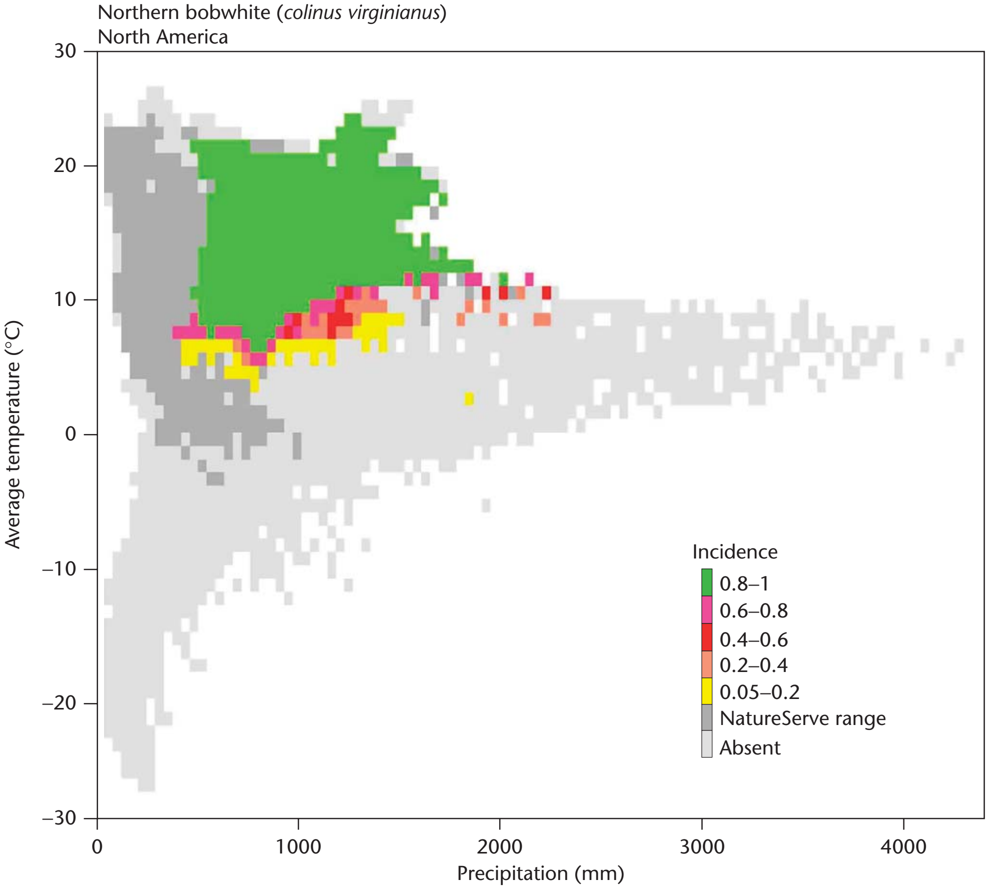
The Earth's climate has been in a state of change for most of the history of life, and ample evidence exists to show how biological systems respond to changes in temperature and moisture. We know from fossils and other remains of long dead organisms that biological systems have undergone dramatic changes in response to past changes in climate. **See also**: Palaeoclimatology; Palaeoenvironments

Recently, scientists have been able to observe how biological systems respond to ongoing climate change. Global mean temperatures increased in the twentieth century, and while the average increase appears relatively modest (*c.* 0.74°C), this warming has occurred unevenly across the globe. Temperatures over land are warming faster than over oceans, and warming of the arctic is occurring almost twice as fast as the global average.

Other changes in the environment follow from climate change. Polar regions have had extensive warming of air and surface ocean temperatures. This has led to a decrease in the extent of Arctic sea ice, especially during summer. Similarly, the West Antarctic Peninsula has also shown sea ice melting. In the Northern Hemisphere the length of the snow-free period has increased 5–6 days per decade since 1972. In addition, the date that snow cover has melted has been occurring earlier (3–5 days per decade).

As scientists became aware of the rate of current climate change, they observed long-term datasets to determine if climate change was impacting biological systems. Some of the longest running quantitative records of biological systems are observations of seasonal biological events. In many areas of the globe, records of the timing, or phenology, of events such as when birds migrate and when leaves or flowers appear in the spring go back decades or more. These data provide strong evidence for widespread changes in the timing of biological events linked to the climate changes experienced over the same time period. For example, Terry Root and her colleagues conducted a review


Northern Bobwhite
Colinus virginianus
120
100
60
40
Legend
Incidence
0.0
0.05–0.2
0.2–0.4
0.4–0.6
0.6–0.8
0.8–1.0
No data
Breeding range
0
500
1000
Kilometers
Northern
RESEARCH STATION


Northern bobwhite (*colinus virginianus*)
North America
Average temperature (°C)
30
20
10
0
−10
−20
−30
Precipitation (mm)
0
1000
2000
3000
4000
Incidence
0.8–1
0.6–0.8
0.4–0.6
0.2–0.4
0.05–0.2
NatureServe range
Absent

of 64 studies of biological events associated with the onset of spring in 694 species of plants and animals; the results indicated that spring phenological events like migration and flowering have been occurring earlier at a rate of 2–7 days every decade.

Not all species will be able to cope with climate change by tracking favourable conditions because the changing climate might exceed the capacity of individuals to alter the timing of activity. Desert dwelling ground squirrels face extreme heat during summer months and also low water availability. As a result, ground squirrels enter a period of seasonal inactivity (aestivation) during the summer months to decrease energetic demands. However, as summers become warmer and precipitation decreases, the length of the inactive season will increase while the wet season, when squirrels obtain food for aestivation, shortens. Piute ground squirrels (*Spermophilus mollis*), from the western United States, have been shown to enter aestivation early in response to early spring drought. If the drying trend continues to increase, these animals may not acquire sufficient energy resources during the shortened growing seasons to aestivate over the longer dry months.

Changing phenology may not always track favourable conditions if it disrupts or decouples species interactions or other biotic factors that influence populations. For example, Marmots in the mountains of Colorado spend the winter hibernating and emerge from hibernation when air temperature warms. As air temperatures have increased, marmots have been emerging from hibernation 23 days earlier than they did in 1976. However, because winter precipitation in the form of snow is increasing, deep snow is still on the ground preventing plants from growing. Therefore, marmots must use their limited fat reserves for longer periods in spring while at the same time they have increased energetic demands and are preparing for reproduction.

Geographical ranges of species have expanded and contracted as climate factors have changed over the past decades. Historic datasets show that geographic ranges of many Northern Hemisphere species are shifting northward at rates consistent with observed climate change. Analysis of the geographic range of 59 species of birds in Great Britain showed a northward shift in range averaging 18.9 km in the span of only 20 years. In mountainous regions an analogous shift has been documented with species spreading to higher elevations where temperatures are cooler. These range expansions lead to a homogenization of alpine plant communities and a decrease in specialized communities, particularly in alpine tundra associated with mountain peaks. **See also**: Alpine Ecosystems

Changes in species geographic ranges in recent decades reflect the processes of local extinction of populations and invasion of other areas creating new populations of species. For example, as climate has warmed isolated populations of Edith's checkerspot butterflies in the southern part of the range in North America have been more likely to go extinct while new populations have emerged to the north of their historic distribution. In this way, geographic ranges shift with climate change.

In some cases it appears that changes in climate have overwhelmed species' abilities to respond. Amphibians living in the mountains of Central America may provide a window into what the future might hold. The Monteverde region of Costa Rica is world famous for its cloud forest and diverse community of frogs. Declines in populations of these frogs have been well documented in recent decades and include the extinction of the golden toad (*Bufo periglenes*). Population decline and species loss are linked to the changing climate, including a reduction in misty days a defining feature of cloud forests, but the full explanation is much more complex. Warmer nighttime temperatures produce ideal growing conditions for a chytrid fungus (*Batrachochytrium dendrobatidis*) that infects amphibians and sometimes kills them. Frogs stressed by warmer and drier climate are less able to resist fungal infection. As a result, populations decline and populations and species go extinct.

In addition to changes in populations and biological communities, earlier spring warming and changes in summer climate have produced significant changes in the fundamental energy dynamics of ecosystems. Satellite and ground-based observations show that over the past 25 years the transfer of energy from plants to higher trophic levels (net primary productivity) has changed at both an ecosystem and global scale. Ecosystems as diverse as northern tundra and the Amazon rainforest have shown increases in productivity. Recently, productivity increases associated with warmer springs have been partly balanced by decreases in productivity from warmer and drier summers.

Trying to Understand the Future

Biological responses to future climate change will depend on the rate and magnitude of continued climate change. Sophisticated models of the Earth's climate system incorporate our best understanding of the variables

Figure 1 Much of the geographic range of species can be explained by climate. In the example shown above, Northern Bobwhite are widespread across the southern two-thirds of the eastern United States. The map on left shows their geographic range and relative abundance based on the North American Breeding Bird Survey. USDA Forest Service scientists evaluated the geographic distribution of Northern Bobwhite (and 146 other bird species) against information about the climate and vegetation in the eastern United States. The importance of different climate and habitat variables in explaining geographic range depends on the bird species. The figure on the right shows the combination of temperature and precipitation found in the eastern United States. The coloured cells indicated the combinations of temperature and precipitation where Northern Bobwhite are found, while the light grey squares represent combinations of temperature and precipitation found in the eastern United States where Northern Bobwhite are absent. Reproduced with permission from Matthews SN, Iverson, LR, Prasad AM and Peters MP (2007). A Climate Change Atlas for 147 Bird Species of the Eastern United States [database]. Northern Research Station, USDA Forest Service, Delaware, OH. http://www.nrs.fs.fed.us/atlas/bird.

that interact to drive the Earth's climate, but a fundamental uncertainty for predicting climate change is how human behaviour will influence the increase in atmospheric greenhouse gas concentrations. The Intergovernmental Panel on Climate Change (IPCC) presents the most comprehensive and authoritative synthesis of possible outcomes by examining several leading climate models and incorporating a range of 'scenarios' for future greenhouse gas concentrations. The IPCC's 2007 report suggests warming is very likely to continue and accelerate during the twenty-first century. The average global temperature by the end of this century is projected to increase 1.8–4.0°C or higher. As with past change, actual changes in temperature experienced by plants and animals will vary. Alpine and polar regions have experienced the greatest change in climate and will likely continue to show dramatic effects of global warming**. See also**: Biotic Response to Climatic Change

How species might respond to climate change

Based on observations of how biological systems have responded to recent climate change, it is clear that climate changes of the magnitude expected will have far reaching effects on biological systems, including humans. Each species is likely to respond differently to changes in climate. For some species, climate will remain within the existing range of tolerances. If local climate shifts outside the species' range of tolerances, one of three responses will occur: adaptation (environmental or genetic change), relocation or extinction.

Changes in behaviour, timing of life history events (phenology), use of microhabitats and changes in physiology can all help species adjust to variations in climate. For some species, these capabilities already exist in individuals and responding to climate change will be relatively straightforward (i.e. phenotypic plasticity). In other cases, the characteristics that determine the climate tolerance of a species will involve a more fundamental, genetically based change (evolution).

Range shifts in response to climate change

As climate changes, the geographic range of some species will shift to track changes in climatic conditions. The total area occupied by a species might increase, decrease or remain constant. The geographic range of species will be a result of how populations of individuals respond. This includes both how the range occupied by a population changes and the gain or loss of geographically separated populations. The potential for the range of species to move with climate will depend on whether there is a net gain or loss of area with a suitable climate. Some species whose ranges are currently limited by climate may expand into suitable areas whereas the potential range of other species will shrink. At a local scale suitable climate conditions may disappear entirely. This might be most dramatic in mountains where the potential shift in habitats to higher elevations is limited by the height of the mountains or near the poles where sea ice habitat will disappear.

Another key factor will be the balance between how fast climate shifts and how quickly species can respond. How far individuals or seeds and other propagules can spread or move will limit changes in geographic range or migration. Freshwater plants and animals may have even more limited abilities to colonize new habitats as lakes and streams warm. Although we might predict distributions of highly mobile species to change quickly, suitable habitat may depend not just on climate conditions but also on the presence or absence of other species or resources. Barriers to movement also exist in the form of mountains and water bodies (or land in the case of aquatic species). Finally, much of the Earth's surface has been transformed by human activities, and the ability of populations of plants and animals to colonize new areas in a human-dominated landscape is uncertain. **See also**: Dispersal: Biogeography

Evolution in response to climate change

As climate changes, heritable characteristics that increase survival or reproduction in the new climate will rapidly spread in a population. The rate at which populations may evolve or undergo change in its genetic make-up will determine whether a species can adapt to new climatic conditions. Although evolution can happen rapidly, not all species will be equally able to evolve in the face of climate change. For evolution to occur rapidly, genetic variability in traits of interest needs to exist in the population; otherwise the rate of change would depend on a suitable mutation arising, an extremely rare event. Furthermore, small or declining populations are less likely to adapt to changing environments due to their low levels of genetic variation. The rate at which evolutionary change could proceed is also a function of the time between generations. Long-lived species such as trees will evolve more slowly than species with short generation times such as insects. **See also**: Adaptation and Constraint: Overview; Adaptation and Natural Selection: Overview; Natural Selection: Responses to Current (Anthropogenic) Environmental Changes

Extinction in response to climate change

Not all species will be able to respond to changes in climate. Species that are unable to respond quickly enough will go extinct. The magnitude of extinctions could be immense. For some areas and groups of plants and animals, 15–37% of species could be at risk of extinction by 2050.

Climate changes may increase the extinction rates of species already at risk. Small populations will have limited potential to evolve in response to new conditions. Climate change may also exacerbate the very conditions that placed species at risk in the first place. For example, invasive species, disease and parasites pose a threat to many populations, and the changing climate may facilitate the invasion of new threats into the range of species at risk. Invasive species are defined in part by their ability to colonize new areas and would be expected to expand their ranges quickly in response to climate change. Lack of suitable habitat places many species at risk of extinction. If climate change reduces habitat further, the species may be unable to recover from the loss and will go extinct. **See also**: Biodiversity – Threats; Extinction

Climate – ecology feedbacks

Climate clearly impacts biological systems but biological systems can also influence climate by changing the amount of heat absorbed from the sun, releasing water vapour and altering levels of carbon dioxide and other greenhouse gasses in the atmosphere. The impact of this feedback on climate is a considerable source of uncertainty for projecting future effects of climate change on biological systems. Plants, both on land and in the ocean, absorb carbon dioxide from the atmosphere during photosynthesis. Some of the carbon trapped this way is transferred to higher trophic levels when animals eat plants, some remains bound up in living or dead plant matter and some is released back into the atmosphere when dead plant material decays. The balance between absorption of carbon dioxide from the atmosphere and release back into the atmosphere has significant effects on the composition of the atmosphere and, ultimately, climate.

Behaviour of these so-called feedback loops is difficult to predict. Warming climate may extend the growing season in some areas, leading to more carbon dioxide being removed from the atmosphere. Whether this has an impact on climate will depend on whether the carbon remains trapped in plant material or is released into the atmosphere.

Climate change has the potential to disrupt current stores of carbon trapped in plant matter and actually increase carbon dioxide in the atmosphere. In the Arctic, vast stores of carbon are stored in peat and other plant material. As the permafrost layer thaws this material could decay at a faster rate, releasing the stored carbon in the form of carbon dioxide and other greenhouse gasses. **See also**: Global Carbon Cycle

Effects of increasing carbon dioxide on biological systems

Most of our attention is focused on changes in climate driven by increasing concentrations of carbon dioxide in the atmosphere. However, carbon dioxide can have other effects on biological systems that will contribute to changes in the coming decades.

Carbon dioxide plays a key role in photosynthesis. Photosynthesis rates can be higher as carbon dioxide concentrations increase. Whether plants are able to take advantage of the enrichment of the atmosphere with carbon dioxide will depend on whether they have the other resources, such as water and nutrients, to support increased productivity. Not all plants in a community will be equally able to respond to increased carbon dioxide. Plants that are able to respond may have a competitive advantage in communities. In the grasslands of North America, this might lead to invasion of grasslands by trees and shrubs as woody plants gain an advantage over grasses. **See also**: Photosynthesis: Ecology; Plant Physiological Responses to Climate and Environmental Change

Increased carbon dioxide in the atmosphere is also having far-reaching direct effects on the world's oceans. Carbon dioxide is soluble in water and decreases its pH by forming carbonic acid. Oceans have become more acidic in recent years as atmospheric carbon dioxide levels have increased. Average pH of the ocean decreased from 8.16 to 8.05 and could fall to 7.9 by 2100. Many aquatic organisms are sensitive to the acidity of water. For example, the carbonate shells of marine animals can dissolve in acidic water. Increased acidity will further stress coral reef communities already suffering the effects of warmer water temperatures. **See also**: Climate Change and Biogeochemical Impacts; Global Carbon Cycle

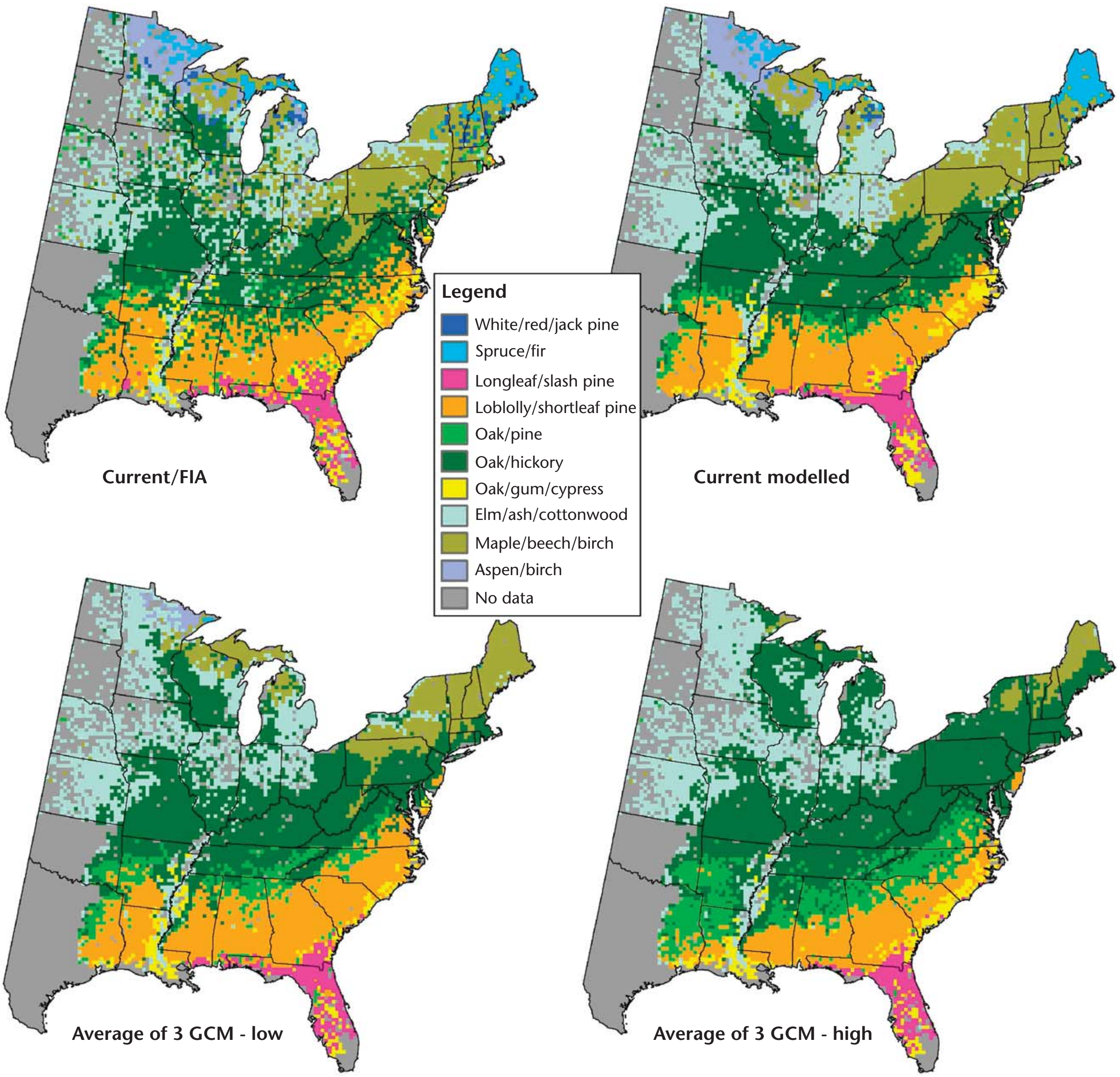
Models and experiments

One approach to understanding complex interactions among species and a changing environment is to take what we know about how species respond to climate (**Figure 1**) and combine it with output from global climate models to forecast how species or communities might respond to future conditions (**Figure 2**). Whereas these models do not predict whether species will be able to respond to climate change successfully, they can provide insights into how potential habitat for different species might shift under different climate conditions.

Another approach to understanding complex interactions is to try to expose current communities to conditions they might expect in the future. Long-term experiments have artificially warmed plant communities, changed moisture levels and even increased carbon dioxide levels in the surrounding air. These studies can be especially useful for understanding how changes in different aspects of the environment can interact to influence biological systems. For example, trembling aspen (*Populus tremuloides*) exposed to higher concentrations of carbon dioxide grow faster, whereas those exposed to increased ozone grow slower (**Figure 3**). When exposed to both carbon dioxide and ozone the effects on growth are neutralized. Indirect effects on trees appeared when trees were exposed to higher levels of carbon dioxide by impacting insects that live and feed on the trees and by altering the competitive balance between aspen and sugar maple trees (*Acer saccharum*). **See also**: Global Carbon Cycle

Summary

There is little doubt that the Earth's climate will continue to change in ways that impact biological systems. Whereas recent and future changes in climate patterns are driven by



Current/FIA

Current modelled

Average of 3 GCM - low

Average of 3 GCM - high

Figure 2 Mathematical models provide one approach for helping us understand how changes in climate will impact biological systems. These maps show the current geographic range of forest types as well as modelled output based on current climate and two scenarios of future climate. Current forest types (panel A) are based on the USDA Forest Service's Forest Inventory Analysis (FIA) data. Information about the geographic range of 134 tree species was evaluated against 38 environmental variables to generate predictive models. The utility of the models can be evaluated by inserting current climate conditions into the models and comparing the output (panel B) to current distributions of forest types (panel A). The general correlation between the actual current FIA data and the modelled current distributions indicates that much of the variation in where the forest types occur can be explained by combinations of climate variables. This correlation also suggests that the Forest Service model can be used to model potential habitat under future climate conditions. The scientists took the output from three widely used global climate models under two scenarios used by the Intergovernmental Panel on Climate Change. The 'Low' scenario assumes that emissions of greenhouse cases will be significantly reduced, while the 'High' scenario assumes that current emission trends will continue. Panels C and D show how the potential habitat for forests might change in the future. Note in particular the loss of potential habitat for northern forest types such as Spruce-Fir forests that are currently found in the northern tier of states but which might disappear in the future. Reproduced with permission from: Prasad AM, Iverson LR, Matthews S and Peters M (2007). A Climate Change Atlas for 134 Forest Tree Species of the Eastern United States [database]. Northern Research Station, USDA Forest Service, Delaware, OH. http://www.nrs.fs.fed.us/atlas/tree.

Figure 3 The Aspen FACE (Free Air Carbon Dioxide Enrichment) Experiment is growing trembling aspen trees in the open under carbon dioxide levels similar to those expected to occur late in the twenty-first century. The pipes surrounding the growing trees release carbon dioxide, mimicking the effects of altered atmosphere in a field setting where plants interact with each other and with other environmental variables in a natural setting. Photograph by JP McCarty.

an overall global warming trend, it is important to remember that biological systems interact with local climate patterns, not the global average. Understanding future impacts of climate change is not a simple matter of asking how biological systems respond to 2°C or 4°C changes in temperature, but the more complicated task of how 2°C or 4°C or more °C warming of the Earth's system will impact the climate patterns where the biological system of interest resides. **See also**: Global Change – Contemporary Concerns

It is clear from both ancient and recent climate change that while some species will adapt to new climate conditions, not all species will have the ability to respond to changes in climate. Extinctions will occur; current communities of species may disassemble as species respond differently to rapid climate change; new species' assemblages will emerge. The fates of those species faced with the rapid changes in climate expected in the coming decades are uncertain, but their extinction will result in permanent, cascading changes to the ecosystems that provide human societies with goods and services we depend on and value.

Further Reading

Björk RG and Molau U (2007) Ecology of alpine snowbeds and the impact of global warming. *Arctic, Antarctic, and Alpine Research* **39**: 34–43.

Bradley KL and Pregitzer KS (2007) Ecosystem assembly and terrestrial carbon balance under elevated CO_2. *Trends in Ecology and Evolution* **22**: 538–547.

IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ and Hanson CE (eds) *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 976. Cambridge, UK: Cambridge University Press.

IPCC (2007) Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK and Reisinger A (eds) *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 104. Geneva, Switzerland: IPCC.

Jurasinski G and Kreyling J (2007) Upward shift of alpine plants increases floristic similarity of mountain summits. *Journal of Vegetation Science* **18**: 711–718.

Lovejoy TE and Hannah L (2005) *Climate Change and Biodiversity*. New Haven, CT: Yale University Press.

McCarty JP (2001) Ecological consequences of recent climate change. *Conservation Biology* **15**: 320–331.

Pounds JA, Bustamante MR, Coloma LA *et al.* (2006) Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* **439**: 161–167.

Reading CJ (2007) Linking global warming to amphibian declines through its effects on female body condition and survivorship. *Oecologia* **151**: 125–131.

Willmer P, Stone G and Johnston I (2005) *Environmental Physiology of Animals*, Second Edition. Oxford, UK: Blackwell Publishing, 754pp.