Courtesy A.L. Batik

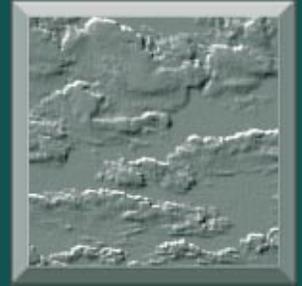# *Global Climate Change*

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Overview Scientists have long recognized climate, especially temperature and precipitation, as one of the major ecological forces affecting the abundance, location, and ecological health of living organisms. This relationship is so strong that in many cases, if biologists know what plants and animals are present in an area, they can approximate the climate of the area. Quantifying these relationships will allow scientists to predict the ecological consequences of global climate change.

Recently the scientific community reached a remarkable consensus on the likelihood and magnitude of global climate change, describing a likely scenario of a 3°C (5.4°F) average global warming, significant changes in the patterns and abundance of precipitation, and 0.6-m (1.9-ft) sea-level rise in the next 60 years (Houghton et al. 1990; LaRoe 1991). These changes will occur faster than previous change in geologic history and are therefore expected to have greater ecological impact.

Because of the strong relation between climate and ecosystem health and distribution, the U.S. Global Change Research Program has as a major component the monitoring of plants and animals to detect, understand, and ultimately predict the effects of global climate change on

living resources (CEES 1990). The National Biological Service's research includes several projects to monitor the effects of climate change on animal and plant populations and ecosystems. Not only will the results of these projects allow a better understanding of the ecological effects of climate change, but they will also give an early, clear indication of the onset and magnitude of climate change because living resources may be sensitive indicators of global change.

Determining if long-term change in a species' population abundance or distribution was caused by specific climate changes is an extremely difficult scientific problem for two reasons: first, both climate and biological factors vary greatly from year to year, and these annual variations often mask long-term trends, making them difficult to detect. Second, several factors such as habitat loss, hunting pressure, competition with other native species and non-native species, and contaminants are simultaneously affecting species' population size and distribution along with climate change so that it is difficult to determine definitively the effect of any one cause.

Some species of plants and animals already may be affected by one type of global climate change: global warming. Much of the evidence

for this, however, is anecdotal or poorly documented. For example, some cold-intolerant species such as opossums (*Didelphis* spp.) and armadillos (*Dasypus novemcinctus*) have expanded their range significantly northward during the last 50 years, and some heat-sensitive species, such as white birch (*Betula papyrifera*), have receded northward during the same period. Data from some recent studies also suggest that global warming may be influencing the distribution or physiology of other plants and animals. Although these data are not sufficient to determine cause and effect relationships, they are intriguing enough to identify future research needs.

The articles that follow all investigate interesting trends between one aspect of climate change—global warming—and plant and animal behavior. Root and Weckstein document long-term change in the winter distribution of some birds; global warming is one possible explanation for these changes. LaRoe and Rusch's article shows change in onset of hatching behavior in selected populations of geese; and Oglesby and Smith's contribution shows a long-term trend in migratory behavior of some birds and in blooming of some plants. Finally, Morse et. al. use existing models to provide a preliminary assessment of patterns of plant vulnerability to climate change.

All four articles are subject to the complexities common to most work on global change; all the trends show dramatic year-to-year variation in response to short-term temperature changes and all have multiple possible explanations; and while all show intriguing statistical correlations, none demonstrates a cause-and-effect relationship. Moreover, these trends do not affect all species, because different species have different sensitivities to temperature and because global climate change is not the only factor affecting species. As discussed in Root and Weckstein's article, a number of competing hypotheses can be used to explain these changes. Nonetheless, together these articles suggest that global warming should be considered as a contributing factor.

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Changes in Winter Ranges of Selected Birds, 1901-89

by
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Over time the ranges of species expand and contract, and abundance patterns shift. Ranges can expand when suitable new habitat becomes available or when population pressure forces migration to new areas. Contractions can occur when populations decline and individuals abandon less-than-ideal habitats, which are often along the edges of species' ranges.

We wish to compare historical and recent range and abundance patterns of selected wintering birds, categorize the type of changes that occurred, and speculate on possible causes of the changes. We found range expansions in most birds examined; only a few species exhibited contractions, and patterns of abundance shifted in almost all species.

Sources of Data

We used data collected by volunteers for the National Audubon Society's Christmas Bird Counts. Wing (1947) summarized data from 1901-40 (from winter 1900-01 to winter 1939-40), which included 6,853 censuses. We obtained data for 32,167 censuses from the U.S. Fish and Wildlife Service for 1960-89, excluding those for 1969, which were not available at

time of analysis. For more information on how we used these data, *see* Root and Weckstein (1994).

Changes in Ranges

We found extensive changes in the ranges and abundance patterns of the birds we examined. Environmental changes that facilitate rearrangements in species' ranges and abundances can be due to natural factors, such as hurricanes transporting cattle egrets (*Bubulcus ibis*) to North America (Bock and Lepthien 1976). In the fairly recent past, however, such changes have been primarily precipitated by humans, including breaking sod in the prairies for farming, which allowed the western spread of American robins (*Turdus migratorius*; Bent 1949), and building cooling ponds for waste heat from power plants, which provided open water for various wintering ducks in the northern states (Root 1988a).

Over the last several decades most ecological studies examining range and abundance changes have focused primarily on investigating direct natural and human-induced effects of habitat change. Consequently, by reading the

literature one gets the impression that such changes are the most common and most important.

Indirect effects of habitat change, however, are probably just as common and important, and perhaps even more so, although obtaining clear obvious evidence for indirect effects is difficult given the fact that other factors are changing at the same time. One such effect is the biotic response to the abiotic changes induced by human disturbance. A good example is changes in birds' ranges in response to increasing temperature.

Range Expansion

One way to examine the possible importance of global warming on changing ranges is examining possible physiological mechanisms constraining birds' ranges to warm areas. Previous work has shown that 50 species of songbirds (e.g., sparrows and warblers) have range boundaries apparently dictated by average minimum January temperatures (Root 1988b). Ongoing studies of a few of these key species have shown significant changes in the location of northern range boundaries from year to year, and these correspond to annual climate changes.

Preliminary studies on northern cardinals (*Cardinalis cardinalis*) suggest that the lack of stored fat, which is needed to fuel increased metabolic rates in colder areas (Root 1991), is the primary factor restraining this bird's range. Consequently, as the earth warms, we expect birds with ranges restricted by low temperatures to readily expand their ranges. Such expansions may indeed be already occurring.

Successfully managed birds show extensive range expansions. Up to 1940, the mute swan (*Cygnus olor*) was recorded only in Pennsylvania and Michigan (Fig. 1a), but since then, programs to introduce and establish it—primarily in parks—have allowed it to spread to 19 states (Fig. 1b).

The wild turkey (*Meleagris gallopavo*) shows even a more dramatic change (Fig. 2). It originally occurred in the Southwest and in all the states east of the 100th meridian, except for North Dakota (Schorger 1966). Hunting pressures, habitat loss, and disease spread by domestic poultry all contributed to its dramatic range contraction (Schorger 1966; Hewitt 1967; Lewis 1973). From 1901 to 1940 it was recorded in only 10 states (Fig. 2a). Turkeys were reintroduced into all but three states within its original range and introduced into all the states outside its original range (Fig. 2b). Obviously, management has had a major effect on this gamebird.

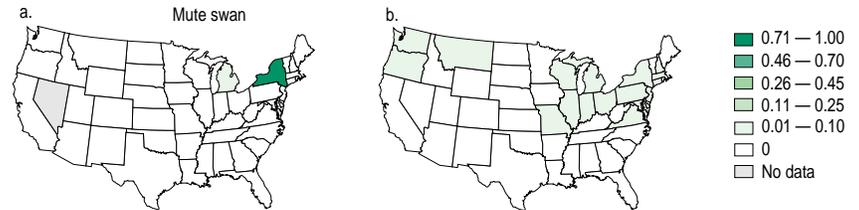Similarly, people may have contributed to a change in both ranges and abundances of various seed-eating birds (Fig. 3). On average, a third of the households in North America provide about 60 lb of bird food a year, with the average being even higher in New England (Ehrlich et al. 1988). Consequently, feeders may have contributed to the expansion of winter ranges of some birds into the northeastern part of the country (e.g., mourning dove [*Zenaida macroura*] Fig. 3; tufted titmouse [*Parus bicolor*]; northern cardinal; and evening grosbeak [*Coccothraustes vespertinus*]).

Habitat change due to logging may have contributed to the extensive and recent range changes of the barred owl (*Strix varia;* Fig. 4), which tends to prefer mixed-aged forests. Before 1972 no northern populations of this owl were reported west of the 100th meridian (Root 1988a). The recent expansion is of concern because this owl's range is now partly sympatric with that of the endangered northern spotted owl (*S. occidentalis caurina*), which prefers ancient forests. The consequences of competition between these two species are not understood well yet, but nesting sites, foraging, and diet are similar, particularly in the Northwest (Taylor and Forsman 1976). Anecdotal evidence, however, suggests the larger, more aggressive barred owl may be able to displace the smaller spotted owl (Sharp 1989).

Other raptors (e.g., northern harrier [*Circus cyaneus*] and ferruginous hawk [*Buteo regalis*]) have also significantly expanded their ranges. In particular, the golden eagle (*Aquila chrysaetos*) has moved east, while the bald eagle (*Haliaeetus leucocephalus*; Fig. 5) has spread into the center of the continent.

Over the years humans have strongly influenced the expansion of the bald eagle's range through water-management programs (Root 1988a). Large lakes and impounds built in the 1930's, locks placed on major waterways,

Fig. 1. Range and abundance patterns of the mute swan. (a) Data from 1901 to 1940, (b) Data from 1960 to 1989 (except 1969).
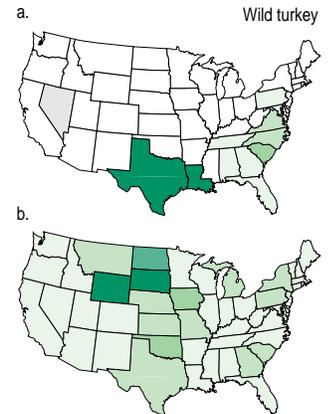

Fig. 2. Range and abundance patterns of the wild turkey. (a) Data from 1901 to 1940, (b) Data from 1960 to 1989 (except 1969).
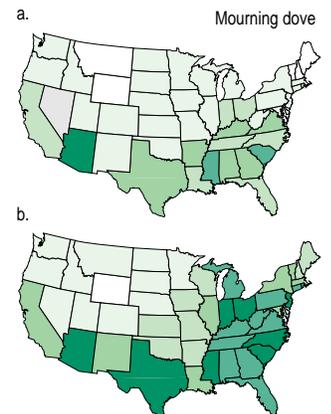

Fig. 3. Range and abundance patterns of the mourning dove. (a) Data from 1901 to 1940, (b) Data from 1960 to 1989 (except 1969).
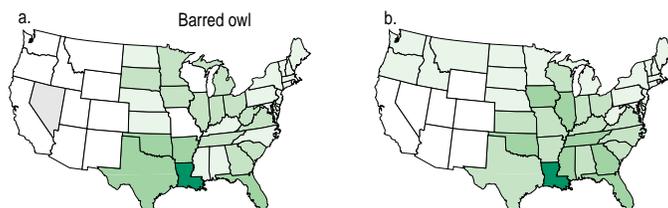

Fig. 4. Range and abundance patterns of the barred owl. (a) Data from 1901 to 1940. (b) Data from 1960 to 1989 (except 1969).

As part of the joint United States-Canada efforts to monitor populations of Arctic geese and to provide data necessary to set hunting regulations, scientists have recorded not only goose population levels, but also nesting behavior. MacInnes et al. (1990) analyzed data from four long-term studies of five different Arctic goose populations. These studies documented the date the eggs hatched and the clutch size (number of eggs per nest) over 35 years (Fig. 1).

The dates of nest initiation and hatch are clearly affected by climate and are delayed by cold weather. The records not only show wide fluctuations from year to year in response to annual variations in climate, but also demonstrate a consistent trend toward

Changes in Nesting Behavior of Arctic Geese

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earlier hatching over the period (Fig. 2). Young Arctic geese today, on the average, hatch about 30 days earlier than they did 35 years ago; during the same time, average clutch size has shrunk (Fig. 3). MacInnes et al. (1990) suggest the change in nest date is a result of climatic amelioration, that is,

warming (although whether from a long-term trend or short-term cycle is unclear), and the change in clutch size is a result of habitat deterioration.

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Fig. 1. Location of four monitoring sites. Sites chosen represent localities with information for 5 or more years. Site 1–McConnell River (60° 50'N, 94° 25'W; snow goose [*Chen caerulescens*] and small Canada goose [*Branta canadensis*]); 2– La Pérouse Bay (58° 24'N, 94° 24'W; snow goose); 3–Cape Churchill (58° 25'N, 93°W; medium Canada goose); and 4–Southhampton Island (63° 60'N, 86°W; snow goose).
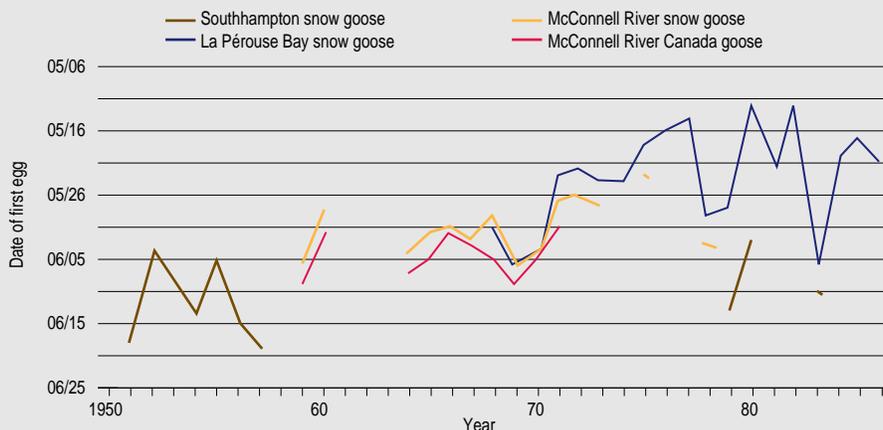

Fig. 2. Date of first egg. Although all sites displayed large fluctuations, both the date of first egg and the mean (average) hatch date became significantly earlier during the period 1951-86. There were no significant differences in the slopes of trends among sites or species.
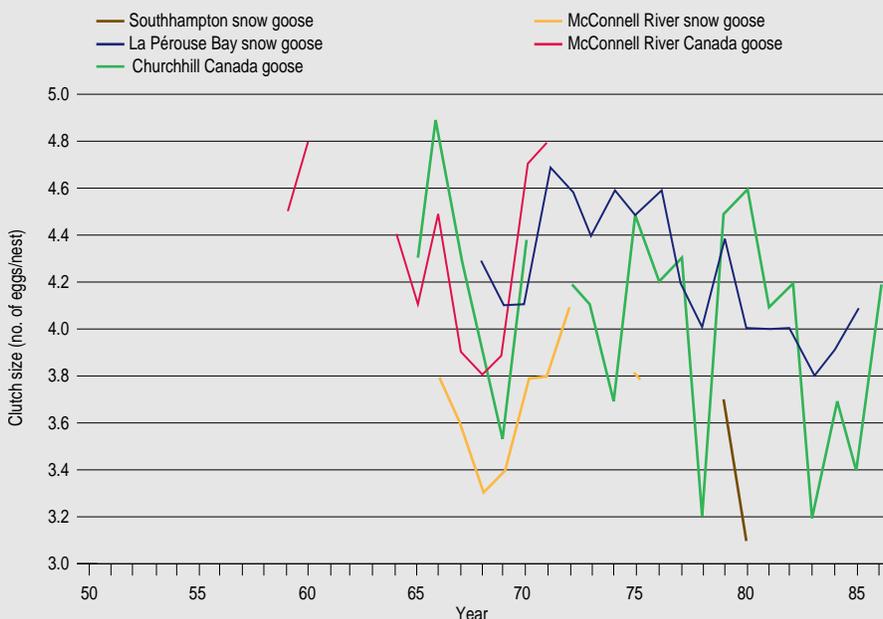

Canada goose (*Branta canadensis*).

Fig. 3. Clutch size of nests of snow and Canada geese at Hudson Bay.

and numerous hydroelectric plants built with cooling ponds provide open water in winter, which this eagle needs for hunting (Southern 1963).

The winter abundance of the bald eagle throughout most of the contiguous United States dropped by about a third from 1957 to 1970 because of the use of persistent insecticides (e.g., DDT) and habitat destruction (Brown 1975). Since World War II, population declines in the East have been blamed on habitat destruction due to human disturbances (waterfront housing and outdoor recreation; Sprunt 1969). Shooting by ranchers from small planes from the late 1930's to the early 1960's could have depressed their abundance during this period and later (USFWS 1992).

Range Contractions

Of the 58 species examined, only 4 showed range contractions. This result could have been partly an artifact of our sample: we did not examine species that have very restricted ranges. It may also be due to our methods of examination because species had to abandon entire states, not just part of them, before we recorded a contraction. Of the four species showing range contractions, one is the brown-headed cowbird (*Molothrus ater*) and the other three depend on open water: pied-billed grebe (*Podilymbus podiceps*), northern pintail (*Anas acuta*), and common merganser (*Mergus merganser*).

The contraction of the northern pintail is of particular concern (Fig. 6). This game species has been extensively managed, yet estimates of its breeding population have shown a fivefold decrease since the mid-1900's (USFWS 1992). The reasons for this large decline are not yet understood.

Conclusion

The data collected by volunteers for the National Audubon Society's Christmas Bird Counts provide excellent information to examine the ranges and abundance patterns of wintering North American birds over both a very broad spatial scale and a long temporal scale. The changes that we found were primarily due to human activity, both purposeful (e.g., management of game species) and accidental. Some of these changes could be viewed as being beneficial (e.g., water management programs increasing bald eagle numbers), while others could be viewed as negative (e.g., logging allowed barred owls to invade spotted owl territories).
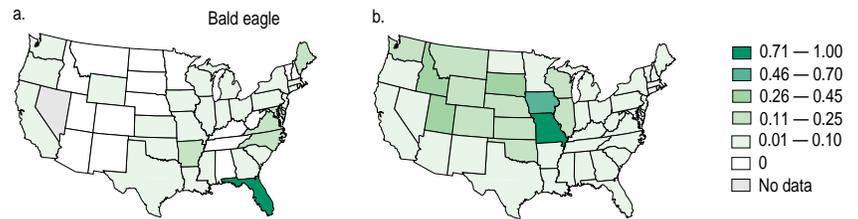

Fig. 5. Range and abundance patterns of the bald eagle. (a) Data from 1901 to 1940. (b) Data from 1960 to 1989 (except 1969).

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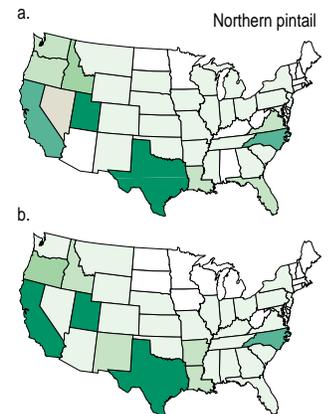
Fig. 6. Maps showing range and abundance patterns of the northern pintail. (a) Data from 1901 to 1940. (b) Data from 1960 to 1989 (except 1969).

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Climate Change in the Northeast

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Climate is a principal determinant of biological distributions and of patterns that characterize the seasonal physiology and behavior of many organisms (Gates 1993). Consequently, a changing climate should elicit responses in these biological properties. Detecting and characterizing such changes are logical early steps in assessing the significance of climate change to species and ecosystems (Schwartz 1990). Most published work on this subject involves species and ecosystem modeling based on known physiological and behavioral traits of selected species. This article presents evidence from an array of phenological data suggesting that climate change is occurring and that its biological effects may already be of considerable magnitude. (Phenological data are those associated with the relationship between climate and periodic phenomena like bird migration and flowering.)

Most research intended to explore possible effects of climate change on vegetation has understandably focused on agricultural and forest plants. Our approach, however, focuses on examining historical trends at the regional level and identifying species of potential value as climate change indicators. With the assumption, based on climate models, that unidirectional warming is already occurring and will probably accelerate over the next few decades, we began to search for evidence of biological responses among very different groups of organisms.

Specifically, dates of the first return of spring-migrating birds and of the first bloom of spring wildflowers in the Northeast were sought in long-term (50 or more years), continuous, reliable records.

We computerized and analyzed two major and several minor long-term data sets from handwritten records from three New York State locations (Fig. 1). An especially rich source was records from the Cayuga Bird Club at Ithaca. Highly reliable observers recorded first spring sightings of migratory birds from 1903 to the present in the Cayuga Lake basin of central New York as delineated by Wiegand and Eames (1925). A second source of extensive, high-quality information was records for dates of first spring arrival for migrating birds and dates of first bloom for spring wildflowers at the Mohonk Preserve, an upland site in the mid-Hudson Highlands region of southeastern New York; these records extend from the late 1920's onward. Both sites are expected to continue generating comparable data sets. A third data set includes dates of first spring arrival for Louisiana waterthrush (*Seiurus motacilla*) and solitary vireo (*Vireo solitarius*) in western New York (1952 to present) on the Allegheny Plateau.

Our general approach to data analysis has been in the form of species plots with date of first arrival or first bloom as the vertical axis and sequence of years as the horizontal axis (Figs. 2-4).

Status and Trends

Flowering Plants

Phenological data were examined for 15 species of spring wildflowers on time of first blooming at the Hudson Highlands site (Fig. 2). Six species of wildflowers all exhibited significantly earlier ($P \leq 0.05$) rather than later blooming (averaging -19.8 days/50 yr; $R^2 = 0.26$). The remaining nine species showed no significant patterns of change. We only can speculate why six species exhibited such a pronounced change and nine others did not. Clues may be obtained when existing data for other plant species at this site are examined. For example, the set of species showing earlier blooming appears to include plants typically found in more open locations where soil temperature would show the earliest and most rapid response to warming. One woody shrub, common witch-hazel (*Hamamelis virginiana*), which blooms in early fall, also showed a significant trend toward earlier bloom.

Fig. 1. New York locations from which phenological data were obtained. 1–Allegheny Plateau (birds); 2–Cayuga Lake basin, Ithaca (birds); and 3–Hudson Highlands (flowering plants and birds).
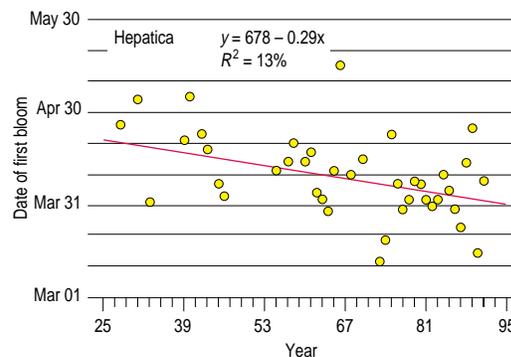

Fig. 2. Trend for hepatica (*Hepatica acutiloba*) from the Hudson Highlands (Mohonk Preserve) of southeastern New York, showing tendency for earlier spring blooming. The negative slope of the trend is significant at $P < 0.05$.
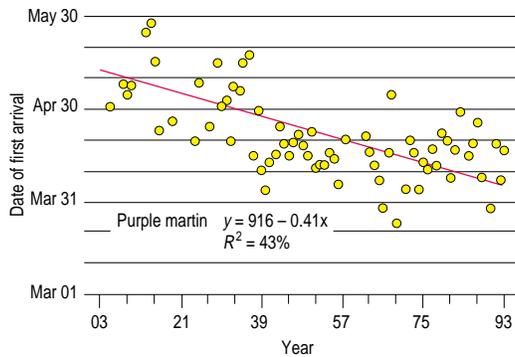
Fig. 3. Trend for purple martin (*Progne subis*) from the Cayuga Lake basin of central New York showing a clear tendency for earlier spring arrival. The negative slope of the trend is significant at $P < 0.005$.
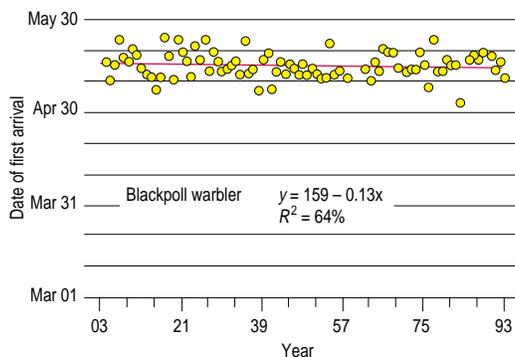

Fig. 4. Trend for blackpoll warbler (*Dendroica striata*) from the Cayuga Lake basin of central New York, showing no tendency for earlier spring arrival. The slope of the trend is not significantly different from zero.

Migratory Landbirds

Records of first sightings of spring migrants from the Cayuga Lake basin of central New York are from 1903 to the present and represent 130 species. More than 5,000 first arrival dates were examined for 76 species of migratory landbirds, excluding waterfowl, hawks, and shorebirds. Thirty-nine species (51%) showed 90-year trends of significantly earlier ($P \leq 0.05$) arrival, with an average shift of about 5.5 days/50 yr (for example, see Fig. 3). Thirty-five species (46%) showed no significant change ($P \leq 0.05$) in dates of first spring arrival (Fig. 4). Louisiana waterthrush and mourning warbler (*Oporornis philadelphia*) were the only species showing significant trends ($P \leq 0.05$) toward later spring arrival dates.

Of those species showing significantly earlier arrival dates, 85% are long-distance Neotropical migrants, which normally overwinter in Central and South America. For the Mohonk Preserve data, 6 of 10 migratory bird species examined showed significant trends toward earlier arrival. For the western

Allegheny Plateau, first-arrival data, covering a 40-year period beginning in 1952, were available for two species of birds, Louisiana waterthrush and solitary vireo. Both species tended to earlier arrival.

Conclusions

The trends reported here toward earlier arrival dates for migratory birds and earlier blooming dates for spring wildflowers are concurrent with patterns of climatic warming and consistent with what might be expected in the context of global warming. At the same time, local changes in land cover, with the forested area of the region increasing by more than 30% since 1900, may provide greater amounts of suitable habitat for attracting and holding migrating landbirds, thereby contributing to observed patterns of change in migratory behavior.

It is noteworthy that only two bird species examined, and no plant species, showed trends to either later spring arrival or later blooming. If explanations of trends for only one of these two major groups were sought, alternative explanations could be advanced, such as expansion of bird ranges due to changes in land use (*see* Root and Weckstein, this section). In addition, a recent examination of dates of fall departure for migrating birds in Germany (Gatter 1992) shows later fall departures. Such fall trends would be expected in the context of climatic warming and agree with the spring trends we report.

Given the patterns reported here, climate change is the one variable affecting diverse groups of organisms that offers a rational and parsimonious explanation for the observed changes in timing of migration in birds and blooming in plants we and others have observed. Research either planned or in progress includes analyzing additional data sets as well as more sophisticated statistical analysis; determining the species most appropriate for monitoring climate change; finding and analyzing data sets that describe the phenology of other taxa; and possibly extending the study to other locations.

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Potential Impacts of Climate Change on North American Flora

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Climate change is a natural phenomenon that has occurred throughout the history of the earth. The frequency and magnitude of climate change have varied substantially during and between glacial periods, and temperatures on both global and local scales have been both substantially warmer and colder than present-day averages (Ruddiman and Wright 1987; Pielou 1991; Peters and Lovejoy 1992). While potential magnitudes of local and global climate change are of concern, it is the predicted rate of temperature change that poses the greatest threat to biodiversity. The ability of species to survive rapid climate changes may partially depend on the rate at which they can migrate to newly suitable areas.

In the next few centuries climate may change rapidly because of human influences. The concentrations of "greenhouse" gases in the atmosphere are being altered by activities such as carbon dioxide emission from burning fossil fuels. Models of climate change (IPCC 1990, 1992) predict an increase in mean global temperature of about 1.5-4.5°C (2.7-8.1°F) in the next century. Temperature changes suggested by general circulation models would present natural systems with a warmer climate than has been experienced during the last 100,000 years. While this would be a substantial change from the current climate, the *rate* of climate change is the greatest determinant of the impact on biological diversity. Future climate change due to human influences could occur many times faster than any past episode of global climate change (IPCC 1990, 1992; Schneider et al. 1992).

The strong association between distributions of plant species and climate suggests that rapid global climatic changes could alter plant distributions, resulting in extensive reorganization of natural communities (Graham and Grimm 1990). Climate changes could also lead to local extirpations of plant populations and species extinctions. The effects of global climate change are likely to vary regionally, depending on factors such as proximity to oceans and mountain ranges. Alteration of the amount and timing of precipitation and evaporation would affect soils and habitats; freshwater ecosystems are likely to be vulnerable to these changes in hydrology (Carpenter et al. 1992). Even minor fluctuations in the availability of water can radically affect habitat suitability for many wetland plant species. Rapid, large-scale shifts in temperature, precipitation, and other climate patterns could have broad ecological effects, presenting major challenges to the conservation of biodiversity.

Analysis of Potential Effects

An analysis conducted by The Nature Conservancy on the potential effects of climate change on the native vascular flora of North America (Morse et al. 1993) provides a preliminary assessment of patterns of plant species' vulnerability. For this preliminary analysis, we made several simplifying assumptions about the relationships between plants and climate to estimate the viable climate "envelopes" for each of over 15,000 native vascular plant species in North America recognized in the checklist by Kartesz (1994).

The principal assumptions are that climate determines the range of plant species; mean annual temperature adequately approximates climate; species distribution appears to be in equilibrium with present climate; and a species' current climate envelope is equivalent to its tolerance of climate variation. Together, these assumptions state that the current distribution of each species is greatly influenced by climate and that temperature adequately represents climate.

Clearly, each of the above assumptions are not actually met for all native vascular plant species. For example, precipitation and soil moisture are extremely important determinants of range limits in some regions. These simplified temperature envelopes, however, allow the initial identification of broad patterns of species' vulnerability to climate change.

In the analysis, the mean temperature was uniformly increased in 1°C (1.8°F) increments up to an increase of 20°C (36°F) above current mean annual temperatures (Fig. 1). Many species would be vulnerable to climate change in all scenarios of uniform temperature increase. With a mean global warming of 3°C
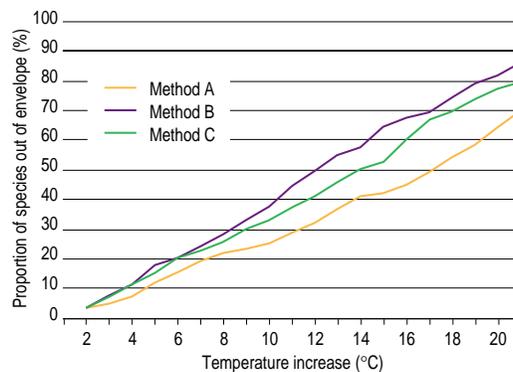

Fig. 1. The proportion of native vascular plant species that were entirely out of their climate envelopes as a function of the increase in temperature above mean annual temperature. Three methods were used to determine climate envelopes (A, B, C).

(5.4°F), 7% to 11% of 15,148 native vascular plant species in North America (about 1,060 to 1,670 species) could be entirely out of their climate envelopes. These species would thus be vulnerable to extinction unless they can migrate rapidly enough or can persist despite climate change. In comparison, about 90 plant species in North America are believed to have gone extinct in the last two centuries (Russell and Morse 1992).

Rarity and Vulnerability

Of the native vascular plant species studied, about 4,100 (27%) are considered rare by The Nature Conservancy (*see* article by Stein et al., p. 399, for definitions of ranking system for rarity). These species occur at fewer than 100 sites or are comparably vulnerable. Our analysis shows that these rare plants are likely to be further affected by climate change. In this analysis, about 10%-18% of the rare species would be vulnerable to a mean 3°C (5.4°F) temperature increase. In contrast, only 1% to 2% of the common species appear vulnerable under these conditions. These results imply that numerous rare vascular plant species could be additionally threatened by climate change. Early warnings of species' vulnerability to a rapidly changing climate might allow the development and implementation of new conservation strategies before a crisis occurs, thus improving the success rate for the protection of rare plants while minimizing the cost.

Regional Patterns of Vulnerability

Based on the uniform 3°C (5.4°F) mean increase in temperature used for this preliminary climate change impacts analysis, there appear to be regional patterns to the proportion of potentially vulnerable species in each state or province (Fig. 2). In this initially simplified analysis, the southeastern states have the highest percentage of species out of their climate envelopes, while the Great Plains states and provinces may experience proportionally fewer species losses. The relatively high proportion of species vulnerability in the Southeast may be due in part to the presence in state floras of Appalachian Mountain species at their southern range limits. Many of these species are already rare in states along their southern range limits and are likely to be lost from the local floras if the climate warms.

Global warming models, however, suggest that the temperature and precipitation changes in the interior of the continent will be far greater than in coastal regions. In the Great Plains, some models suggest increases in summer tem-
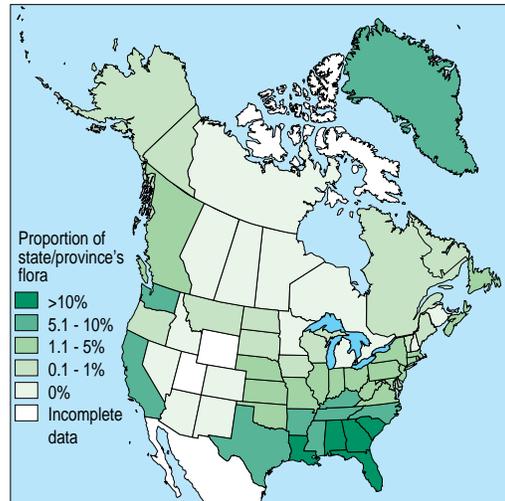

Proportion of state/province's flora

- >10%
- 5.1 - 10%
- 1.1 - 5%
- 0.1 - 1%
- 0%
- Incomplete data

Fig. 2. The proportion of species that would be out of their climate envelope in each state or province with a +3°C (+5.4°F) temperature change.

peratures by 4-7°C (7.2-12.6°F), accompanied by dramatic decreases in precipitation. Future analyses that incorporate regional changes in climate projected by models will further refine our understanding of regional patterns of plant species' vulnerability to climate change.

Dispersal and Persistence of Vascular Plants

The survival of species during periods of changing climate will be determined in part by their abilities to disperse to new sites or to persist in place. For this analysis, a dispersal-ability scale was used to assess the potential for different species to migrate. The scale is based on characteristics important to species mobility such as pollination mechanisms, dispersal mechanisms, reproductive characteristics, degree of self-compatibility, growth form, trophic type, and number of populations. Biological factors likely to increase species mobility include wind pollination, at least partial self-compatibility, dispersal of propagules by wind or birds, and a short generation time. Characteristics such as dependence on specific pollinators (e.g., yucca and yucca moth), dispersal by ants, or a long generation time reduce the chances for successful rapid dispersal and establishment. By using these criteria, most of the species studied appear to have an intermediate dispersal potential.

The species in this analysis that would be vulnerable in a +3°C (5.4°F) climate appear to have characteristics that limit long-distance dispersal (Fig. 3). This suggests that the plants potentially most vulnerable to climate change may be those forced to adapt in place to new conditions. In general, rare plants and narrow endemics will be particularly endangered by climate change. These plants often have restricted ranges, a reduced seed source, and may depend on specific microclimatic conditions for
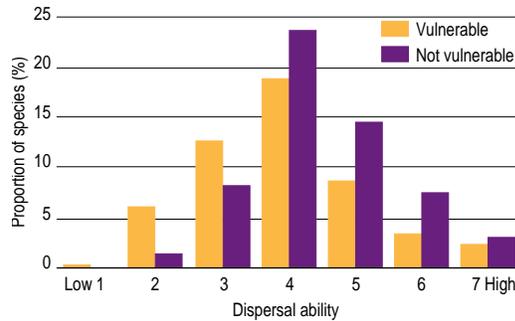
Fig. 3. The proportion of species on the dispersal-ability scale that are out of their climate envelopes (vulnerable) or in their climate envelopes (not vulnerable) with a +3°C (+5.4°F) temperature change. Full data were available for 8,668 species.

survival. Rare plants would thus potentially have trouble migrating to comparable new sites, regardless of their ability to disperse. For example, Boott's rattlesnake-root (*Prenanthes boottii*) and mountain avens (*Geum peckii*), endemic to alpine habitats in the northeastern United States, would be particularly sensitive to global warming.

Migration Rate

During the warming at the end of the last glacial period, plant migration rates, as calculated from the fossil pollen record, ranged from about 5 to 150 km (3-90 mi) per century (Shugart et al. 1986). Human-caused climate change may occur at rates more than five times faster than any changes since the last glacial maximum, including the period of most rapid deglaciation (Overpeck et al. 1991). Various studies have suggested that such rapid climate changes would require shifts of plant ranges of up to 500 km (300 mi) within the next century, exceeding the known rates of migration for many plant species (Davis 1984; Davis and Zabinski 1992).

Since species respond individually to climate change, migration rates will vary within and among natural communities. It is unlikely that entire biological communities would move together in response to climate changes (Graham and Grimm 1990). Some plants may respond rapidly to changes; others may survive for several generations in place or persist as long-lived clones despite significant climate change. The fossil record provides evidence of decade- or even century-long time lags in species migration (Davis 1989). The process of changing community composition in response to climate change has been documented in the fossil record through the disassociation and reassembly of plant and animal taxa (Graham and Grimm 1990). This variation in species assemblages displays the transitory nature of former as well as existing and future community types.

Temperature extremes and changes in the frequency and severity of local disturbances may have a greater influence on the survival of plant species at particular locations than small shifts in the average climate. More frequent droughts, fires, and pest and pathogen outbreaks are predicted to act in conjunction with climate change to significantly transform the landscape (Peters 1992). This prediction is supported by paleoecological evidence that altered disturbance regimes can intensify the effects of climate change on plants and increase the amount of overall vegetational change (Davis 1989).

Threats by Weedy Exotics

With global climate change, some exotic weeds may be favored over native species. Many weeds are able to expand relatively quickly, posing serious threats to existing species and overall biodiversity (Schwartz 1992). Many weedy species are widespread, prolific, fast-growing annuals capable of establishing in disturbed habitats and are often favored by disturbances. Climate-induced changes could expose native plants to non-native competitors for the first time (Peters 1992), stressing the balance established between native plants and their habitat. Exotic weeds may become a greater problem in the management of many preserves and natural areas.

Landscape Fragmentation

The potentially rapid rates of warming, combined with habitat loss and fragmentation from human development, suggest that many species will not adjust as successfully to climate change as in the past. Most native plant species exist in a highly fragmented landscape that further separates appropriate habitat patches, increasing the dependence of many species on relatively rare events of long-distance dispersal. Furthermore, species often must disperse across hostile habitats, including roads, cities and suburbs, and farmland (Peters 1992). Finally, plants would need to establish themselves in landscapes where many of the open or disturbed areas have been colonized by aggressive weedy exotics.

Climate Change and Conservation Planning

Rapid climate change could place novel demands and constraints on plant species conservation. Vulnerability to climate change could affect selection and design of new preserves and management procedures in existing preserves, especially in southern or low-elevation portions of species' ranges. Management of species threatened by climate change could involve

restoration and transplantation of species among preserves or into new locations. Actions such as removal of exotic species or hydrological controls may not be qualitatively different than those that are currently required of land managers, but climate change may increase the intensity and frequency of threats from exotic species, drought, and fire. In view of the unpredictable and potentially devastating effects of global climate change on species' viability and distribution, conservation strategies such as propagation of critical species outside of their natural range to provide materials for reintroductions are likely to become increasingly important to preserve biological diversity.

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