Uncovering, Collecting, and Analyzing Records to Investigate the Ecological Impacts of Climate Change: A Template from Thoreau's Concord

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Historical records are an important resource for understanding the biological impacts of climate change. Such records include naturalists' journals, club and field station records, museum specimens, photographs, and scientific research. Finding records and overcoming their limitations are serious challenges to climate change research. In the present article, we describe efforts to locate data from Concord, Massachusetts, and provide a template that can be replicated in other locations. Analyses of diverse data sources, including observations made in the 1850s by Henry David Thoreau, indicate that climate change is affecting the phenology, presence, and abundance of species in Concord. Despite recent work on historical records, many sources of historical data are underutilized. Analyses of these data may provide insights into climate change impacts and techniques to manage them. Moreover, the results are useful for communicating local examples of changing climate conditions to the public.

Keywords: climate change; Concord, Massachusetts; historical data; phenology; Henry David Thoreau

Climate change has emerged as one of the most important topics in ecology and provides new challenges and opportunities for research. As a group, the ecologists who investigate climate change perform four important functions. First, they investigate the current impacts of changing climate on ecosystems. This research is often undertaken by comparing present conditions with records from the past (e.g., Woodward 1987, Parmesan et al. 1999, Aono and Kazui 2008). Second, they predict how ecosystems will respond to future changes in climate. Such predictions are significant because climate change will affect the abundance and distribution of species and ecosystems across the globe (Parry et al. 2007). Third, ecologists plan and propose practical ways to conserve biodiversity and maintain ecosystem services in the face of a changing environment. Finally, ecologists educate the general public and political leaders about the enormous environmental, social, and economic implications climate change.

When we began our investigations of climate change in 2003, there were few studies of the ecological effects of climate change on the eastern United States, despite documented changes in the climate of the region (National Assessment Synthesis Team 2001). The lack of examples gave the impression that climate change was happening far away, which diminished its relevance to the citizens and leaders of this country, a problem that persists today (Leiserowitz et al. 2010). A deliberate goal of our research was to find biological records—both historical and modern—that we could analyze to determine whether warming temperatures and other aspects of climate change were demonstrably affecting ecosystems in the United States. A second goal was to convey our results widely and to engage the US public's interest in climate change research based on familiar locations and recognizable species.

Other researchers have taken similar approaches—finding various sources of biological records and testing for long-term responses to climate change (Lavoie and Lachance 2006, Tingley and Beissinger 2009, Crimmins et al. 2010)—including those who revisited Aldo Leopold's phenology observations in Wisconsin (Bradley et al. 1999) and Joseph Grinnell's observations of the distribution of mammals and birds in the mountains of California (Moritz et al. 2008,

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Tingley and Beissinger 2009). However, sources of ecological data, including naturalists' journals, club and field station records, museum specimens, and photographs, are still underutilized in ecological research (Sparks 2007, Johnson et al. 2011).

In the present article, we describe our work in Concord, Massachusetts, including how we have found and analyzed the data and have communicated the results to the public. Although our research in Concord is ongoing, we have confined this review and synthesis to work that has already been published, along with some updates of those studies. We highlight some of the challenges we have overcome—some of which may partially explain why historical data are still underutilized—and we describe additional promising areas of research. We hope that this might provide a template for similar research that can be implemented elsewhere.

Finding and transcribing historical records

Our approach, beginning in Massachusetts in 2003, was to try to locate historical data sets and contemporary observations of changes in species' phenology, abundance, and distribution that could be analyzed from the perspective of climate change (box 1). Initially unsure of what records might be available and where we might find them, we sought information by word of mouth. We talked with biologists, amateur naturalists, and citizen groups. We wrote articles for newsletters and newspapers describing our project and what types of data we needed. We used e-mail lists to reach specialized groups. At one point, we also tried posting signs in parks, the public library, and other gathering points, asking the public for help.

Right away, people contacted us with information about data sets that they had been gathering or with suggestions regarding other people we might contact. The most common types of data were records of the dates when people first saw birds arriving in their back yards or neighborhoods in the spring. People sometimes mentioned work that other people or organizations were gathering or old records that they knew about. These data sets were scattered throughout eastern Massachusetts and New England, and many were quite useful for tracking long-term changes in phenology (table 1; Ledneva et al. 2004, Primack D et al. 2004, Miller-Rushing et al. 2006, 2008a, 2008b). Using this approach, we found many more data sets of phenology records than we have been able to analyze or publish.

The most detailed data sets that we found pertained to biological phenomena in Concord, Massachusetts. We found many data sets from Concord, but two were particularly valuable. The first was collected by the writer and naturalist Henry David Thoreau, author of *Walden*. He had made observations of first flowering dates for over 500 species of wildflowers in Concord from 1851 to 1858. Brad Dean, an independent Thoreau scholar, helped us obtain Thoreau's unpublished tables containing these observations of flowering. Thoreau also observed and recorded the dates of initial leaf out for trees and shrubs and the first sightings

Box 1. Phenology as an indicator of ecological response to climate change.

A warming climate has the potential to affect many aspects of the life cycle of individual species and ecosystems. However, of all biological characteristics, one that is thoroughly documented and particularly sensitive to temperature is *phenology*, or the timing of seasonal biological events (Parmesan and Yohe 2003, Root et al. 2003). The phenologies of temperate plants, such as flowering and leaf-out dates, are known to be especially sensitive to temperature (Cleland et al. 2007). Warm weather in the early spring in particular can cause plants to be active earlier in the growing season, and cold weather can delay flowering and leaf-out. In addition, phenology is relatively easy to observe. There is a long tradition of amateur and professional naturalists recording observations of the phenology of plants and animals, whether as a way to track the seasons or for specific applications, such as agriculture (figure 1; e.g., Hopkins 1918, Sparks and Carey 1995, Bradley et al. 1999). Because phenology is particularly responsive to climate change and is a critical aspect of ecosystem dynamics and because phenology observations are so commonly collected, phenology is a very good indicator of ecological responses to climate change.

Figure 1. Thoreau kept detailed records of plant flowering dates in Concord from 1852 to 1858. A statue of Thoreau in front of a replica of his cabin at Walden Pond. Photograph: Richard B. Primack.

Table 1. Selected sources of historical and modern phenological data in eastern Massachusetts.

Collector	Location of record	Type of record	Timeframe
Henry David Thoreau[a]	Various libraries and private copies	Handwritten tables of flowering dates	1851–1858
Alfred Hosmer[a]	Concord Free Public Library	Handwritten tables of flowering dates	1878, 1888–1902
Penny Logemann[a]	Logemann's personal records	Handwritten tables of bird-arrival dates	1963–1993
Primack and Miller-Rushing[a]	Primack lab	Digital spreadsheets of flowering dates	2003–present
Arboretum staff and visiting scientists[b,c]	Arnold Arboretum Herbarium	Dated herbarium specimens	1881–2002
Arboretum staff and visitors[c]	Arnold Arboretum Library and individual staff	Dated photographs of plants in flower	1904–2004
Herbert Wendell Gleason[c]	Concord Free Public Library	Dated photographs of plants in flower	1900–1921
Kathleen Anderson[d]	Anderson's personal records	Personal journals with entries on spring phenology	1970–2002
Manomet Center for Conservation Sciences[e]	Manomet Center for Conservation Sciences	Digital spreadsheets of birds arrivals	1970–present
Mount Auburn birdwatchers[f]	*Bird Observer*	Periodic reporting of bird sightings	1980–present
Henry David Thoreau[g]	Museum of Comparative Zoology, Harvard University	Handwritten tables of bird arrivals	1851–1854
William Brewster[g]	Museum of Comparative Zoology, Harvard University	Handwritten tables of bird arrivals	1886, 1900–1919
Ludlow Griscom[g]	Peabody Essex Museum	Handwritten tables of bird arrivals	1930–1954
Rosita Corey[g]	Personal records	Personal journals of bird arrivals	1956–1973, 1988–2007
State workers[h]	Massachusetts State Laboratory	Digital and paper records of mosquito trapping	1957–present
Butterfly collectors	Natural history museums	Labels on butterfly specimens	Mainly mid-1800s to 1950; some more recent
Butterfly enthusiasts	Massachusetts Butterfly Club	Digital records of butterfly sightings	1986–present

[a]Miller-Rushing and Primack 2008.
[b]Primack D et al. 2004.
[c]Miller-Rushing et al. 2006.
[d]Ledneva et al. 2004.
[e]Miller-Rushing et al. 2008c.
[f]Miller-Rushing et al. 2008b.
[g]Ellwood et al. 2010.
[h]Hachiya et al. 2007.

of migratory birds in springtime. The second important Concord data set was a table of flowering dates collected by Alfred Hosmer, a local botanist. Hosmer had recorded the flowering dates of over 600 species of wild plants in Concord in 1878 and from 1888 to 1902. Although Hosmer had never written anything about the details of his observations, his notebooks were stored in the special collections of the Concord Free Public Library. These two data sets were particularly valuable and unusual for the length of the time period covered (although the data sets were not continuous) and the number and diversity of the species they described.

Transcribing these Concord data sets from paper to electronic formats represented a significant challenge. Thoreau had notoriously bad handwriting; reading his plant names was particularly difficult. Also, plant names—both common names and scientific names—have changed substantially since the 1850s. Therefore, we spent a large amount of time working with old floras to match old names with modern names.

Collecting modern data to match historical observations

To document the long-term changes in species phenology, diversity, and abundance that had occurred since the 1850s, we needed a set of modern observations focused on the same species. Therefore, we began to replicate Thoreau and Hosmer's phenological surveys. Starting in April 2003, we walked around Concord two to three days per week, searching for the first flowers of each species. In our first year, we primarily explored the places where each species historically occurred and learned to identify some of the more problematic species. We spent a lot of time talking with the community of naturalists who live in Concord, asking them where we could find many species, particularly rare species. Our entire phenology data set from 2003 was not usable for analysis because we had often located a species a week or more after it had started to flower, whereas Thoreau and Hosmer had recorded the first flowering of species. However, this initial survey showed us where to find the earliest flowering plants of most species so that we could collect usable data in repeated phenological surveys from 2004 on.

Analyzing combined data sets

Initially, we analyzed the complete data set in several different ways. However, we were able to get the clearest results and most of the crucial information by focusing on the common plant species that Thoreau, Hosmer, and our survey team had seen every year. There were 43 such species, representing a mixture of native and introduced species. We found that the trends based on these 43 species matched the trends based on the full suite of species included in the data set (Miller-Rushing and Primack 2008). This approach allowed us to avoid the complicated data manipulations needed to account for missing values for different species in different years. Using this subset of data, we were able to demonstrate unambiguously that the plants in Concord, on average, are now flowering 10 days earlier than they were in Thoreau's time (ANOVA, $p < .001$; figure 1; Miller-Rushing and Primack 2008). In addition to the trend toward earlier flowering over time, we observed that the studied plants tend to flower earlier in warmer years than in cold years (43 species; 3.1 days earlier per degree Celsius [°C] for the mean January, April, and May temperatures; linear regression, $R^2 = .61$, $p < .001$), and that average annual temperature values recorded in the greater Boston area since Thoreau's time have grown steadily warmer, in part because of global warming and the urban-heat-island effect (2.4°C warming over 155 years, $R^2 = .57$, $p < .001$; box 2; Miller-Rushing and Primack 2008). The year 2010 had the warmest April on record, and as was expected, the flowering dates for 2010

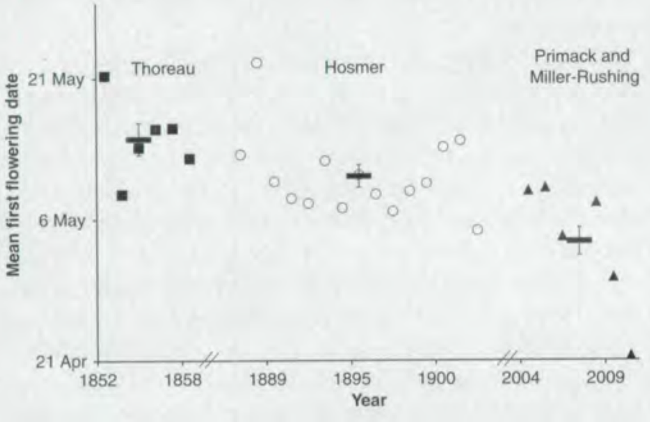

Figure 2. The average first flowering dates of 43 common plant species. The first flowering dates observed by Thoreau in the 1850s are later than the recent observations of Primack and Miller-Rushing, with Hosmer's observations (1878–1902) intermediate between the two. The horizontal bars represent the mean values for the years of each observer. The error bars each represent one standard error. Adapted from Miller-Rushing and Primack (2008); the data from 2008–2010 are published here for the first time.

Box 2. Urban areas as models for climate change.

Large urban areas, like metropolitan Boston, which includes Concord, can provide model locations to study the impacts of climate change. Whereas global temperatures have increased by around 0.7 degrees Celsius (°C) over the past 100 years, many cities have warmed more than that because of the urban-heat-island effect (Arnfield 2003). Buildings, paved roads, sidewalks, and parking lots absorb heat during the day and release that heat during the night, creating a much warmer environment than the surrounding countryside. Boston and Concord have warmed over 2°C since the time of Thoreau, with about two-thirds of this increase probably caused by the urban-heat-island effect (figure 3; Miller-Rushing and Primack 2008). As a consequence, we can expect to see more effects of climate change in places like Boston than in nonurban areas. Furthermore, the warming temperatures that places like Boston have experienced in recent decades are similar to the amount of warming forecast for more rural areas in the coming century (Hayhoe et al. 2007). Therefore, urban areas may provide reasonable model systems to examine some of the effects of climate change on plants and animals.

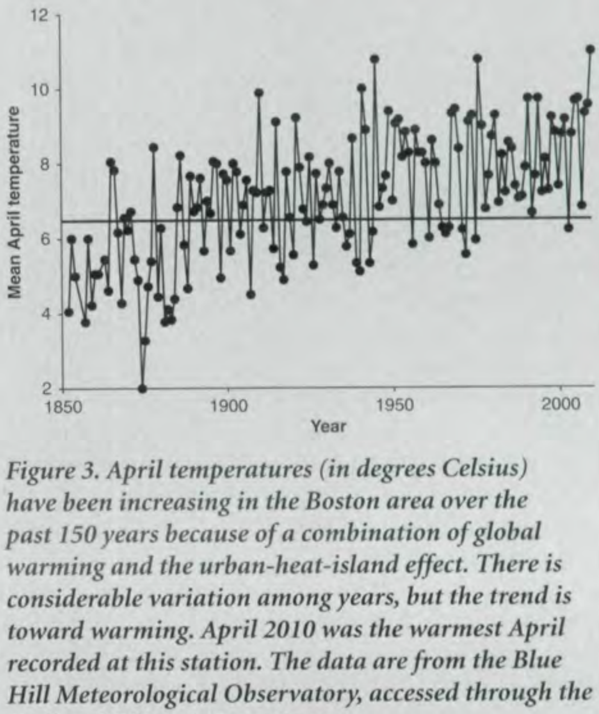

Figure 3. April temperatures (in degrees Celsius) have been increasing in the Boston area over the past 150 years because of a combination of global warming and the urban-heat-island effect. There is considerable variation among years, but the trend is toward warming. April 2010 was the warmest April recorded at this station. The data are from the Blue Hill Meteorological Observatory, accessed through the National Climatic Data Center.

were earlier than those of any previous year and three weeks earlier than the average of Thoreau's observations. During our analyses, we tested the relationship between changes in phenology and many environmental variables other than temperature—including precipitation, land-use changes, and air quality—and found that they were not correlated with the yearly variation in spring flowering dates.

By using species that were common in Concord 100 years ago (as they were recorded by Hosmer) and are still common in Concord today (according to our own observations; see Primack RB et al. 2009b for detailed methods for documenting abundance), we were able to avoid the problems associated with the first flowering dates of species that change in abundance over time. For example, if a species is declining in abundance over time in Concord—in terms of both the number of populations and the size of its populations—there would probably be less genetic variation for flowering dates and a smaller range of environmental microclimates (e.g., hot spots, cold spots, wet spots, dry spots) that the species occupies. As a result, we would expect that the range of the species' flowering dates would decrease, with a later first flowering date and an earlier last flowering date (Miller-Rushing et al. 2008c). Later first flowering dates caused by declining abundance would tend to obscure a trend toward earlier flowering dates associated with a warming climate. Similarly, a species that was growing in abundance, with more numerous and larger populations, would tend to show a larger range of flowering dates, with both earlier first flowering and later last flowering dates. Increasing abundance would exaggerate an earlier flowering date associated with a warming climate and might even make a species appear to be responding to climate change when no such effect actually existed. By using only common species that did not change appreciably in abundance over the period of study, we minimized these effects associated with first flowering dates. Peak flowering dates are not similarly affected by population size, but Thoreau did not record these dates.

Photographic records

In addition to direct observations of flowering dates, we also investigated whether dated photographs could be used to examine the impacts of climate change on plant phenology. Between 1900 and 1921, the noted landscape photographer Herbert Wendell Gleason undertook a project to photograph species and places in Concord mentioned in Thoreau's writings. Part of his collection, housed in the Concord Free Public Library, contains a set of dated photographs of spring-flowering wildflower species, many of which were taken when the plants were in full flower—that is, all or most of the flowers are visible and open in the images. Each of these 34 photographs could be considered a data point approximating when that species was in full flower in a particular year. We could then compare the date from Gleason's photograph with the date at which the same species was in peak flower in 2005, matching the historic observations to our own observations in Concord. Our results indicated that the plants flowered on average 5.3 days earlier for each 1°C increase in spring temperature during the period of 1900–1921 ($R^2 = .28$, $p < .001$; Miller-Rushing et al. 2006). The rate of change in flowering dates was statistically indistinguishable from the rate of change that we had seen using independently collected field observations of the same species in Concord (multiple regression test, $p = .84$; Miller-Rushing et al. 2006).

The close correspondence of the results from our analyses of field data with the photographs suggests that data from the photographs could be used to characterize phenological responses to a changing climate. With a large enough sample size, the effects of temperature on plant-flowering dates can be detected despite measurement errors caused by photographers taking pictures toward the beginning or end of the peak flowering seasons when most or all of the flowers on the plant were open. Related studies that we completed at the Arnold Arboretum of Harvard University in Boston between 2003 and 2005 had already shown that dated herbarium specimens and photographs collected over the past 100 years combined with 1–3 years of current observations could be used to demonstrate plant responses to warming temperatures (Primack D et al. 2004). In several subsequent studies, the utility of using photographs and herbarium specimens to document changes in phenology for a variety of species in a variety of settings have been verified (e.g., Lavoie and Lachance 2006, MacGillivray et al. 2010, Robbirt et al. 2011).

The changing flora of Concord

When we started our fieldwork in 2003, our initial goal was to repeat the phenological surveys that Thoreau and Hosmer had done. After our first two field seasons, however, we still had not found hundreds of the species that they had seen. We searched for these missing species ourselves and asked local botanists and naturalists where we could find populations of particular species. In some cases, they were able to help us find populations of these species, often directing us to very specific and sometimes isolated locations. In other cases, they told us where they had seen a species years or decades earlier, but we found that the species was no longer present there.

By 2005, during our third year of fieldwork, we recognized that many of the species for which Thoreau and Hosmer had observed flowering dates were either no longer present in Concord or were very hard to find. We began to search intensively for these missing species and to quantify the abundance of the species that we could find. This became a secondary goal of our project. We had information on earlier species abundance because Hosmer had recorded the abundance of species, and a local botanist named Richard Eaton made similar observations in the mid-twentieth century. Building on these past records, we showed that many species that had formerly been common in Concord were now reduced to a single population, sometimes with just a few individuals, or were no longer present in Concord at all. In the end, we concluded that 27% of the species that Thoreau and other botanists had recorded from Concord were no longer present, and a further 36% of formerly common species were now rare (Primack RB et al. 2009b). Many of these rare species existed only in small populations—in some cases, only a few individuals, or even just one plant—and so were in imminent danger of local extinction. This great loss and decline of species was somewhat surprising, considering that approximately 35% of Concord's land area is protected and another 27% remains undeveloped.

What could account for this loss in species? There are many potential factors. In Thoreau's time, Concord's landscape consisted predominantly of fields and agricultural lands, with only small patches of secondary forest. Now, Concord is about 50% forested, with a suburban landscape. Only a few fields and farms remain on the unforested land.

Such land-use changes and succession leading to shaded forests could account for the loss of some open-field species. Similarly, direct habitat destruction has resulted in the loss of some species that occurred at specific sites. Furthermore, grazing by deer may have reduced certain wildflower species, and invasive plants may be outcompeting others. However, such changes do not provide a general explanation for the overall pattern of species loss. Rather, there is a general loss of species across all habitats, including fields, forests, and wetlands: Each habitat lost an approximately equivalent proportion of its wildflowers ($\chi^2(3) = 1.32$, $p = .724$; Primack RB et al. 2009a). Also, the grazing preferences of deer for particular plant species do not explain the pattern of species decline as it is determined when deer preference was tested alone (generalized estimating equations controlling for phylogeny, $p = .195$) or in combination with other variables, such as habitat, initial abundance, and species latitudinal range ($p = .517$) (Willis et al. 2009).

We analyzed the changes in the abundance of wildflowers in Concord in collaboration with Harvard University evolutionary biologists Charles Davis, Charles Willis, and Brad Ruhfel. This phylogenetically controlled analysis showed that the plant species that are most responsive to temperature in terms of their flowering date—that is, species that flower earlier in warm years and later in cold years—are the ones that on average have increased in abundance or have remained stable in abundance over time in Concord ($p < .001$; Willis et al. 2008). In contrast, the species that have inflexible flowering dates—that is, species with flowering dates that are minimally affected by temperature—have on average declined in abundance or have gone locally extinct (Willis et al. 2008). The results indicate that climate change is not only changing the phenology of plant communities, causing them to flower earlier than in the past, but is also affecting the abundance and composition of Concord's flora. The mechanism for the link between a phenological response and a change in abundance is not clear. One possible explanation is that species with responsive flowering dates have maintained better temporal matches with their pollinators and are more likely to be pollinated and to set seed (Bartomeus et al. 2011). Another possibility is that species that flower earlier in warm years also leaf out earlier, giving them a longer growing season and a competitive advantage for light over species that do not leaf out earlier (Sola and Ehrlén 2007, Xu et al. 2007).

There is also a distinct phylogenetic signal to the pattern of phenological responses to changes in temperature—species in certain clades tend to have more-flexible flowering dates and increased in abundance in Concord, and species in other clades tend to have less-flexible flowering dates and decreased in abundance ($p = .01$; figure 4; Willis et al. 2008). This result suggests that evolutionary relationships can sometimes be used to predict which species are more likely to increase or decrease in the future in the face of climate change (Davis et al. 2010). In addition, we found that species with a more southern distribution (presumably better adapted to warmer weather) tended to increase in Concord, and species with a more northern distribution (presumably better adapted to colder conditions) tended to decline in abundance ($p < .001$; Willis et al. 2008).

Another change evident in Concord is the increasing prominence of nonnative plant species. In Thoreau's time, 79% of the Concord flora was native species, but this figure has declined to 61% today—a significant decline ($p = .002$; Primack RB et al. 2009b). This change in the flora is likely to continue because of the continuing effects of habitat fragmentation, air pollution, and other human impacts that contribute to the spread of nonnative species. Most of the new species that have arrived in Concord over the past 150 years are nonnative species, and most of the species that have increased in abundance are nonnative species as well. These changes appear to be related to climate change: Further analysis has shown that the nonnative species had flowering dates that were more highly correlated with spring temperatures than were those of the native species ($p < .001$; Willis et al. 2010). Furthermore, the species that were independently classified as *invasive* had the most-flexible flowering dates of all and had shifted their flowering dates to a point earlier in the spring, more so than had the native plants or the noninvasive nonnative plants ($p = .01$; Willis et al. 2010). One of the most aggressive invasive species—the purple loosestrife (*Lythrum salicaria*)—shifted its flowering date by several weeks, whereas the flowering dates of many other species, such as most native lilies and orchids, did not shift. Again, the explanation for the success of such species may be their ability to leaf out earlier in warm years and outcompete less-flexible native species (Sola and Ehrlén 2007, Xu et al. 2007). Other plant traits, such as habit (e.g., herb, woody), height at maturity, leaf mass per area, seed weight, and pollination syndrome (e.g., insect, wind), did not differ significantly between native and nonnative plants in Concord ($p > .05$).

Bird-arrival dates

In addition to these data sets on plants, we found that there was a surprisingly large number of bird watchers who record the arrival dates of migratory birds in the spring and who were willing to share their observations. These bird watchers sometimes keep their own journals of arrival dates around their homes, towns, or special locations favored by migrating birds. Other bird watchers keep records as a part of clubs, such as the Nuttall Ornithological Club, which has been meeting for over 100 years. Club members record the first arrival of birds across a region, such as Massachusetts, or

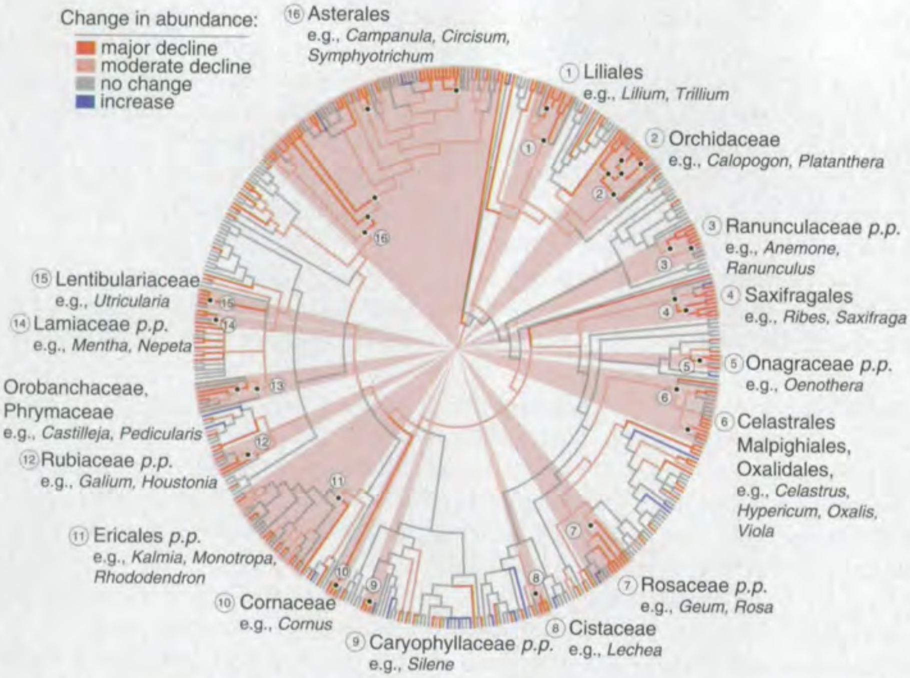

Figure 4. Composite phylogeny of 429 flowering plant species from the Concord flora depicting changes in abundance from 1900 to 2007. The branch colors indicate a parsimonious character-state reconstruction of the change in abundance. For simplicity, we have indicated this reconstruction by using four colors: red (a major decline), pink (a moderate decline), gray (little to no change), and blue (an increase). Clades exhibiting major declines are indicated with black dots. Each of the most-inclusive clades exhibiting these declines are indicated in pink and referenced numerically with their clade name. The subclades in major decline that are nested within more widely recognized clades are labeled with the more-familiar name, followed by pro parte (p.p.)*. These clades include some of the most charismatic wildflower species in New England, such as anemones and buttercups (Ranunculaceae* p.p.*); asters, campanulas, goldenrods, pussytoes, and thistles (Asterales); bedstraws and bluets (Rubiaceae* p.p.*); bladderworts (Lentibulariaceae); dogwoods (Cornaceae); lilies (Liliales); louseworts and Indian paintbrushes (Orobanchaceae); mints (Lamiaceae* p.p.*); orchids (Orchidaceae); primroses (Onograceae* p.p.*); roses (Rosaceae* p.p.*); saxifrages (Saxifragales); Indian pipes (Ericales* p.p.*); and St. John's worts and violets (Malpighiales). The species and clades exhibiting increases or no change in abundance tended to have flowering dates that tracked changes in temperature, whereas species that declined in abundance tended not to track changes in temperature with their flowering dates. Source: Adapted from Willis et al. 2008.*

at specific locations, such as Mount Auburn Cemetery—a favorite birding locale on the border of Cambridge and Watertown (Butler 2003, Miller-Rushing et al. 2008b). At many bird-banding stations, mist nets are used to capture birds, and data are recorded in a systematic way and have been for decades (e.g., Marra et al. 2005, Mills 2005, Miller-Rushing et al. 2008a).

Of the various bird data sets that we found, the oldest records in Massachusetts again came from Concord and were gathered by Thoreau. Thoreau made a table of bird-arrival dates during the 1850s in the same style as his plant tables. This table of bird observations was available in the library of the Museum of Comparative Zoology at Harvard University. However, we did not learn about Thoreau's bird observations until the fifth year of our study, which emphasizes the difficulty of learning about old records. We also found many other records of spring arrival in Concord. William Brewster (1851–1919), who founded the American Ornithologists' Union and the Nuttall Ornithological Club and served as curator of birds at Harvard University, observed bird-arrival dates in Concord in 1886 and the years 1900–1919. Ludlow Griscom (1890–1959), also curator of birds at Harvard, a president of both the American Ornithologists' Union and the Nuttall Ornithological Club, and author of *The Birds of Concord* (Griscom 1949) and *Birds of Massachusetts* (Griscom and Snyder 1955), recorded the first arrivals of birds in Concord between 1930 and 1931 and between 1933 and 1954. Brewster's field books are at the Harvard University library, and Griscom's records are at the Peabody Essex Museum in Salem, Massachusetts. Like Thoreau's records, these observations had lain underappreciated and underutilized for decades despite being available to generations of researchers.

We next searched for modern records of bird-arrival dates—ideally, observations made by a single individual who roamed around Concord in the spring, like the earlier historical figures. The most-complete and longest-running data set that we found was collected by a former schoolteacher named Rosita Corey. She had made observations of the first arrivals of birds from 1956 to 1973 and from 1988 to 2007.

By combining these data sets, we were able to examine changes in the dates that migratory birds arrived in Concord. We analyzed the observations of 22 passerine bird species. We could not use the data for many species because those species no longer occurred in Concord or they were not observed very often. There were also species, such as field sparrows (*Spizella pusilla*), that could not be used because they were migratory during Thoreau's time but now had overwintering populations in the Concord area.

We found that there was no clear pattern of arrival dates changing over time. Of the 22 species, 15 had arrival dates that had not changed, 3 arrived significantly earlier over time, and 4 arrived significantly later, determined by *t*-tests (comparing data from 1851 to 1973 with data from 1988 to 2007; Ellwood et al. 2010). However, banding records in the region indicated that almost all of these species declined in abundance over time in eastern Massachusetts, and such declines in numbers may have obscured the effects of climate change on arrival dates (Miller-Rushing et al. 2008a).

Changes in spring temperatures were related to the variability in arrival dates for eight of the species that we examined in Concord, which was indicated by the results of a linear regression for each species: Seven species tended to arrive earlier in warmer springs, and one tended to arrive later in warmer springs (Ellwood et al. 2010). These results suggest that the effects of temperature on migration dates, when combined with the effects of declining populations, are not strong enough to show significant changes in arrival dates over time.

To avoid the confounding effects of declining population sizes, we also analyzed observations of mean arrival dates collected by the Manomet Center for Conservation Sciences, near Plymouth, on the south shore of Massachusetts. Mean arrival dates are generally the best value to use to assess changes in the phenology of cohorts (Moussus et al. 2010). Since 1970, Manomet has used the same procedure to capture birds in mist nets; to record the species, sex, and age; to attach identification bands on their legs; and to then release them. From their records, we were able to extract the mean date of arrival for 32 species of migratory passerines.

We found that the birds arrived on average about two days earlier over the last 30 years of data collection, with 8 of the 32 species having significantly earlier arrival dates as determined by linear regression. The rate of change was inversely related to the length of migration—that is, the arrival dates of short-distance migrants changed faster than the arrival dates of long-distance migrants (Miller-Rushing et al. 2008a). Spring temperature was the best predictor of the spring arrival for short-distance migrants from the United States, whereas the arrival dates of middle-distance migrants from Central America and the Caribbean appeared to be most affected by the Southern Oscillation Index, which is linked to a variety of climate variables. The arrival dates of long-distance migrants from South America did not appear to be affected by any environmental variable that we examined (Miller-Rushing et al. 2008a).

Perhaps the two most-significant conclusions from our analyses of bird migration phenology were that the phenology of bird species was less responsive to the effects of climate than was the phenology of plant species—a finding also made elsewhere (Marra et al. 2005)—and that the rate of change in arrival dates was related to the distance of migration. The first conclusion suggests that there is potential for the development of phenological mismatches between birds and plants, which has important implications for nesting habitat. It is also possible that phenological mismatches could develop between birds and insects, particularly if insect phenology matches pace with that of plants, as was found by Bartomeus and colleagues (2011). Phenological mismatches between birds and their insect prey have already been documented in Europe (Both et al. 2006).

The second conclusion suggests that long-distance migratory birds, which have migration dates that have not been shown to have changed significantly, may be particularly susceptible to phenological mismatches with their migratory and breeding environments. There is evidence that bird species that are arriving earlier in Europe in the spring, a claim based on changes in their mean arrival dates, have increased in abundance or remained stable, whereas species that are not changing their arrival dates have declined in abundance (Møller et al. 2008). This finding is comparable with the results that we obtained from our analysis of wildflowers in Concord: Species with flexible phenologies that track changes in climate have increased in abundance relative to those species that were unable to change (Willis et al. 2008). We do not yet know whether changes in migration phenology are linked to changes in abundance in North America, but data from Manomet and other bird observatories can yield answers to this question.

Another important result of our analyses of changes in bird-arrival dates was the role that methods of observation played in the observed patterns. We compared the results from four studies of changes in bird-arrival dates in Massachusetts that differed in the type of observation (by sight or sound or by capture in mist nets), the size of the sampling area, the number of observers, observer effort, and the length of the observation time period and found that the results differed substantially depending on the method used (Miller-Rushing et al. 2008c). The studies all showed that the birds on average arrived earlier in warm years and that there was substantial variation among species, but different species showed different changes depending on the study. This finding highlights the need to be mindful of the sampling methods used in previous studies when combining historical data sets or repeating historical observations.

Potential corroborating data from other historical and modern sources

A current and future goal of our research is to extend our work on flowering dates in Concord to leaf-out dates. We learned only in 2008 that Thoreau had made detailed observations on the leaf-out dates of trees in Concord in the 1850s. The Morgan Library in New York City holds this data table, and we were given permission to make a handwritten copy of the data. Leaf-out dates are less precise to measure in the field, since there is no standard definition of *leaf out*, unlike the more clear-cut definitions of *first flowering* and *first arrival* of migratory birds. Thoreau did not indicate how he defined *leaf out*, leaving the type of observation open to question. Did he define it as when the leaf tips could first be detected emerging from the bud, when the leaves had expanded halfway and their outlines could be seen, or when the leaves were fully expanded? Did he measure leaf out when the whole tree was in leaf or when just one or several branches on a tree were in leaf? Even with such problems in methodology, it is clear that trees in Concord are leafing out earlier than they did in Thoreau's time. Our long-term goal is to link these leaf-out data from Concord with green-up—increases in the greenness of the surface of the Earth as viewed from outer space—data from the region using remote sensing (Morisette et al. 2009).

Insects are a key missing link in the story of the ecological responses to climate change in Massachusetts and many other locations. The intertrophic interactions (e.g., herbivory, pollination, predation) that involve insects could be disrupted by changes in phenology (Visser and Both 2005). For example, if migratory birds arrive at their breeding grounds too early in the spring, the insects they feed on may not yet be active, which would deprive adult birds of adequate food and would possibly lead to death or reproductive failure. Similarly, if insects become active earlier and birds arrive too late, the peak of abundance of insects may have already passed, and there may not be enough insects to feed developing nestlings (e.g., Both et al. 2006). If plants flower too early in the spring, they may miss their pollinators and consequently have low seed set, with long-term negative consequences for their survival (Memmott et al. 2007, but see Bartomeus et al. 2011).

For the past seven years, we have been actively searching for information on the appearance of insects in the spring, with only limited success. We have pursued many leads that have not yielded useful information. For example, we have sought out data on when honeybees become active in the spring, but we have not located any beekeepers with records of this type of information. Another idea was that fly fishermen, fishing lodges, or government fishery departments might keep track of when aquatic insects emerge in the spring as a way to determine what types of lures to use. However, we have not found such data in Concord or the surrounding area.

We have, however, found data describing butterfly phenology, a group known to be sensitive to temperature (figure 5; Stefanescu et al. 2003). Butterflies are well represented in museum collections, so there is historical information on when they were actively flying. And many butterfly clubs post pictures and dates of appearance to their club Web sites. A combination of past museum collections with modern sightings is now providing us with a method to examine the effects of climate change on this insect group. These sources of data have already been used to document changes in the distributions of butterflies (Parmesan et al. 1999) but have been less frequently used to document changes in phenology. A key will be to select one or more spring-emerging species that are easily recognized and that have a short lifespan as adults. Another potential source of data is the journals kept by people who have developed butterfly gardens. Butterfly enthusiasts sometimes go to great lengths to grow "butterfly plants" on their property. Such plants include those that provide abundant floral nectar for the adult butterflies and those with leaves favored for larval development. We have found such butterfly enthusiasts from some locations in Massachusetts and are presently working with one of them to analyze her records.

Figure 5. Butterflies and mosquitoes are two groups of insects that are currently being analyzed for their response to climate change. (a) A butterfly garden north of Boston. The owner records the dates of first appearance of each species. Photograph: Sharon Stichter. (b) A mosquito trap in a swamp placed by the Massachusetts State Laboratory. Mosquitoes are attracted to a light inside the trap. Photograph: Richard B. Primack.

Another resource that we have recently discovered is records of mosquito emergence and changes in abundance at weekly intervals over the growing season (Hachiya et al. 2007). The State Laboratory of Massachusetts has been gathering such records at 10 wetland locations in eastern Massachusetts since 1957, using a standard trapping method. After collection, mosquitoes are separated by species; counted; and tested for the presence of eastern equine encephalitis, a potentially fatal disease of people and horses. The resulting data are then used to predict disease risks to human populations and to guide insecticide-spraying programs. The data for this enormous data set are available primarily as paper data sheets, with those for more recent years available as electronic files. This data set could potentially be used to analyze how climate variation and warming temperatures have affected mosquito populations over the past half century.

Conclusions and future work

When we began this research project in 2003, we did not know if we could find any information that could be used to test for the biological impacts of climate change. Our research over the past eight years has shown that eastern Massachusetts has an abundance of records that can be analyzed to detect the impact of climate change. The situation in the United States is quite different from that in many European and East Asian countries, where phenological observations are made over large areas using standard procedures either by government agencies or under their supervision, with most records being held by one central authority (Chen 2003, Menzel 2003, Ibáñez et al. 2010). On the basis of what we have found in Massachusetts, the initial challenges in the United States are to locate the diversity of records, to obtain copies when possible, and then to determine how the records can be used. We believe that the approach we have used will yield comparable records in other parts of the United States, particularly in and around metropolitan areas, university and college towns, research institutions, national parks, areas frequented by naturalists clubs, and places where there is a strong tradition of natural history observations.

Similar projects have had great success in other locations. Records kept by Aldo Leopold, his family, and other naturalists have yielded important insights into long-term changes in phenology—largely, shifts toward activity earlier in the year—in Wisconsin (Bradley et al. 1999). These records have contributed to studies suggesting that the availability of pollinators may constrain how rapidly flowering dates shift in response to warming (Rafferty and Ives 2011). In California, research in which historical observations made by Joseph Grinnell were used has yielded several important findings, including evidence of changes in the ranges of small mammals (Moritz et al. 2008) and birds (Tingley et al. 2009) in the Sierra Nevada Mountains. We have also had success applying such an approach to Japan and South Korea, turning up a number of novel data sets in the process (Primack RB et al. 2009a, 2009b). In these projects and others, methods have also been developed and refined for using historical records to investigate long-term ecological changes (Tingley and Beissinger 2009, MacGillivray et al. 2010).

In the United Kingdom, long-term phenological records are being gradually gathered together in one central location through the Royal Meteorological Society, and similar record keeping is now being started in the United States by the new USA National Phenology Network (*www.usanpn.org*). However, because of the scattered nature of US records, most of the records will remain outside of central locations for the near future, and researchers must still spend the time and effort to determine what records are available.

We were fortunate in this project to be able to locate many unique, unanalyzed, and underappreciated data sets that could be analyzed in light of climate change. The importance of libraries, research institutes, and museums in maintaining such valuable historical records cannot be overestimated. Without such records, this work could not be done.

The changes that we observed were certainly caused in part by the increased warming of the urban areas. Because of this increased warming, studies of past and ongoing changes in metropolitan areas may provide indications of future effects of climate change in more-rural areas of the country.

The link of our work to that of Henry David Thoreau and the localities of Walden Pond and Concord greatly added to the public impact of our work. We capitalized on this connection when we wrote press releases and talked to science journalists. As a result, this work has been widely reported in the popular media, including newspapers, magazines, and public radio. We facilitated this process further by making ourselves available for interviews, often held on the shores of Walden Pond, and by supplying photos. We also accepted invitations to talk with the public and school groups in the region to explain what we had found. We believe that such efforts at public outreach—particularly on issues of great public significance—are part of the responsibility of scientists in today's complicated world.

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