Herbarium Specimens as a Novel Tool for Climate Change Research

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Many changes in plant and animal behavior point to the effects of global climate change. In recent years, biologists have observed birds migrating earlier in the spring, tropical frog populations declining, and insects relocating to higher altitudes on mountain slopes. Yet the most convincing evidence that living organisms are responding to global warming comes from flowering plants, which are especially responsive to warm weather in the spring. The data on plant flowering times is particularly compelling because there is so much of it. Thanks to the professional and amateur botanists who have kept annual records for a variety of plant species and locations, there exists more long-term data on first flowering dates than on other biological phenomena. As described in a 2003 article in *Arnoldia*, analyses of these records show conclusively that both wild and cultivated species are flowering earlier than in the past because of warmer growing conditions. Although these data sets have proven valuable for understanding how certain plants in certain places have already been affected by global climate change, there are too few long-term data sets available to predict future impacts worldwide. To build a more geographically complete picture, scientists must seek new sources of data. Botanical gardens and museums might be those sources.

In the spring of 2002, we decided to investigate whether the extensive collection of herbarium specimens at the Arnold Arboretum could be used in conjunction with the Arboretum's living collections to determine how plants in Boston are responding to global warming. If so, our study would show that herbarium collections throughout the world could be valuable tools for studying plants' responses to climate change.

Boston, like other large cities, is an especially good place to study climate change because its average annual temperatures have risen over the last hundred years by 1.5 degrees centigrade (2.7 degrees Fahrenheit)—more than in less urbanized parts of the world. Only half of Boston's increase corresponds to the increase in the average global temperature. The other half is related to urbanization—more paved surfaces to absorb sunlight and radiate it as heat, less plant cover to remove heat through transpiration, and more sources of greenhouse gas emissions, such as buildings and cars—a phenomenon collectively labeled as the "urban heat island effect." As a result, the increase in Boston's average temperatures has already reached the magnitude expected for the entire planet later in this century. Thus, Boston provides a preview of the warming that will occur elsewhere in the world.

Prior to 2002, the Arnold Arboretum did not systematically collect phenological data—that is, records of the dates of seasonal biological events such as flowering or fruiting, which have been used in previous studies of climate change. However, the Arboretum does possess an alternative source of phenological data extending well over a hundred years: the Arnold Arboretum Herbarium, a collection of 80,000 dried plant specimens, most of which were taken from the woody plants of the living collections as part of the Arboretum's standard documentation process. The record that accompanies each dried and pressed specimen includes the name of the species, the identification number of the plant, the date of collection, and—importantly—the phenological state of the plant on that date, such as flowering, past flowering, or in fruit. Many of the plants from which the specimens were taken are still among the 15,000 plants growing on the grounds of the Arboretum. Together with the 80,000 herbarium specimens, of which a large number were collected while the plant was in flower, the Arboretum's living collections provided a potential sample size large enough to compensate for any species-specific phenological changes unrelated to temperature change. Thus, we could detect general patterns of response common to most of the species despite occasional anomalies.

Studies published by other researchers have typically tracked the date of first flowering within a certain population to measure a species' response to climate change. This method is potentially sensitive to changes in population size: if the population is growing over time, or the plants getting larger and producing more flowers, first flowering dates might come earlier even without a warming trend and even though the average flowering time within the population remains constant. (Increasing population sizes and larger individual plants tend to cause the first flower to appear earlier and the population to flower for a longer duration.) Herbarium specimens, however, are generally taken when the flowers are most visible and interesting to collectors—that is, when the plant is in full flower. As a result, a herbarium specimen reflects more accurately the date of peak flowering, a measurement that is not affected by the size of the population or the individual plants.

Another advantage of using the plants at the Arboretum for climate research derives from the controlled environment found there. Individual plants are well spaced and grown under conditions considered ideal for their species, with the grounds being carefully mulched, weeded, fertilized, and kept free of pests. This level of care probably reduces the possibility of unrepresentative flowering times that might result elsewhere from crowding, scarcity of nutrients or light, or other suboptimal conditions. Finally, one would expect the relatively high temperature increase in metropolitan Boston to have produced a greater magnitude of phenological change at the Arboretum than in rural areas, making it easier to detect changes in flowering times.

HOW WE WENT ABOUT IT

In 2003, using a computerized list of all plantings currently in the living collections and of all specimens in the herbarium, we selected herbarium specimens and corresponding plants on the Arboretum grounds for our study sample. We chose only living plants that are represented in the Arboretum's herbarium by at least one preserved specimen taken between 1880 and 2002 when the plant was in peak flowering condition—that is, with most of its flowers open and in good condition.

Our second criterion was that the plants had to have flowers that were easy to recognize, observe, and census; we typically chose plants with large, dramatic flowers, such as cherries and magnolias, and usually avoided plants with small flowers lacking petals, such as birches

25 April 2004
Almost flowering

30 April 2004
Full flowering

7 May 2004
Past flowering

Weekly monitoring of a pear tree (Pyrus) *progressing through its seasonal stages demonstrates that it has a short flowering period that peaked on April 30 Monitoring once a week appears to be sufficient to determine flowering phenology.*

Researchers at the Arnold Arboretum standing in front of Rhododendron vaseyi *on May 11, 2004, holding a herbarium specimen collected from the same plant on May 19, 1938. Both living plant and specimen were captured in full flower. This is a visual demonstration that plants are now flowering earlier than they did in the past.*

and oaks. Third, we selected primarily spring-blooming species; these were likely to show greater response to increases in spring temperatures than later-blooming plants because their flower buds are preformed the season before.

Fourth, we selected plants known to have short flowering cycles, which would permit us to more accurately estimate a single date of full flowering by calculating the average between the dates on which the plant was observed in full flower. We could be reasonably confident that herbarium specimens taken from plants that flower for less than three weeks—azaleas and apple trees, for example—had been collected within a week of the time of peak flowering. Specimens taken from species with longer flowering times, on the other hand—spring-flowering witch hazel, for example, which flowers for a month or more—could have been collected up to two or three weeks from the plant's peak flowering date. Finally, in order to minimize possible phenological effects caused by unknown alterations to plant physiology, we selected plants that are representative of wild species, whether native to the New England region or introduced, rather than cultivars or hybrid plants.

Using these criteria, we selected 229 living plants encompassing 35 different genera. Major genera (represented by ten or more individuals) were *Amelanchier* (shadbush), *Cornus* (dogwood), *Corylopsis*, *Enkianthus*, *Halesia* (silverbells), *Magnolia*, *Malus* (apple), *Prunus* (cherry), *Rhododendron* (including azalea), and *Syringa* (lilac). Because multiple herbarium specimens were often collected from the same plant, we found 372 herbarium specimens taken from these 229 plants. (A complete list of specimens and species is available online at the Arboretum's website, http://www.arboretum.harvard.edu/).

We readily located the 229 selected plants using the Arboretum's computer-generated map of the living collections. Then, during the spring and summer of 2003 two people observed the individually numbered plants weekly between April 13 and July 14. Plants were recorded as being in one of four stages: not flowering, almost in full flower, full flower, or past full flower. (A plant in full flower was defined as having at least fifty percent of its buds in full bloom and being suitable for herbarium specimens.) Once a plant was recorded as past full flower it was no longer observed because the plants in our sample flower only once a year. These weekly observations enabled the observers to determine the peak flowering date and duration of flowering for each plant in 2003.

We also determined a single Julian date (day numbers that run from 1 to 365 over a year) of full flower for each plant, although this date could have missed the true flowering peak by several days because of sampling only once a week. For example, if a plant reached its highest number of flowers on day 110 but was sampled on days 108 (when it had lots of flowers) and 115 (when it retained only a few flowers), then the day of peak flowering would be listed as day 108 rather than the true peak flowering day of 110. In cases where full flowering was observed on multiple dates, the mean of the Julian dates for those days was used. If a plant was recorded as being in peak flower on days 121 and 129, its date of full flowering would be calculated as day 125. Once the Julian date of full flowering in 2003 was determined for each plant, we subtracted it from that of the corresponding herbarium specimen to estimate a change in flowering time. If a plant was observed in peak flower on day 120 in 2003 and flowered on day 110 in 1990 according to the herbarium specimen, then it flowered 10 days earlier (-10) in the past than it did in 2003. We then investigated how changes in spring flowering times correlated with the temperature differences between individual years as recorded at the Boston weather station.

WHAT WE FOUND

The spring of 2003 (February through May) was colder than in any previous year since 1967, with temperatures typical of the early twentieth century. As a result, the 229 plants examined in this study flowered at about the same time in 2003 as they had between 1900 and 1920. In contrast, typical plant flowering times between 1980 and 2002 were about eight days earlier than in 2003, and eight days earlier than between 1900 and 1920, thereby showing a significant trend toward earlier flowering over the last one hundred years (Figures 1 & 2).

While the data showed wide variations in historical plant flowering times, it is clear that plants have been flowering earlier in recent years than they did in the past because of warming temperatures in Boston. Eight days may not seem like much, but it constitutes a major change. For plants that flower for three weeks, it represents more than one third of the entire flowering season. Changes of this magnitude can significantly affect relationships between plants and the animals that pollinate their flowers, eat their leaves and seeds, and disperse their fruits. In many cases these relationships rely on a synchrony between the phenology of the plant and that of the animal—for instance, between the flowering of a plant and the activity of a pollinator—which may be disrupted if the timing of events shifts too quickly. Evidence from elsewhere in the world shows that some of these relationships are already changing.

CAVEATS AND STATISTICAL CONSIDERATIONS

Although we found a significant correlation between changes in temperature and flowering times, the use of herbarium specimens raised several questions. First, as noted earlier, we could not be certain that the herbarium specimens were all collected on the exact day of peak flowering. Specimens identified as "flowering" may have been collected when the plant first started to flower or when it had just finished flowering. In the case of short-flowering plants, the error would be small: if the collector took a sample from a plant with a one-week flowering period, for example, the collection date would

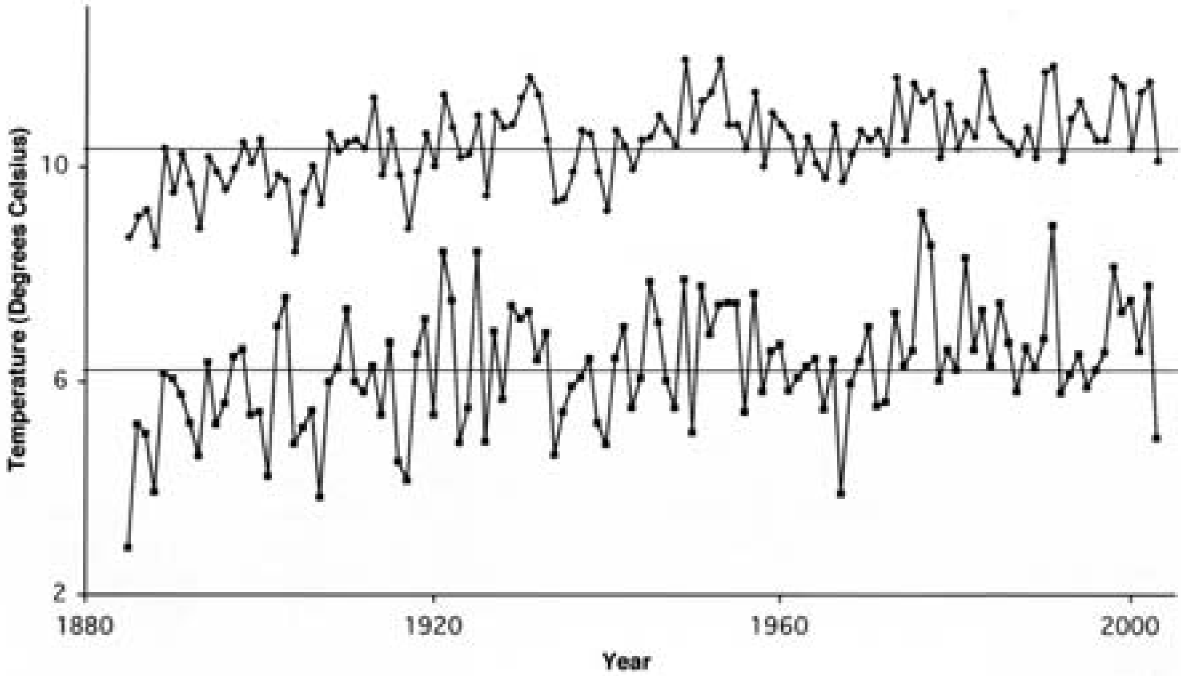

Figure 1. Boston temperatures from 1885 to 2003 as reported by the National Oceanic and Atmospheric Administration in 2004. The top series (diamonds) represents mean annual temperatures. The bottom series (squares) represents mean temperatures in February, March, April, and May Boston temperatures are clearly increasing over time. The two horizontal lines represent the long-term mean temperatures for each series (annual = 10.3 degrees centigrade or 50.5 degrees Fahrenheit; February through May = 6 1 degrees centigrade or 43 degrees Fahrenheit; °F = (°C x 1.8) + 32).

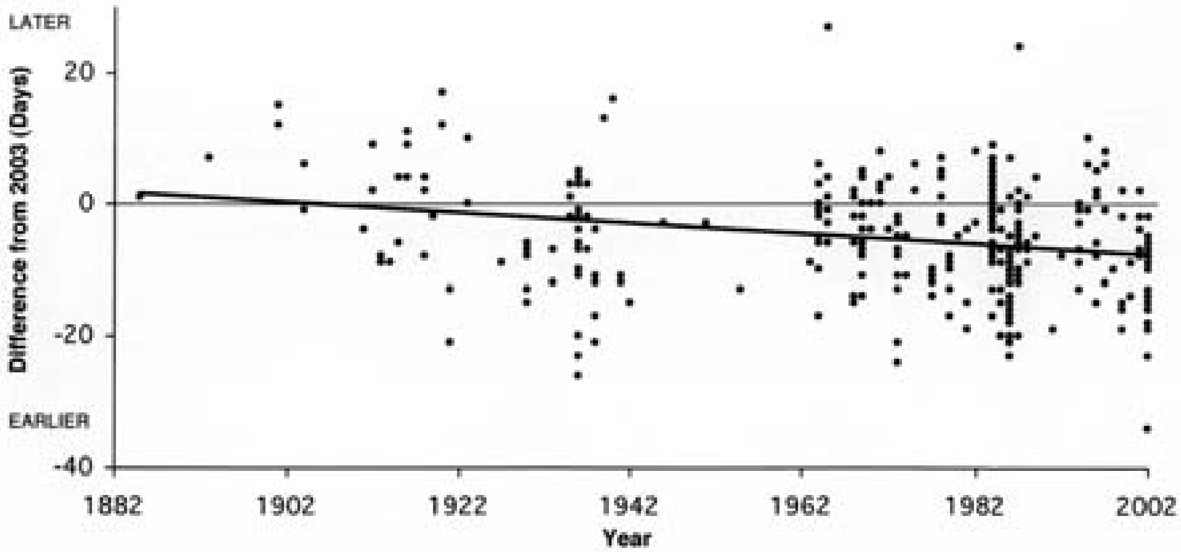

*Figure 2. This graph tracks changes in flowering times of plants at the Arnold **Arboretum** over time: The dots indicate the number of days plants flowered earlier or later in the past than they did in 2003 calculated as the Julian date the herbarium specimen was collected subtracted from the peak flowering date in 2003 Negative values indicate that a plant flowered on an earlier date than it did in 2003. Note that 2003 was a relatively cool year; plants from the cool 1900 to 1920 period flowered about the same time that they did in 2003 In contrast, plants flowering in the warm period of 1980 to 2002 flowered about 8 days earlier than they did in the cool year of 2003 The line is the best fit line for the series.*

be only 3.5 days away from the actual date of peak flowering. In the case of a plant with a 20-day flowering period, on the other hand, the amount of error would be 10 days. However, our statistical tests found no evidence of this type of bias; data were no more variable over time for long-flowering plants than for short-flowering plants.

A second concern was that trends would be obscured by outlying data points resulting from plants that had flowered many weeks earlier or later in the year that they were collected for the herbarium than they did in 2003. Examples of outlying data points include a dogwood (*Cornus mas*) that flowered 27 days later in 1965 than in 2003 and a cherry tree (*Prunus apetela*) that flowered 24 days later in 1987 than in 2003. These apparent anomalies may have been caused by someone collecting the specimen at the very end or very beginning of an unusually long flowering season in those years. But again, thanks to our large sample size the few outlying data points did not have a statistically significant effect on the results.

Finally, we were concerned about the uneven collection of herbarium samples: in different years, different numbers of herbarium specimens were collected, creating gaps in the period between 1940 and 1960 that could give disproportionate weight to certain years in our analysis. We resolved this problem by dividing the data into two subsets, one on either side of the 1940–1960 gap, and separately analyzing each subset using the same methods that were used for the entire group. In each subset, we found the same significant trend toward earlier flowering times, indicating that the irregularity in specimen collection (i.e., the gap in collection) did not affect the outcome.

Given these concerns about the quality of data from herbarium specimens, our results are quite striking and show clearly that plant flowering times are highly responsive to changes in average temperatures in the four months before and during flowering. (For the spring-flowering species we studied, we used the mean temperature for February, March, April, and May to calculate changes. See Figure 3.) In general, flowering times advance 3.9 days per one degree centigrade increase in mean spring temperature, as calculated using a statistical technique known as multiple regression that considers the flowering time of plants in warm years and cold years. This rate falls within the

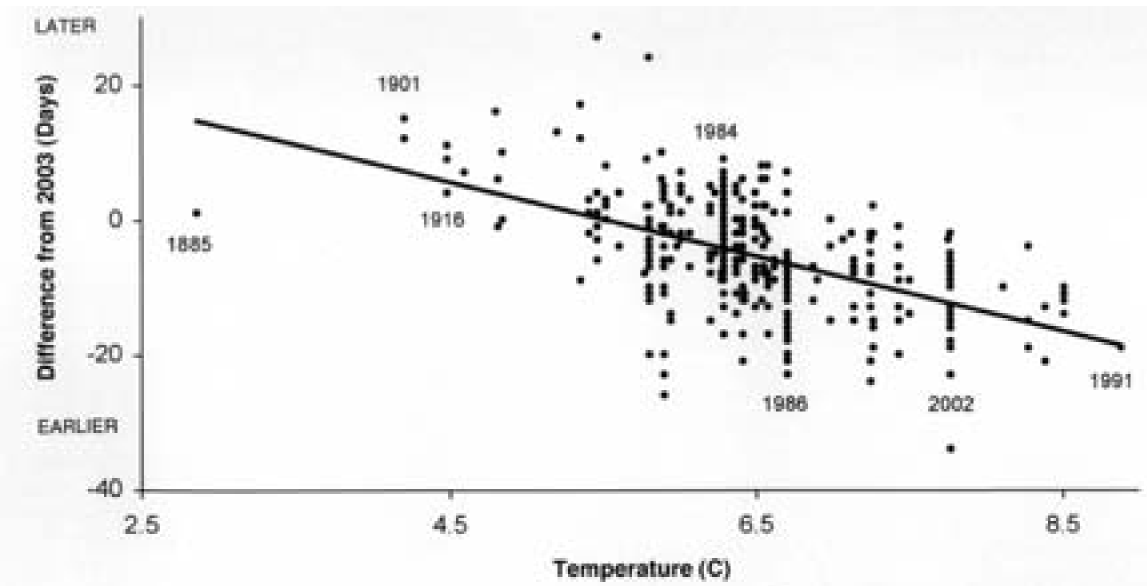

Figure 3 This graph demonstrates changes in flowering times of plants at the Arnold Arboretum as temperatures increase, showing the number of days plants flowered earlier or later in the past than they did in 2003 in relation to the average temperatures in the February through May preceding flowering. Plants flower earlier in warm years, and later in cool years. Years with many specimens or with extreme temperatures are noted. The line is the best fit line for the series.

range of findings of other published studies from the U.S. and Europe, which record flowering times occurring from two to ten days earlier for each degree centigrade of increase in temperature. Since Boston's temperatures in February through May have warmed approximately 1.5 degrees centigrade over the past hundred years, the recorded temperature increase can account for nearly six (5.85) of the eight days that flowering time has advanced over the past hundred years. Factors other than the temperature increase recorded at the Boston weather station must account for the other three days of increase.

These other factors might include temperatures during other months of the year or other climatic variables such as rainfall and humidity. Local conditions within and around the Arboretum may also be affecting flowering times. Construction of roads and buildings on adjacent land, for example, may have led to a very localized increase in temperature that was not registered at the Boston weather station. Finally, if plants were flowering over a longer period as they increased in size and age and were consistently collected for the herbarium at the beginning of their flowering periods—while our baseline observations in 2003 were made at peak flowering—there could be a false trend toward earlier flowering over time. Further investigations are needed in order to determine the relative importance of these factors.

WHERE WE GO FROM HERE

We have shown that herbarium collections and data collected by botanical gardens can be used to measure the effects of climate change on phenological events, and we know that many large collections of herbarium specimens exist at other institutions. Even more collections probably exist in dispersed form as samples collected at different times by many individuals from a single location and now held at multiple storage sites. In the past, biologists have collected intensively in places with unusual concentrations of endemic or rare species, especially mountain peaks, islands, swamps, lake shores, and dunes; examples include the top of Mount Washington in New Hampshire, the Florida Everglades, the northern tip of Newfoundland, and Cape Cod in Massachusetts. If information on flowering times from one of these locations could be gathered into one data set, an analysis could assess the responses of native species to local climate change and improve our capacity to predict the effects of future climate change on biological communities. We believe that many data sets of this sort could be assembled from around the world, covering the last one hundred to one hundred fifty years. Botanical gardens are an especially promising source for these dispersed specimens. We hope that our own study will contribute to the ongoing discussion of global climate change and encourage others to take advantage of this novel methodology of documenting biological response to climate change.

For Further Reading on Climate Change

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