Using herbarium specimens, botanical gardens, historical data, and citizen science to study climate change

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Over the past two decades, researchers and others involved in plant science have developed innovative and powerful methods to investigate the effects of climate change on plants. First, botanical garden staff are using their diverse collections to understand plant responses to climate change, test possible conservation actions, and engage the public in climate change science (Primack et al. 2021). These approaches are evident at two international networks of botanical gardens (Fig. 1). One network, focusing on the phenology of over 1000 species of woody plants, has demonstrated that leafing out phenology is strongly connected to spring temperatures, phylogeny, whether plants are deciduous or evergreen, and plant anatomy, whereas leaf senescence in autumn responds to a wider range of environmental triggers and local factors. Another network focused on perennial wildflowers has demonstrated that plant phenology is affected by plant functional traits, particularly plant height and leaf size, as well as local site factors.

Second, scientists are using historical databases of plant phenology and abundance combined with modern observations to determine how climate change has already affected plants. In many cases, these data sets demonstrate that plants are flowering and leafing out earlier over time and in warmer years. This is illustrated most distinctly by comparing data collected in the 1850s by the famous environmental philosopher Henry David Thoreau with modern observations. In this study, plants that have flowering times that are less responsive to spring temperature variation and plants that generally grow in colder climates have tended to decline and go locally extinct to a greater extent than other plant species. These striking results have been confirmed by studies elsewhere. As more historical data sets become available online, scientists are using powerful analytical tools to understand how climate change responses of plants vary around the world, improving forecasts of future global changes. These botanical data sets are also demonstrating that groups of species that interact with one another have different phenological responses to climate change, setting up the possibility of phenological mismatches. Such possibilities of phenological mismatches are being actively investigated among birds, plants, and insects, and between trees and wildflowers, using field observations and experiments.

Third, millions of herbarium specimens and photographs of plants are being digitized, allowing researchers to study flow-

Keywords
Flowering times, Leafing times, Mismatches, Phenology

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Accepted
9. 12. 2022

DOI
https://doi.org/10.12685/bauhinia.1376

Fig. 1. Botanical gardens are great places to do climate change research, such as the Arnold Arboretum of Harvard University.

Fig. 2. Herbarium specimens can be used to investigate the effects of climate on flowering, leafing out, and fruiting times.

Fig. 3. Using citizen science in climate research is an exciting opportunity for both science and public education, illustrated by this example from the Royal Botanical Garden Edinburgh.

ering, fruiting, and leafing out times at unprecedented geographic, temporal, and taxonomic scales (Fig. 3). These studies convincingly demonstrate that herbarium specimens are a powerful tool to determine quantitatively that plants flower and leaf out earlier now than in the past and earlier in response to a warming world (Lee et al. 2022). One recent example illustrates that phenological mismatches between trees and wildflowers are more likely to occur in eastern North America than in East Asia and Europe. Also, the correlations between temperature and phenology are substantially stronger in eastern North America than in East Asia and Europe, a novel result that requires further inquiries.

Fourth, community and citizen science programs, such as iNaturalist, iSpot, and the National Phenology Network (USA), have greatly expanded, increasing the data available to researchers and engaging the public in climate change research Fig 3). Researchers are now challenged to develop methods to combine these diverse data sources in ways that take advantage of the special characteristics of each. For example, a study from Denmark found that flowering dates from herbarium specimens and photographs submitted to iNaturalist could be readily combined in phenological studies because they both represent peak flowering dates, whereas observations from a citizen science network captured first flowering dates, which is a different metric (Iwanycki et al. 2022).The insights gained from such plant ecology research at botanical gardens, herbaria, and citizen science programs will greatly advance our understanding of the effects of past climate change, and anticipate the impacts of future climate change, on plants and ecosystems around the world. Such research with plants also has the potential to educate the public about climate change happening in their own communities and motivate them to become advocates for addressing the crisis of climate change.

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