Generating ecological insights from historical data

Richard B Primack[1*], Tara K Miller[1], and Abraham J Miller-Rushing[2]
[1]Department of Biology, Boston University, Boston, MA [*](primack@bu.edu); [2]US National Park Service, Bar Harbor, ME

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Ecologists worldwide are searching for historical datasets that can provide insight into how ecosystems and species are responding to climate change, often with a focus on changes in species' phenology, distribution, and abundance (Primack and Miller-Rushing 2012; Vellend *et al*. 2013; Primack *et al*. 2022). Once confined to libraries, museums, attics, and overlooked file cabinets, physical or offline records are increasingly being digitized, made available online, and used by ecologists in innovative ways.

In many cases, these records provide detailed descriptions of changes that occurred in particular places. Resurveying the records of ecologist Joseph Grinnell from the Sierra Nevada Mountains is yielding information about bird species' range shifts and helping to identify climate-change refugia (Tingley *et al*. 2009). Revisiting amateur naturalist David Bertelsen's observations of the Santa Catalina Mountains has generated insights into community-level changes in phenology in an arid ecosystem (Crimmins *et al*. 2009). Likewise, our own work with the records of the environmental philosopher Henry David Thoreau (Figure 1a), and less well-known naturalists like Alfred Hosmer, from Concord, Massachusetts, has provided evidence of changes in phenology and abundance in plant communities and across trophic levels (Primack *et al*. 2022; Miller *et al*. 2023).

Are the changes observed in these well-documented places – range shifts in the Sierra Nevada, phenology shifts in the Santa Catalinas, or changes in community ecology in Massachusetts – representative of what is happening elsewhere or across larger spatial scales? While researchers are already assessing the generality and transferability of phenological results, we feel that there is much untapped potential in exploring these cross-scale connections further (Gallinat *et al*. 2021).

Traditionally, investigations into variation across systems rely on replicating studies in different locations, analyzing comparable data across locations, or testing hypotheses experimentally. For example, an experiment might be designed to disentangle the effects of snowmelt and temperature on plant phenology, as those effects are difficult to separate using historical data alone (Jerome *et al*. 2021). Meta-analyses can add rigor and assess the degree to which phenomena are common across systems and detectable across methodologies. However, given the urgency of understanding and forecasting environmental changes, researchers should take advantage of the full suite of tools now available.

The digitization of museum collections and the recent explosion in citizen-science projects, such as Nature's Notebook and eBird, are offering new sources of data to test possible links between ecological phenomena observed at various scales.

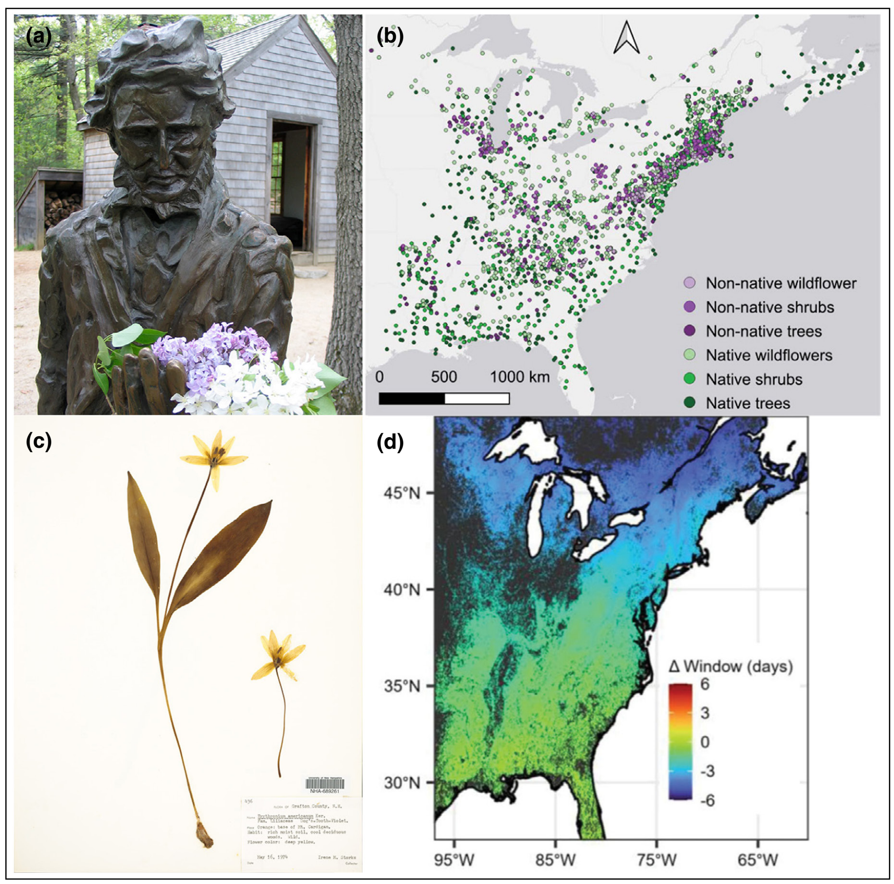

Figure 1. (a) Statue of Thoreau with a replica of his cabin at Walden Pond State Park (credit: AJ Miller-Rushing). (b) Locations of herbarium specimens used to determine if Concord phenological patterns occur across eastern North America (from Miller *et al*. 2023). (c) Herbarium specimen of trout lily (*Erythronium americanum*), a woodland wildflower (credit: Hodgdon Herbarium, U of New Hampshire [CC0 1.0]). (d) Using herbarium specimens, the window of spring sunlight available to woodland wildflowers is predicted to decrease by 2100, with the strongest effects in the north (from Lee *et al*. 2022).

Researchers not only can remotely examine digitized museum specimens for hundreds of thousands of species collected over the past 200 years or more from around the world but also can download more recent taxonomic records from citizen-science platforms like iNaturalist, which has amassed over 100 million observations. While generally lacking the in-depth site-specific detail found in Grinnell's, Bertelsen's, and Thoreau's datasets, these data can still be used to explore broad patterns and test specific hypotheses (Fuccillo Battle *et al.* 2022).

A growing number of studies are already using museum specimens and citizen-science records to connect local and broad-scale phenomena. For instance, we were surprised to find that over the past 170 years, trees in Concord have shifted their phenology more than wildflowers have, because trees were more responsive to temperature (Heberling *et al.* 2019). The window of full sunlight on the forest floor that early spring wildflowers experience has become shorter and may continue to shorten in the future (Figure 1d), potentially reducing energy budgets for wildflowers and impeding their ability to grow, reproduce, and survive. To test the generality of this mismatch between tree and wildflower phenology, we worked with colleagues to examine thousands of herbarium specimens (Figure 1c) collected over the past 100 years from across eastern North America, East Asia, and Europe. We found that the tree–wildflower mismatch is occurring across eastern North America (Figure 1b) (Miller *et al.* 2023) but is absent from East Asia or Europe, where trees are less responsive to temperature (Lee *et al.* 2022).

In other cases, researchers may find unexpectedly detailed regional-scale datasets. For example, Fuccillo Battle *et al.* (2022) recently began analyzing data from one of the oldest citizen-science networks in North America, a network started by the New York State Regents in 1826 to monitor weather and phenology. After comparing the historical data to modern citizen-science observations to assess changes in plant phenology across the state of New York, the research team found significant variation in phenological changes across functional groups (e.g., insect- versus wind-pollinated taxa) and locations (e.g., urban versus rural), with implications for altered ecological interactions. Because their study is already based on statewide citizen-science data, it is well positioned to be integrated with or compared to other regional or larger-scale datasets.

Beyond addressing pressing ecological questions, approaches such as these – linking detailed site-specific historical datasets with larger-scale data from museum collections or citizen-science records – provide two additional benefits: they can help assess the quality of local-scale datasets and can create compelling stories for communicating about science in general and climate change in particular.

Because historical datasets tend to be poorly documented, concerns about their accuracy persist. In the past, naturalists have questioned, for example, whether Thoreau was a careful and accurate observer, in part because he combined nature observation and philosophy (Primack *et al.* 2022). Researchers can sometimes evaluate the scientific accuracy and utility of historical datasets; however, when the documentation is too poor to do so directly, experiments, replicate studies, and comparisons with larger-scale patterns can be used.

Resurveying the work of Thoreau, Grinnell, and Bertelsen, and the New York State Regents data, can also create compelling narratives, linked to historical figures and places, to communicate ideas about science and climate change to the public. Using museum specimens to link such local stories to larger-scale patterns, like shifts in the phenology, ranges, and abundance of species, can further increase interest in and awareness of ecological changes that people might not otherwise notice. These narratives can garner attention from popular media and can motivate the public to participate in resurvey efforts and biodiversity surveys.

In summary, we believe there is still much untapped potential in using historical datasets combined with citizen-science data, museum specimens, and modern observations to address some of the most pressing questions about how ecosystems have responded and will respond to climate change.

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