Was Henry David Thoreau a Good Naturalist? An Approach for Assessing Data from Historical Natural History Records

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Ecologists are increasingly combining historical observations made by naturalists with modern observations to detect the ecological effects of climate change. This use of historical observations raises the following question: How do we know that historical data are appropriate to use to answer current ecological questions? In the present article, we address this question for environmental philosopher Henry David Thoreau, author of Walden. Should we trust his observations? We qualitatively and quantitatively evaluate Thoreau's observations using a three-step framework: We assess the rigor, accuracy, and utility of his observations to investigate changes in plants and animals over time. We conclude that Thoreau was an accurate observer of nature and a reliable scientist. More importantly, we describe how this simple three-step approach could be used to assess the accuracy of other scientists and naturalists.

Keywords: climate change, Henry David Thoreau, natural history data, naturalist, phenology

The records of ecologists and naturalists from past decades and centuries represent powerful tools for examining human impacts on the environment (Primack and Miller-Rushing 2012, Hédl et al. 2017, Verheyen et al. 2017). These records vary widely and can include maps, museum specimens, field notes, inventories of plants and animals, personal journals, photographs, and other sources (figure 1). Some records may have been collected intentionally to provide scientific data, whereas others may have been collected for personal use but still contain data relevant to current questions. Ecologists can compare data from historic records of plants and animals with modern surveys to investigate such topics as changes in community composition, species' abundance, and phenology (Sparks and Carey 1995, Alfonsi et al. 2017, Socolar et al. 2017, Sperandii et al. 2019, Gotelli et al. 2021). Researchers have used resurveys such as these to help understand the loss of native species in locations around the world, the lengthening of growing seasons across temperate regions, and variations in species' responses to human activities (Johnson et al. 2003, Cornish and DiDonato 2004, Lips et al. 2004, Vellend et al. 2013a, Dornelas et al. 2014). In some cases, old naturalist records provide some of the best or only records of past ecological conditions and provide insights that new studies cannot (Wolkovich et al. 2012, Vellend et al. 2013b). Researchers are actively searching for historical data to address new questions, such as how insect abundance and community composition are changing in response to human activities (Hallmann et al. 2017, Leather 2017, Sánchez-Bayo and Wyckhuys 2019, Thomas et al. 2019).

Used incorrectly, however, historical natural history data sets can lead to erroneous conclusions because of errors in determining the locations of past observations; mistakes in matching past species names with current species names; incorrectly assigning a day, month, and year to observations; and other factors (Kapfer et al. 2017, Verheyen et al. 2018). Several papers have described methods to deal with these limitations—most often through sophisticated statistical techniques (Tingley and Beissinger 2009, Pearse et al. 2017) or approaches that apply to specific cases, such as when survey plots cannot be relocated (Kopecký and Macek 2015, Verheyen et al. 2018). However, when we review papers and grant proposals for journals and agencies, we find that many researchers fail to address relatively straightforward questions essential to assessing the quality of historical data and their appropriateness for their chosen research questions, such as how accurate the records are and how appropriate they are for addressing a particular research question.

BioScience XX: 1–10.
https://doi.org/10.1093/biosci/biac063

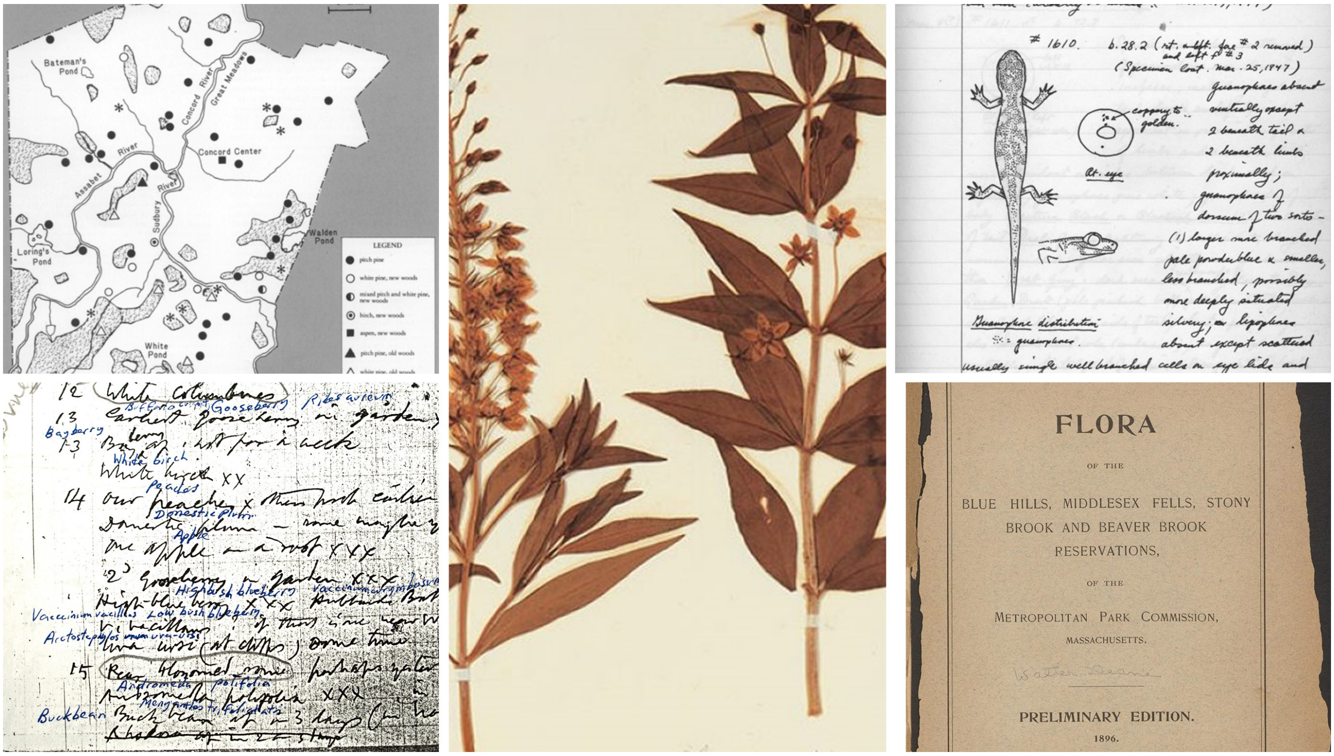

Figure 1. Examples of historical naturalist records. Clockwise from the top left: nineteenth century map of woodlots of Concord, Massachusetts (Whitney and Davis 1986); an herbarium specimen collected by Sophia Thoreau (courtesy Concord Museum); a page from Robert Stebbins' field notebooks (courtesy University of California Museum of Vertebrate Zoology); 1896 flora of Middlesex Fells and other locations; copy of a table of flowering phenology from May 1857 by Henry David Thoreau with notes by Richard B. Primack.

Historical data may not include explicit descriptions of sampling methods, sampling intensity, skill levels of the naturalists involved, or other relevant information. Rather, researchers may have to infer these metadata from other documentation—such as journals or letters—if any exists. These metadata are important because differences in methodology, sampling intensity, and skill level can affect subsequent analyses and make it difficult to interpret results (Miller-Rushing et al. 2008a, 2008c, Tingley and Beissinger 2009). For example, a past naturalist who was skilled at recognizing bird calls or went out several days each week might develop a large list of species and determine exactly when they arrive in spring, whereas a less skilled naturalist or one who went out less frequently might have a shorter list of species and recorded later, less accurate arrival dates. Similarly, an adequate flora done 100 years ago by a competent botanist with modest local knowledge of the flora might document most of the species in a location. If a team of naturalists with excellent local knowledge subsequently works more intensively to fully document the flora, their species list could give the impression that new species have arrived, even in cases when no such species gain actually occurred (Primack et al. 2014).

It is important to evaluate the accuracy of historical natural history data in the context of particular research questions. Some questions and analyses are forgiving of uncertainties in historical data, whereas others require more precision. For example, questions about shifts in community composition (e.g., presence and absence) require less detail in historical natural history data than do questions about shifts in abundance (Tingley and Beissinger 2009, Kopecký and Macek 2015). Similarly, researchers looking for species that have shifted phenology by a week or more may be able to handle more uncertainty in past phenology observations compared with researchers exploring shifts in relationships between plants and pollinators or other interacting species, where errors of a day or two could have large effects (Bolmgren et al. 2012, Stegman et al. 2017). The importance of accuracy in locality data will also depend on the scale and other details of the questions being investigated.

So how do researchers evaluate the accuracy and utility of historical natural history observations in the context of particular research questions? Researchers sometimes describe their methods for assessing historical data quality in their publications, but they often omit them, and they might sometimes miss biases in the historical data that could affect their results (Tingley and Beissinger 2009, Willis et al. 2017). In the present article, we describe a relatively simple three-step approach to assess historical natural history observations that is focused on the rigor of methods, the accuracy of

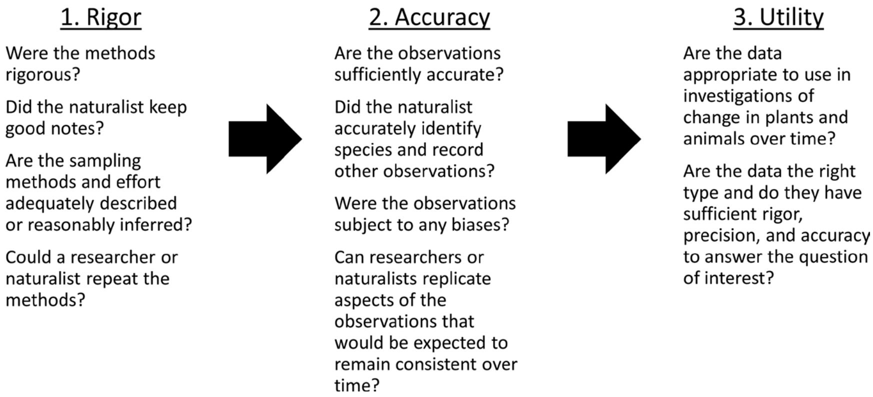

Figure 2. Diagram of the three-step approach to assess the usefulness of historical natural history observations in current ecological and climate change research.

observations, and the utility to answer questions of scientific interest (figure 2). In this framework, *rigor* refers primarily to documentation of methods, and *accuracy* refers primarily to accuracy of observations (or the results of the methods). Replicability is important to both. For assessing rigor, are the methods documented well enough that researchers could repeat them? For assessing accuracy, if researchers repeat the methods, can they replicate the observations or results (at least those that we would expect to be consistent over time)?

We demonstrate this method using the observations of species occurrence and phenology made by Henry David Thoreau, the famous environmental philosopher and author of the book *Walden*. Thoreau lived 1817–1862 and made phenology and natural history observations during the years 1851–1858. We and others have used his natural history observations in studies documenting changes in species composition and phenology, including potential mismatches among species (e.g., Miller-Rushing and Primack 2008, Primack et al. 2009, Ellwood et al. 2010, Heberling et al. 2019). We also describe how this approach could be applied to other natural history data sets. The general approach that we describe in this article complements more specific approaches offered by others, especially descriptions of the strengths, limitations, and uses of particular sources of historical ecological data (land survey records, vegetation data, historical maps and photographs, and herbarium specimens) given by Vellend and colleagues (2013b), as well as advice for more specific applications of historical data, such as scientific surveys of plants and animals (Tingley and Beissinger 2009, Kapfer et al. 2017, Verheyen et al. 2018).

Critiques of Thoreau's natural history observations

Thoreau recorded the timing of plant flowering, tree leafing out, bird arrivals, plant fruiting, and spring ice out (i.e., the breaking up of ice) in Concord, Massachusetts, in the United States. He also recorded the occurrence of numerous species, especially plants, in Concord. In Thoreau's time and since, naturalists and researchers have praised his natural history skills, but others—particularly John Burroughs, one of the leading nature essayists of American literature—have sharply criticized Thoreau's skill (Burroughs 1919).

In 1919, Burroughs dismissed the accuracy of Thoreau's observations in an influential essay, “A Critical Glance into Thoreau,” published in *The Atlantic Monthly* (Burroughs 1919). Burroughs built on earlier criticisms made by James Russell Lowell, a contemporary of Thoreau (Lowell 1871). Burroughs recognized Thoreau's original and skillful writing; however, he also wrote, “Thoreau was not a great philosopher, he was not a great naturalist, he was a not a great poet, but as a nature-writer and an original character, he is unique in our literature” (Burroughs 1919, p. 780). Burroughs argued that Thoreau was more concerned with fanciful analogies than whether he wrote fiction or fact. His journals “are mainly a record of his mental reactions to the passing seasons and to the landscapes he sauntered through.” (Burroughs 1919, p. 785). His observations are frequently at fault, or wholly wide of the mark” (Burroughs 1919, p. 779).

As specific examples, Burroughs (1919) questioned whether Thoreau knew that hickory trees grew in Concord and whether he knew that pine trees have seeds. In fact, Thoreau did recognize the hickory species that grew in Concord; he referenced hickories dozens of times in his journals (Thoreau 1906). Similarly, Thoreau referenced pines hundreds of times in his journals (Thoreau 1906); he was one of the earliest Western scientific observers of the process of forest succession in which seeds from trees such as pines establish forests in abandoned agricultural fields (Thoreau 1860). Despite this, the damage done by Burroughs (1919) to Thoreau's reputation as a scientific observer persisted for decades.

In more recent years, Thoreau's ability as a botanist was recognized by Ray Angelo, a botanist who has thoroughly explored Concord and investigated Thoreau's journals (Angelo 1985). According to Angelo, Thoreau did not focus on the scientific study of natural history during his early years, but by 1850, he recognized the limitations of his plant knowledge and used the best available botanical guides to learn to identify species. At the same time, he began to increasingly use scientific names for plant species. Angelo (1985, p. 16) stated, “By 1857 Thoreau had clearly progressed beyond the fledgling stage and was perhaps one of the more competent amateur botanists in Massachusetts.” However, Thoreau's goal was not primarily scientific but, rather, to use his knowledge of natural history to understand what he was observing in nature. As was stated by Angelo (1985, p. 23), “for a writer to acquaint himself so completely and consciously with the flora of his native region was unprecedented, and inspires wonder as to what grand work of prose this insistent pursuit of botany was meant to nurture."

Other researchers, including us, have since credited Thoreau as a pioneering scientist in the fields of geology, hydrology, and ecology (Primack 2014, Thorson 2014, 2017). But were Thoreau's observations of natural history phenomena in Concord during the mid-nineteenth century really accurate and appropriate for use in studies of ecological change in Concord? Or was Thoreau just recording his own mental fantasies, as Burroughs asserted? How do we know? In the present article, we describe an approach for evaluating past natural history observations, using Thoreau as an example, and extend the approach to other naturalists.

Assessing Thoreau's observations

To assess the accuracy and utility of Thoreau's observations, we analyzed natural history observations—first flowering, leafing out, migratory bird arrivals, fruiting, and plant species presence—that Thoreau made in Concord, Massachusetts, and recorded in his journals from 1851 to 1858 (Primack and Miller-Rushing 2012). He later compiled these observations into tables, which are archived at the Morgan Library in New York City, the Ernst Mayr Library of Harvard University, and the Peabody Essex Museum in Salem, Massachusetts. We extracted the data from Thoreau's tables and matched his species names with modern species names. This required a considerable effort, because his handwriting is difficult to read, because he used a mix of common names and scientific names and sometimes abbreviations, and because many of the names he wrote down are no longer in use.

For first flowering dates, we included records for 32 species of spring-flowering wildflowers (herbaceous and woody); Thoreau recorded observations of almost all of these species in every year between 1852 and 1857 (Miller-Rushing and Primack 2008, Ellwood et al. 2013). For leafing out, we included records for 42 species of trees, shrubs, and vines that Thoreau observed in 1853, 1854, 1855, and 1860 (Polgar et al. 2014). For bird arrivals, we included records for 22 species of migratory birds that Thoreau observed between 1851 and 1854 (Ellwood et al. 2010). For fruiting, we included records of peak fruiting for 31 species of woody plants made by Thoreau in the 1850s, reported in the book *Wild Fruits* (Thoreau 2001). For plant species presence, we included records of 578 flowering plant species that Thoreau recorded in Concord; this excludes grasses, rushes, and sedges (Primack et al. 2009).

We compared Thoreau's data with our lab group's field observations made between 2004 and 2018 in Concord and with select data sets collected in Concord during the time period between Thoreau's observations and our own. In each case, we included only data for the same species that Thoreau observed. For first flowering, we included observations made by Alfred Hosmer, a Concord resident, in 1878 and from 1888 to 1902 (records stored at the Concord Free Public Library), and our own observations made between 2004 and 2018 (Miller-Rushing and Primack 2008, Ellwood et al. 2013). For leafing out, we included our own observations made between 2009 and 2018 (Polgar et al. 2014). For bird arrivals, we included records made by well-known ornithology professors and Concord residents William Brewster and Ludlow Griscom from 1886 and between 1900 and 1919, and from between 1930 and 1931 and between 1933 and 1954, respectively, and records made by Concord resident Rosita Corey from between 1956 and 1973 and between 1988 and 2007 (Ellwood et al. 2010). For fruiting, we included mean fruiting dates of species obtained from herbarium specimens from across New England; the number of specimens ranged from 26 to 181, depending on the species (Miller et al. 2021). For plant species presence, we included records compiled by Edward Jarvis (1823–1837), Alfred Hosmer (1888–1902), Richard Eaton (1920s–1960s), and ourselves (2008–2018; Primack et al. 2009, Willis et al. 2008). Each of these data sets has strengths and limitations that we have considered in previous publications. Although the observations were made in Concord, it is likely that each observer or group of observers had particular places in Concord that they favored for making observations.

We used these data and accompanying records (primarily Thoreau's journals and the tables of observations he compiled) to address questions relating to the rigor of his methods, the accuracy of his observations, and the utility of his data to investigate changes in plants and animals over time (figure 2). In particular, we used his field records to assess the rigor of his methods and as evidence of his ability to accurately identify species and phenological phases. We used correlation analysis and linear regression to compare Thoreau's data with data from later sources and to test whether the sequence of species' phenologies and the observations of species were similar across time. Finding that the sequence of phenologies, for example, was largely consistent between Thoreau's observations and our own would provide evidence that Thoreau's phenological observations were accurate. This assumes that phenology relative to other species is a comparatively stable characteristic of plant species, which has been borne out by a variety of studies (Kochmer and Handel 1986, Davies et al. 2013).

Rigor

Thoreau recorded his observations in the field on pieces of paper and later used these notes to enter more complete observations in his journal. His journal entries included dates and descriptions of his observations, locations, and often additional details, such as weather or people he saw. He made observations nearly daily throughout the year. He also described his motivation for recording phenology observations; he intended to develop "a book of the seasons, each page of which should be written in its own season and out-of-doors, or in its own locality wherever it may be" (Thoreau 1906, vol. VIII, p. 239, Stoller 1956). He later compiled his phenological observations to develop tables separate from his journals. Thoreau's journals and his tables of phenological observations show that he went for walks almost every day for around 4 hours per day. He went for walks in all weather—hot, cold, rainy, or dry. His journals also provide information on where he was on most days and on which days he did not make observations.

On the basis of his notes, Thoreau anticipated when and where in Concord a species would first flower and monitored specific plants in specific locations. He sometimes traveled miles to observe plants that he anticipated would be coming into flower. He wrote, “It will take you half a lifetime to find out where to look for the earliest flower” (Thoreau 1906, vol. VII, p. 240). His notes are not specific enough to allow us to go back to these exact places in Concord where he made his observations, and the microclimates of these places have likely changed considerably over the past 170 years because of trees growing up.

Given the detail of Thoreau's notes, the main challenge in repeating his methods is matching the criteria he used to determine the phenological phases he recorded. He did not explicitly describe the criteria he used to determine first flowering, leafing out, bird arrival, and peak fruiting in his notes. First flowering time is a fairly unambiguous character to measure in most plants (i.e., visible stamens or pistils, corolla fully open and with its final color). In contrast, there are no clear criteria for describing leafing out or peak fruiting, so we are not certain what criteria Thoreau used to determine these phenological phases. On the basis of the naturalist skills evident in his journals, it seems likely that his criteria were internally consistent. Generally, leaf out occurs very rapidly in the spring, so differing criteria for determining leafing out, which could document any stage between leaf bud break and full leaf expansion, should have minimal impact on leafing out dates relative to the differences in leafing out times between species and between years (Ellwood et al. 2019). In our case, we defined leaf out as the time when the leaves have emerged from the bud and the adult shape can be discerned. Criteria for determining peak fruiting, however, could be more variable but almost certainly relate to when the majority of fruits on a plant have a coloration and size that reflect ripeness.

Like first flowering, bird arrival is unambiguously the first date Thoreau saw or heard a particular species. It is noteworthy that between Thoreau's time and now, the techniques of field ornithology have evolved; Thoreau lacked good field guides and binoculars but, instead, relied on a small telescope and substantial ornithological manuals by Alexander Wilson and Thomas Nuttall (Allen 2019).

Accuracy

From his journals and books, it is clear that Thoreau's skill at identifying species improved over time. During the 1850s, the period during which he made intensive observations of plant and bird phenology and plant species presence, his ability to identify species appears to have been strong. The first edition of Asa Gray's *Manual of Botany* was published in 1848, and at this time, Thoreau began noting scientific names of plants and animals in Concord and other areas he explored. He collected around 900 herbarium specimens, which are now housed at the Harvard University Herbaria, although these generally lack collection dates or locations, limiting their scientific value. In his journals, Thoreau named and recorded phenological observations of over 500 plant species in Concord. He sought advice from local experts and became recognized as a botanical expert for the state of Massachusetts (Angelo 1985). His identifications are considered accurate except where field guides and experts of the time were confused and are still confused—for example, difficult-to-distinguish groups, such as species of oaks (*Quercus*), raspberries (*Rubus*), and shadbushes (*Amelanchier*; Angelo 1985). Thoreau's natural history knowledge of birds did not match his in-depth knowledge of plants, but his bird knowledge and identifications were good for their time and were informed by comprehensive ornithological texts by Wilson and Nuttall (Allen 2019).

In terms of biases, we might be concerned about biases in Thoreau's ability to find the first flowers, leaves, or birds, which can be influenced by population size or sampling effort (Miller-Rushing et al. 2008a, 2008b, Moussus et al. 2010). Thoreau systematically searched Concord to uncover locations of rare species that he thought might occur in the town. His searches often took him to out-of-the-way locations, including into the middle of bogs and swamps. Writing about his searches, Thoreau stated, “how long some very conspicuous [flowers] may escape the most diligent walker, if you do not chance to visit their localities the right week or fortnight” (Thoreau 1906, vol. V, p. 128). These detailed searches and targeted monitoring suggest that Thoreau had a strong natural history knowledge. As with all observations of first events, Thoreau's observations may often have occurred 1 or more days after the true events (e.g., first flowering or leafing) occurred in Concord. Because he went out daily, we believe this bias or error was relatively small (Pearse et al. 2017).

The dates of first flowering that Thoreau observed were highly correlated with our observations ($r = .87$, $p < .001$; figure 3); that is, Thoreau recorded the flowering of spring wildflowers in almost exactly the same sequence that plants currently flower. Some species—such as marsh marigolds (*Caltha palustris*) and bluets (*Houstonia caerulea*)—flower early in the spring, and other species—such as pink lady's slipper orchids (*Cypripedium acaule*) and yellow star-grass (*Hypoxis hirsuta*)—flower relatively late in the spring. The dates on which Thoreau recorded the leafing out of woody plants—including trees, shrubs, and vines—are also highly correlated with our own observations ($r = .88$, $p < .001$; figure 3). Certain species—such as elderberry (*Sambucus canadensis*) and European barberry (*Berberis vulgaris*)—consistently leaf out early, whereas other species—such as

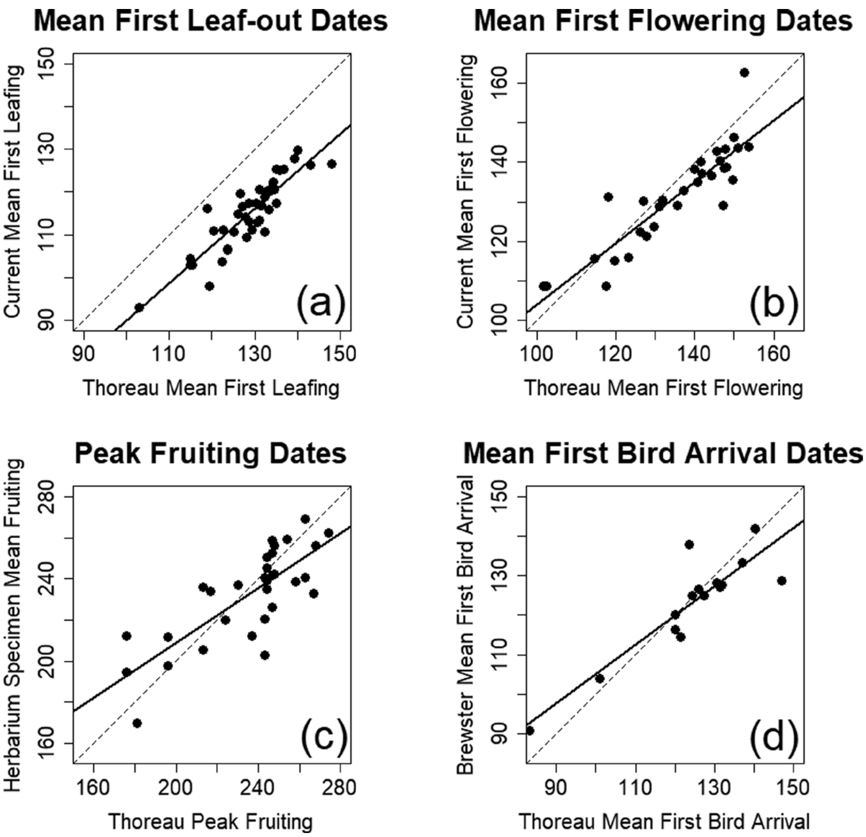

Figure 3. Comparisons between Thoreau's historical observations in the 1850s and more recent observations: (a) leaf out and (b) flowering observations made by the Primack Lab, (c) fruiting data from herbarium specimens, and (d) bird arrival observations made by William Brewster (1886–1919). Each dot represents a species. The dates are indicated as the day of year. The solid lines are regression lines, and the dotted lines are 1:1 lines.

poison sumac (*Toxicodendron vernix*) and bayberry (*Myrica pensylvanica*)—leaf out relatively late. Thoreau's observations of peak fruiting dates were highly correlated with mean fruiting dates using herbarium specimens from across New England ($r = .78$, $p < .001$; figure 3). The two data sets show a consistent sequence of fruiting; certain species—such as shadbush (*Amelanchier* sp.) and lowbush blueberries (*Vaccinium angustifolium*)—fruit early, and other species—such as greenbriars (*Smilax rotundifolia*) and winterberries (*Ilex verticillata*)—fruit later.

The dates that Thoreau observed birds arriving in Concord were significantly correlated with those of other naturalists (Brewster, Griscom, and Corey; $r > .77$, $p < .001$ for all correlations between data sets), with William Brewster's arrival dates most strongly correlated with Thoreau's ($r = .89$, $p < .001$; figure 3). All observers observed certain birds (such as eastern phoebes, *Sayornis phoebe*) arrive early and other species (such as eastern wood pewees, *Contopus virens*) arrive late. The observations of Brewster (1886–1919) and Ludlow Griscom (1930–1954) were most strongly correlated among the data sets ($r = .97$, $p < .001$).

Utility

A variety of lines of evidence demonstrate that Thoreau's observations have utility for investigating the effects of a warming climate on the plants and birds of Concord. Comparing Thoreau's observations, as well as those of Alfred Hosmer, with our own shows that plants are flowering about 1 week earlier now than they did in Thoreau's time; subsequent analysis has shown that these changes have largely been driven by a warming climate (Ellwood et al. 2013, Miller-Rushing and Primack 2008, Willis et al. 2008). Plants tend to flower earlier in warm years and later in cool years, and species vary substantially in their phenological sensitivity to temperature (Ellwood et al. 2013, Miller-Rushing and Primack 2008). Woody plants are leafing out about 2 weeks earlier now than in Thoreau's time, suggesting that trees are more responsive to a warming climate than spring wildflowers, which are flowering just 1 week earlier now than in Thoreau's time (Polgar et al. 2014, Heberling et al. 2019). Woody plants also leaf out earlier in warm years than in cold years (Polgar et al. 2014). We are not able to use Thoreau's data to determine whether species are currently fruiting earlier, because no one has yet made the comparable observations in Concord (Miller et al. 2021).

Bird arrival dates in Concord do not appear to be changing, on average, from Thoreau's time to more recent years (Ellwood et al. 2010). Three species—warbling vireos (*Vireo gilvus*), yellow warblers (*Setophaga petechia*), and Baltimore orioles (*Icterus galbula*)—appear to be arriving earlier, four species—bank swallows (*Riparia riparia*), barn swallows (*Hirundo rustica*), wood thrushes (*Hylocichla mustelina*), and ovenbirds (*Seiurus aurocapilla*)—appear to be arriving later, and 15 are not changing (Ellwood et al. 2010). The arrival dates of eight species are significantly correlated with temperature; seven tend to arrive earlier in warmer springs (Stegman et al. 2017).

In addition to these changes in phenology, the flora of Concord is changing. Of the 578 plant species that Thoreau observed in the 1850s in Concord, we determined that 156 (27%) of these species could no longer be found in Concord 160 years later, and a further 87 (15%) of these species are now rare (Willis et al. 2008, Primack et al. 2009). The loss of species is particularly severe in certain families, such as orchids (Orchidaceae) and lilies (Liliaceae). The loss of species is similar no matter which Concord naturalist is used as a starting point (Jarvis, 1823–1837; Thoreau, 1852–1857; or Hosmer, 1888–1902). Similarly, each of the historical botanists found that roughly 79% of the flora was native; now just 61% of the Concord flora is native (Primack et al. 2009). Moreover, the changes in the flora of Concord, on the basis of Thoreau as a starting point, are similar to changes reported in other floras across New England and New York, which have also lost significant numbers of native species (McDonough MacKenzie et al. 2019).

Was Thoreau a good naturalist?

We find (unsurprisingly) that Thoreau was a strong naturalist. He made rigorous, likely-accurate observations of plants and birds and his observations are adequate to provide the foundation for an extensive body of research on the effects of climate change on the plants and animals of New England (Primack and Miller-Rushing 2012, Primack 2014). He kept exceptional notes, which reflected his natural history knowledge, and he documented his sampling effort in his detailed personal journal and through the dates and locations of his observations. He did not describe how he defined particular phenological phases, which is not a problem for first flowering and bird arrivals, because the definitions are unambiguous. Because leafing out occurs relatively rapidly, the variability in the data caused by uncertainty in the definition is small relative to the differences between species and years. We are not certain what definition Thoreau used for assessing peak fruiting, but the differences among species in fruiting times, on the order of several months, is likely greater than the variation that might be caused by different definitions of peak fruiting.

On the basis of comparisons with independent data sets—for example, comparisons of phenological sequence and proportion of native species between Thoreau's observations and more recent observations—Thoreau's observations were likely accurate, and appropriate to assess changes in phenology and community composition over time and in relation to a warming climate. Given that Thoreau was recording observations of hundreds of plants and animals, both terrestrial and aquatic, it is possible that he made mistakes in identifications. Good guides to plants and animals, such as Gray's *Manual of Botany* (1848), were very new, and field tools, such as binoculars, were not nearly as powerful as today. Burroughs (1919), who faulted Thoreau's naturalist skills, had the benefit of far better field guides and field tools than Thoreau did. Even so, Thoreau's observations appear to have been quite accurate.

In fact, it is remarkable that Thoreau's observations have been as useful as they have. When compared with more recent observations, his records show plant and animal responses to changes in climate despite potential confounding influences of changes in land-use patterns, changing plant population sizes, and sampling intensity that introduce variation into the analysis (Miller-Rushing and Primack 2008, Ellwood et al. 2013, Polgar et al. 2014). Comparisons of his data with modern observations have suggested potential mismatches between birds and plants and between canopy trees and understory wildflowers, mismatches that we are continuing to investigate (Ellwood et al. 2010, Heberling et al. 2019). And his observations show declines in abundance of plants in Concord that have occurred despite the protection of roughly 35% of the land area of the town, indicating that climate change and other causes are likely driving the declines (Willis et al. 2008, Primack et al. 2009). Because of his rigor and accuracy, his observations provide one of the most valuable case studies of the ecological effects of climate change (Primack and Miller-Rushing 2012, Primack 2014).

Applying this approach more widely

This approach of evaluating historical natural history observations can be applied to other data sets. For example, researchers have resurveyed much of the species occurrence observations that Joseph Grinnell and colleagues made in California between 1904 and 1969 (Moritz et al. 2008, Tingley et al. 2012). Grinnell's team was diligent about recording most locations and sampling effort, identifying most species accurately, and recording all species they encountered. They also collected many specimens and photographs to document their work. However, their sampling effort was sometimes unclear and uneven, some of their sampling routes could not be relocated, and members of the group sometimes recorded different species at the same locations. Migrating birds and dispersing juveniles could also have biased use of their data to describe species ranges (Tingley et al. 2012). The uncertainty in the Grinnell records makes some of their data inappropriate to help answer certain questions (such as changes in abundance of species with high amounts of uncertainty in sampling), but recent resurveys of their observations—with appropriate use of the data (Tingley and Beissinger 2009)—have yielded many important insights about how species ranges are shifting in response to climate change (Moritz et al. 2008, Tingley et al. 2009, Morelli et al. 2012, Tingley et al. 2012, Iknayan and Beissinger 2018).

Similarly, researchers have revisited Robert Whittaker and William Niering's observations along elevational transects in the Santa Catalina Mountains in Arizona (Whittaker and Niering 1964, Brusca et al. 2013). Whittaker and Niering's observations were very detailed, but they did not have GPS and did not precisely record or mark the locations of their plots. The resurvey team, which was looking for changes in species distributions along the elevational transects, compensated by increasing the density of their sampling along the same transect (located along a highway) and by being conservative in their conclusions regarding shifts in distributions (Brusca et al. 2013).

Museum specimens represent another source of quantitative natural history data. Such specimens generally include information about the dates and locations where they were collected, although the location information can vary in its resolution (e.g., latitude and longitude, town, or county; Willis et al. 2017). The presence of physical specimens largely eliminates uncertainty around species identification and preserves morphological, phenological, and other traits that naturalists may not typically note when making field observations. Museum collections, however, frequently contain certain sampling biases—for example, overrepresentation of particular species, locations, seasons, and years preferred by the most active collectors (Daru et al. 2018, Willis et al. 2017). These biases can reduce the utility of museum specimens for answering certain questions that require more precision or other information (e.g., fine-scale shifts in ranges or changes in population sizes), but the abundance of herbarium specimens and the strengths of their rigor and accuracy, for example, make them excellent tools for assessing changes in plant anatomy and flowering, leafing, and fruiting phenology. For example, herbarium specimens have been used to show long-term changes in stomata and intrinsic water use efficiency, environmental cues driving plant phenology, and regional-level differences in the fruiting phenology of native and nonnative invasive species (Miller-Rushing et al. 2009, Davis et al. 2015, Gallinat et al. 2018).

The flora of the Middlesex Fells Reservation near Boston illustrates some of the challenges of working with historical data sets. In the 1890s, a group of volunteers and professional botanists documented the flora of this area (Deane 1896). Their methods were described and were associated with a collection of voucher specimens and field observations recorded on index cards (Hamlin et al. 2012). However, the thoroughness (sampling effort) of the original survey was not clear and has led to some debate about how to interpret differences between the flora in the 1890s and two modern floras, one less intensive and another more intensive than the original flora (Drayton and Primack 1996, Hamlin et al. 2012). This debate highlights the need for authors using historical data to clearly communicate the data's rigor, accuracy, and utility, including strengths and limitations, and to be careful when interpreting and communicating results.

In many cases, researchers find historical natural history data sets with little if any documentation associated with them. The data may be found in a journal of observations from someone's daily walks, a collection of photographs, or birder reports to an ornithological club newsletter. In these cases, the observations may still contain some information about their rigor and accuracy. For example, the frequency of the data may contain information describing sampling effort (e.g., observations are made every day, weekly, or at some other frequency). Researchers can also compare data with similar observations collected in different years and places to help infer methods or to assess accuracy. Even poorly documented data may be useful in addressing some ecological questions, or they may suggest new hypotheses deserving of further study. The approaches described in this article, outlined in figure 2, provide some ideas about how these data can be evaluated and used.

Acknowledgments
The authors thank Elizabeth Ellwood, Amanda Gallinat, Mason Heberling, and Nick Gotelli for providing comments that improved the manuscript, and we thank the numerous colleagues, students, and volunteers who recorded observations that contributed to the data included in this work. Work on this project was funded in part by the National Science Foundation (award no. 1950447). The findings and conclusions of this article are those of the authors and do not necessarily represent the views of the US Department of Interior or the US government.

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