Metadata for Data Paper in *Ecology*

Plant and bird phenology and plant occurrence from 1851 to 2020 (non-continuous) in Thoreau's Concord, Massachusetts

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INTRODUCTION

Phenology is an invaluable metric for measuring the impacts of climate change on plants and animals, particularly those in temperate climates (Parmesan and Yohe 2003). Robust phenological studies depend on long-term data that can account for year-to-year variability in phenological events, and ideally provide pre-climate change baselines that can be used to evaluate climate-driven phenological shifts (Parmesan 2007, Bolmgren et al. 2013). Such data sets are difficult to find (Vellend et al. 2013). Here we describe an exceptional example of such a data set; it includes some of the earliest known phenological records in the United States and features observations made by the naturalist and philosopher Henry David Thoreau.

While he is well known for his writings about his two years living on Walden Pond, throughout the mid-nineteenth century Thoreau observed and recorded leaf-out, flowering, fruiting, and bird migrations in Concord, Massachusetts, United States. He was curious about the timing and regularity of these events and aimed to create a calendar of natural events (Stoller 1956, Dimick 2018). His observations in Concord were continued by other amateur naturalists and university biologists over the subsequent 150 years. Starting in 2003, we began compiling these data and collecting contemporary plant observations consistent with those of Thoreau and his successors (Primack and Miller-Rushing 2012). Thoreau's phenological observations have been very influential—Aldo Leopold and Sara Elizabeth Jones referred to him as the father of phenology in the United States (Leopold and Jones 1947). His phenology data have been used in dozens of ecological studies (see list below in Class V. Supplemental descriptors, History of data set usage). His observations also represent an early example of community science—science involving amateurs (whether novice or expert amateurs) in some part of the scientific process, also known as citizen science—in the United States (Miller-Rushing et al. 2012).

These Concord data have been crucial for investigating the phenological responses of trees, wildflowers, and birds to a changing climate, tracking phenology changes over time, and quantifying phenological responses to climatic variation. The data demonstrate that the leafing times of trees are highly sensitive to climatic variation (Heberling et al. 2019), the flowering times of wildflowers are moderately sensitive to climate change (Ellwood et al. 2013, Heberling et al. 2019), and the arrival time of migratory birds are only minimally responsive to climate variation (Ellwood et al. 2010, Primack and Gallinat 2016). These differences among taxonomic groups suggest potential phenological mismatches which could alter ecological relationships, community structure, and population sizes.

In addition to phenological observations, this data set includes estimates of plant species' relative abundance in Concord that span a century (Primack et al. 2009). We used the combination of data describing phenology and relative abundance to demonstrate that phenological plasticity allows certain plant species to persist in the face of climate change (Willis et al. 2008). The relationship between plant relative abundance (or performance) and phenological response to climate change was first discovered in Concord and has since been replicated (Cleland et al. 2012, Wolkovich et al. 2013, Springate and Kover 2014, but see Iler et al. 2019). In addition, these data have been used to show that climate change disproportionately benefits some species, such as nonnative invasive plants (Willis et al. 2010, Polgar et al. 2014b), and harms others, such as native wildflowers (Heberling et al. 2019), through relative shifts in phenology. The broad pattern of gain of nonnative species and loss of native species is occurring throughout New England (Bertin et al. 2005, Bertin 2013, McDonough MacKenzie et al. 2019). The Concord data set has also been important in demonstrating that the changing relative abundance of species can influence the date of first observation and needs to be considered in studies of phenology and climate change (Miller-Rushing et al. 2008, Stuble et al. 2021).

Our compilation of this data set benefited greatly from the expertise of library, university, and museum staff, and Thoreau scholars—they helped us find and understand the documents and how to appropriately use them in addressing our research questions (Primack and Miller-Rushing 2012, Angelo 2020, 2021). We also learned a great deal from the deep knowledge and experience of current long-time Concord residents, amateur naturalists, botanists, and birders who shared data, pointed to new-to-us locations for observations, and welcomed us at their meetings, thereby deepening our community associations. Concord has an exceptionally lively public intellectual life—residents and friends encouraged our work, but some in the community questioned our results in print and during public presentations (e.g., Willis et al. 2009, Angelo 2014a, 2014b, Primack and Miller-Rushing 2014, Primack et al. 2014, Willis and Davis 2014). Such vibrant public debate on scientific topics is welcome and should be encouraged. Our connections to Concord strengthened over time as we continued field work, shared results in public talks and newspaper articles, and developed new lines of research. The Concord phenology data set therefore goes deeper than the data themselves and highlights strategies for data collection, data interpretation, community building, and education and outreach that are broadly applicable to research beyond phenology.

Over the past 17 years, research resulting from these data has been widely presented to the public through newspaper articles, magazine articles, press releases, blog posts, radio, television, and documentary interviews, a major exhibition at the Concord Museum, on-line outlets, and a popular book (Primack 2014). In addition to the wealth of publications, media attention, and various research products, the research has provided, and continues to provide, opportunities for numerous undergraduate and graduate students, early career professionals, members of the general public, and a wide network of researchers and educators. These opportunities have most often taken the form of field work that has introduced a growing network of people to phenological research, local impacts of climate change, local history from a variety of perspectives including scientific, literary, and political histories, and appreciation for Concord's hidden natural gems. In sharing this data set and associated metadata, we look forward to continuing to build this community and inspiring others to be observers of their local surroundings.

METADATA

CLASS I. DATA SET DESCRIPTORS

A. Data set identity

Phenological observations of plant leaf-out, flowering, and fruiting, and bird migration in Concord, Massachusetts, United States

B. Data set identification code

Concord_phenology_dataset.csv

C. Data set description

a. Originator(s)

Richard Primack, Boston University

b. Abstract

Concord, Massachusetts, USA has served as an active location for phenological observations since philosopher and naturalist Henry David Thoreau began recording plant and animal occurrence and phenology in 1851. Since that time, numerous naturalists, scientists, and researchers have continued this tradition, creating an invaluable time series of 758 species in a single location. A total of 13,441 phenological records, spanning 118 years, now exist, with observations of many species ongoing. Relative abundance data for an additional 200 plant species is also provided. Thoreau's published journals and records in Special Collections libraries at the Concord Free Public Library, Harvard University, Peabody Essex Museum, and Morgan Library and Museum provide insight into his methods of routinely walking around Walden Pond, through natural areas, and within the town of Concord, seeking the first leaf or flower on plants, seasonal observations of migratory birds, and fruit maturation times. Several amateur naturalists, and most recently the present research group, have followed this method of regularly searching Concord for the earliest signs of seasonal events, visiting many of the same locations including Walden Pond, the site made famous by Thoreau. While Thoreau's observations were initially made out of a curious desire to document the natural world, these data have led to dozens to contemporary studies, addressing timely issues such as climate change, conservation, ecology, and invasive species. This time series of data, initiated by Thoreau and continued by others, has resulted in dozens of peer-reviewed publications, a

popular science book, and numerous educational and outreach opportunities. These data grow increasingly valuable with time and as new and creative studies are undertaken with Thoreau's historic records. No copyright restrictions apply to the use of this data set other than citing this publication.

D. Key words

climate change; Concord, Massachusetts; conservation; migration; phenology; Thoreau, Henry David

CLASS II. RESEARCH ORIGIN DESCRIPTORS

A. Overall project descriptions

a. Identity

Phenological observations in the spring of plant first leaf-out, first flowering, and first fruiting, first fern and gymnosperm spore release, and first arrival of migratory birds in Concord, Massachusetts, United States. Species relative abundance for subset of plant species.

b. Originator(s)

Richard Primack, Boston University

c. Period of study*

See Figure 3.

Henry David Thoreau recorded observations of plant leaf-out, flowering and fruiting, and bird arrivals: 1851-1858.

Alfred Hosmer recorded plant flowering, plant relative abundance, and spore release dates of ferns and gymnosperms: 1878, 1888-1902.

William Brewster recorded arrival of migratory birds: 1886, 1900-1919.

Ludlow Griscom recorded arrival of migratory birds: 1930-31, 1933-1954.

Richard Eaton recorded plant relative abundance: approximately 1950-1972

Rosie Corey recorded arrival of migratory birds: 1956-1973, 1988-2007.

Richard Primack, along with graduate and undergraduate students, recorded timing of plant leafing and flowering and relative abundance: mainly 2003-2007, and also ongoing and reported here through 2020.

*The time period provided reflects the years during which the researcher was active, and data for each phenological event or species may be discontinuous within that period.

d. Objectives

1. To record phenological observations of plants and birds in Concord, MA
2. To record relative abundance of plants in Concord, MA

e. Abstract

Same as above.

f. Source(s) of funding

B. National Science Foundation
    a. Flowering Times and Climate Change in Thoreau's Concord; DEB Award 0413458; Sep 2004
    b. Collaborative Research: Spatiotemporal models of phenology: Integrating the effects of climate change on plants and animals; Award DEB 0842749; May 2009

c. Collaborative Research: Digitization TCN: Mobilizing New England Vascular Plant Specimen Data to Track Environmental Changes; Award DEB 1208989; Jul 2012
d. Graduate Research Fellowship (to Gallinat); Award DEB 247312; Jun 2014
e. Collaborative Research: Phenological mismatch between trees and wildflowers mediated by environmental variability and plant invasions; Award 1936877; February 2020
f. OPUS: CRS: The impacts of changing phenology on species, ecological interactions, and conservation; Award 1950447; May 2020

C. Arnold Arboretum of Harvard University
D. Botanical Society of America
E. Boston University
F. Manomet Inc.
G. Nuttall Ornithological Club

B. Specific subproject description

a. Site description

Concord, Massachusetts (42°27'N 71°20'W, 43 m elevation) is approximately 28 km northwest of Boston, in the northeastern United States (Figure 1). Concord is the location of numerous sites of major historic and literary importance (site of an early Revolutionary War battle, now protected as Minuteman National Historical Park; home to formerly enslaved residents and significant authors such as Thoreau, Ralph Waldo Emerson, Louisa May Alcott, and Nathaniel Hawthorne; site for the development of intellectual and political movements such as transcendentalism and abolition), protected natural spaces, and opportunities for recreation. Most notably, Walden Pond, made internationally famous by the writings of Thoreau, is in Concord. These features have made it a destination for intellectuals, naturalists, and environmentalists for over 150 years. Importantly, the draw of Concord and traditions initiated by Henry David Thoreau have resulted in the wealth of phenological data presented here.

There is a diversity of ecosystems and microclimates within the 67.4 km^2 of Concord. Concord is dominated by temperate forest which today is composed largely of maple (*Acer spp.*), oak (*Quercus spp.*), birch (*Betula spp*.), pine (*Pinus spp*.) and hickory (*Carya spp*.) trees. Shade-tolerant shrubs, particularly blueberry (*Vaccinium*) and huckleberry (*Gaylusaccia*) species in the Ericaceae, and wildflowers can be found in the understory. Open fields maintained since forest clearing in the 17th and 18th centuries by European settlers provide habitat for sun-loving wildflowers. Opportunistic wildflowers are also found in human-dominated parts of the Concord landscape – in cemeteries, along roadsides and railroad tracks, on the edges of parking lots, and near buildings. Local, state, and federal agencies maintain environments, such as Great Meadows National Wildlife Refuge and Minute Man National Historical Park, that have become dependable habitats for resident and migratory bird species. Concord is at the confluence of three major rivers, Concord, Assabet, and Sudbury, and has numerous springs, streams, and ponds. Notably, Walden Pond State Reservation, the historic site of Thoreau's cabin and foundation for much of the present work, is located on the southeastern corner of Concord. Much of Concord's landscape is also protected by land trusts and nonprofit educational institutions, including the Estabrook Woods, a tract of 490 ha owned by Harvard

University and the Middlesex School. This abundance of protected land in natural conditions contributes to Concord being well-suited to long-term observations of a wide variety of organisms that occur in a diversity of habitats.

Several environmental characteristics of Concord are of particular relevance to plant and animal phenology and the long-term data set presented here. This region is within the warm summer subtype of the humid continental climate (Dfb) in the Köppen-Geiger climate classification (Beck et al. 2018), with year-round precipitation, winter months that are often below freezing, and summers that are warm and humid. Transitions between seasons are times of temperature variability, with, for example, frost or snow events that may occur after spring thaw and the start of the growing season. An advantage of working in Concord is that it is only 43 km to the Blue Hill Observatory, which is the oldest continuously operating weather observatory in the United States, with weather records going back to the 1830s (Magee et al. 2014). This region of southern New England is also noteworthy for having an increasing trend of warming temperatures that is approximately twice as fast as the average rate of warming for the United States as a whole (Miller-Rushing and Primack 2008; Heberling et al. 2019).

Plant phenology in temperate regions of the northern hemisphere is generally negatively correlated with spring temperature, leading to earlier leafing (Polgar and Primack 2011, Everill et al. 2014, Polgar et al. 2014b, 2014a), flowering (Primack et al. 2004, Miller-Rushing and Primack 2008, Ellwood et al. 2013) fruiting (Gallinat et al. 2015, 2018) and spore release in warmer years (Ellwood et al. 2011). The impacts of climate change on bird migration are much weaker than they are for plants, and are less dependent on local temperatures at arrival sites (Miller-Rushing et al. 2008, Ellwood et al. 2010, 2015). Long-term records, such as those initiated by Thoreau and presented here, have been critical in advancing our understanding of the effects of climate change on migration timing.

Because of the strong link between local temperature and plant phenology, the first individuals of a plant species to exhibit a given phenophase are likely to be found in the warmest microclimates. Like Thoreau, we sought flowering plants in warm microclimates. During the 2003 field season, we spent considerable effort finding where plants occurred and where they first flowered and leafed out in Concord; when we located plants of a particular species in this initial season, they were often already in flower or leaf. Thus, the data from that season were not useful for comparison with earlier records, and are omitted here (Miller-Rushing and Primack 2008).

b. Sampling design

Thoreau flowering, leaf out, fruiting, and bird arrival—From 1851-1858, Henry David Thoreau took walks around Concord and recorded his observations in journals (Figure 2). His primary motivation for doing this was to gain a better understanding of the plants and animals around him, as well as to record the cyclical phases of development and movement for these organisms. He later compiled these observations into tables for particular years. Thoreau's botanical tables are now housed in the Morgan Library in New York and his bird observations are at the Ernst Mayr Library, Museum of Comparative Zoology (MCZ), Harvard University

Cambridge, Massachusetts. While Thoreau's methods, such as the amount of time spent on his field excursions or his exact walking routes, are unknown, his dated journal entries and descriptions provide insight into the fact that he sought the earliest leaves, flowers, and fruits and often found them in the warmest locations. Thoreau's flowering, leafing and bird arrival records are available as single dates of observation in given years. Fruiting phenology data, however, are given as representative dates, in which a single value is provided as an estimated date of "first", "peak", or "last" fruiting phenophase based on observations made from 1850-1860 (Thoreau 2001).

Hosmer flowering—From 1878-1902, Alfred Hosmer, an amateur botanist who was inspired by Thoreau, continued flowering observations in a way comparable to those of Thoreau, and also recorded estimates of species relative abundance in Concord and the surrounding area. Hosmer also recorded spore release dates of fern and gymnosperm species that are included in this data set. Hosmer's data are in the form of an unpublished book housed in Special Collections at the Concord Free Public Library.

Eaton flowering—Richard Eaton was an accomplished botanist who conducted fieldwork in Concord during the mid-twentieth century. Eaton published a flora of Concord (Eaton 1974) and recorded estimates of species relative abundance.

Primack and Miller-Rushing flowering—Primack and Miller-Rushing transcribed relevant entries of Thoreau's plant phenology tables into digital spreadsheets. From there, Primack and Miller-Rushing added comparable records of flowering times from Alfred Hosmer and species relative abundance from Hosmer and Richard Eaton (Miller-Rushing and Primack 2008, Primack et al. 2009). In 2003, Primack and Miller-Rushing began searching Concord for the earliest flowers (Primack and Miller-Rushing 2012). The data from this pilot year are not included here as species were often first located well after they had started to flower (Miller-Rushing and Primack 2008). From 2004 to the present, Primack, along with undergraduate and graduate students and various colleagues, visited Concord two to three days a week to search for and record flowering times of the same species of plants described in Thoreau's journals. Plants were recorded as flowering when the first open flowers of the species were found anywhere in Concord.

Primack and Polgar leaf out—In 2009, Primack along with Caroline Polgar and others started to also record leaf-out dates of common woody trees and shrubs that were observed by Thoreau, following a similar method to the flowering field work (Polgar et al. 2014a). Species were recorded as leafing out when a plant could be found anywhere in Concord in which the leaves were unfolded on at least three branches on one tree and their adult shape was discernable, even if the leaf was still small and unexpanded.

Relative abundance—All phenological and abundance observations were of plants *in situ*, in habitats that ranged from protected conservation areas to relatively disturbed in-town areas such as train stations and roadsides. Plants growing in cultivation, especially from current and abandoned ornamental gardens, were not included, except in the few cases where Thoreau

recorded the leafing out time of woody nonnative plants, such as lilacs and apples. Data reflect the phenology and relative abundance at the scale of the Town of Concord, though Hosmer included observations made in the surrounding vicinity as well. Hosmer and Eaton used many terms to describe species relative abundance but did not define them quantitatively. Primack and Miller-Rushing defined the following categories: very common (found throughout the area), common (occurring in >3 localities), frequent (occurring in 3 localities), infrequent (occurring in 2 localities), rare (occur in 1 locality), and very rare (10 or less individuals in a single locality. For all observers, abundance data represent the result of several years of observations, rather than annual assessments of abundance, which can be influenced by species that may be present but not detectable in each year (Chen et al. 2013). In the case of Primack and Miller-Rushing, observations on abundance were based on five years of fieldwork (2003-2007) with some later updates. See Willis et al. (2008) and Primack et al. (2009) for more details on how we treated abundance categories in our own analyses. Readers might want to take note of two articles by Angelo (2014 a, b) and our replies (Primack and Miller-Rushing 2014, Primack et al. 2014) on the effectiveness and rigor of our methods. Also, as this article was in the final stages of review, Ray Angelo (2021) made available on-line the flowering times of Concord plants, and their relative abundances based on observations and flowering times based on herbarium specimens (https://archive.org/details/calendar-flowering-times-concord-massachusetts). Detailed information the distribution and past collection of species is provided by Angelo (2020).

Bird arrivals—Thoreau also faithfully recorded the first arrivals of migratory birds each spring and sought favorable locations for these observations. William Brewster, founder of the American Ornithologists' Union and the Nuttall Ornithological Club, and curator of birds at the MCZ, recorded observations of migratory birds for the years 1886 and 1900-1919 and donated these to MCZ's library. Ludlow Griscom followed in Brewster's footsteps in many ways – he was president of the American Ornithologists' Union and the Nuttall Ornithological Club and was also curator of birds at the MCZ. He authored *The Birds of Concord* (Griscom 1949) and *Birds of Massachusetts* (Griscom and Snyder 1955) and his observations of migratory birds for the years 1930, 1931, and 1933-1954 are included here. Griscom's records are housed at the Peabody Essex Museum in Salem, Massachusetts. Rosita Corey, a schoolteacher in Concord and avid birder, provided us with her observations of migratory birds that span two distinct periods, 1956-1973 and 1988-2007. These observers produced numerous arrival records for 22 species, totaling 1,106 data points. There are also observations available for fewer years for some species, which are not included here.

Ice out—In addition to phenology observations, Thoreau also recorded the date of ice-out of Walden Pond (1845-1854, discontinuous). The timing of ice-out is a further metric of warming temperatures in Concord, and the impact of climate change on organisms and the environment. Ice-out is not explicitly defined in Thoreau's records, but a common definition, and the one used in contemporary observations, is when ice covers less than ten percent of the pond and does not return later in the winter or early spring. Our dataset includes ice-out records for 1995-2014 from the citizen science project, Journey North (journeynorth.org).

Phenology definitions—Most past observers (e.g., Thoreau, Hosmer) did not explicitly define the phenophases they observed, but we were able to infer their definitions based on material in their journals, notes, and data. Based on the historical materials, we defined the phenophases as below. See referenced literature for more information.

- Leaf out: the date that at least one fully unfolded leaf on at least three branches of an individual plant is observed (Polgar et al 2014)
- First flower: the date that a single open flower with petals extended such that it can be pollinated is observed
- First fruit: the date that ripe fruit is first observed (Miller et al 2021)
- Peak fruit: the date or estimated date of 'prime' fruiting (2 of 31 Peak fruit dates are estimated; see Miller et al 2021 Table 1). While this likely refers to the time when the majority of plants have ripe fruits or the majority of fruits on a plant are ripe, Thoreau did not record a precise definition for this phenophase.
- Last fruit: the date or estimated date that the last ripe fruit is observed (26 of 29 Last fruit dates are estimated; see Miller et al 2021 Table 1)
- Spore release: the date that the first spore capsule, or numerous capsules, are observed to be open
- First arrival: the date when the first individual of a migratory bird species is observed (Ellwood et al. 2010)
- Ice out: the date when ice covers <10% of Walden Pond, and does not return later in the season (Primack 2014; journeynorth.org)

Dates of observations— Dates of observations were recorded as the day of year such that during most years January 1 = 1, January 2 = 2, March 1 = 60, … and December 31 = 365. During leap years the calendar has 366 days and therefore February 29 = 60, March 1 = 61, etc. Thoreau observed fruiting phenology from 1850-1860 and compiled them in aggregate for that time period. We therefore present records of fruiting phenology during this time as decadal, as opposed to annual, to reflect his aggregated observations (Miller et al. 2021).

Other data—Our research based on these records has also benefited from the inclusion of other types of data sources such as photographs, herbarium specimens, and observations from gardeners and birdwatchers, (e.g., Primack et al. 2004, Primack and Miller-Rushing 2012, Everill et al. 2014, Willis et al. 2017, Gallinat et al. 2018, Miller et al. 2021, Miller-Rushing et al. 2021), though we do not include those data in this dataset. Most notably, the Concord Public Library has a large collection of dated photographs taken by the landscape photographer Henry W. Gleason (1855-1937), many of which are of wildflowers. Working with a combination of data types has helped to fill in spatial, taxonomic, and temporal gaps.

Total records—Since Thoreau's first observations in the 1850s, a total of 13,441 phenological records were documented in Concord and are presented here. These data include phenology and/or abundance data for 958 species. Additional information about the observations can be found in Thoreau's and Hosmer's notebooks, Eaton's book and our publications.

i.Taxonomy and systematics

Plant names have changed considerably since Thoreau's time, and have continued to change in the past several decades. In our data set, we have used the names given by Eaton (1974), as these are widely known and used in our region. Users of our data set may wish to consult other data sources for updated names.

CLASS III. DATA SET STATUS AND ACCESSIBILITY

A. Status

a. Latest update

August 2020

b. Latest archive date

August 2020

c. Metadata status

Metadata is complete.

d. Data verification

All data has been quality checked.

B. Accessibility

a. Storage location and medium

Publication as Supporting Information to this Data Paper in *Ecology*. Additionally available in Dryad at https://doi.org/10.5061/dryad.tx95x69z3 (Ellwood et al. 2021)

b. Contact person(s)

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Richard Primack, Department of Biology, Boston University

c. Copyright restrictions

None

d. Proprietary restrictions

Please cite this data paper when using its data in research, publication, or for educational purposes. We would also appreciate being informed by email or other means when these data are used for research or educational purposes, and when any publications are published that use this data.

CLASS IV. DATA STRUCTURAL DESCRIPTORS

A. Data set file

a. Identity

Concord_phenology_dataset.csv

b. Size

1088 rows + 160 columns (579 KB)

c. Format and storage mode

Comma-separated values (.csv)

d. Header information

See column descriptors in Section B, below.

e. Alphanumeric attributes

Mixed.

B. Variable information

Variable	Description	Levels	Example
Kingdom	Taxonomic kingdom	2	Plantae
Genus	Taxonomic genus	442	Acer
Species	Taxonomic species	688	rubrum
Ice	The single row of ice-out data	1	Ice
Habitat	Habitat where species was most commonly observed	5	Forest
Abundance (Hosmer)	Relative abundance of the species population	6	VeryCommon
Abundance (Eaton)	Relative abundance of the species population	10	VeryCommon
Abundance (Primack and Miller-Rushing)	Relative abundance of the species population	9	VeryCommon
Phenophase	Phenological event that was recorded (or indication of abundance only value)	9	LeafOut
Date of observation	Day of year that the observation was recorded, measured in days after 31 December of the previous year	366	116 "-#-", i.e., a number with a dash on each end, indicates a representative decadal value as opposed to an annual observation
(Missing value code)	No information available for a given species or year		NA

Class V. Supplemental descriptors

A. History of data set usage

Select publications that have used this data set

Cleland, E. E., J. M. Allen, T. M. Crimmins, J. A. Dunne, S. Pau, S. Travers, E. S. Zavaleta, and E. M. Wolkovich. 2012. Phenological tracking enables positive species responses to climate change. Ecology 93:1765-1771.

Davies, T. J., Wolkovich, E. M., Kraft, N. J., Salamin, N., Allen, J. M., Ault, T. R., ... & Travers, S. E. (2013). Phylogenetic conservatism in plant phenology. Journal of ecology, 101(6), 1520-1530.

Davis, C.C., Willis, C.G., Connolly, B., Kelly, C. and Ellison, A.M., 2015. Herbarium records are reliable sources of phenological change driven by climate and provide novel insights into species' phenological cueing mechanisms. American Journal of Botany, 102(10), pp.1599-1609.

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Heberling, J. M., C. McDonough MacKenzie, J. D. Fridley, S. Kalisz, and R. B. Primack. 2019. Phenological mismatch with trees reduces wildflower carbon budgets. Ecology Letters 22:616-623.

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Miller-Rushing, A. J., and R. B. Primack. 2008. Global warming and flowering times in Thoreau's Concord: a community perspective. Ecology 89:332-341.

Miller-Rushing, A. J., D. W. Inouye, and R. B. Primack. 2008. How well do first flowering dates measure plant responses to climate change? The effects of population size and sampling frequency. Journal of Ecology 96:1289-1296.

Miller-Rushing, A. J., R. B. Primack, D. Primack, and S. Mukunda. 2006. Photographs and herbarium specimens as tools to document phenological changes in response to global warming. American Journal of Botany 93:1667-1674.

Pearse, W. D., C. C. Davis, D. W. Inouye, R. B. Primack, and T. J. Davies. 2017. A statistical estimator for determining the limits of contemporary and historic phenology. Nature Ecology and Evolution 1:1876-1882.

Polgar, C. A., and R. B. Primack. 2011. Leaf-out phenology of temperate woody plants: from trees to ecosystems. New Phytologist 191:926-941.
Polgar, C. A., R. B. Primack, J. S. Dukes, C. Schaaf, Z. Wang, and S. S. Hoeppner. 2014. Temperature effects on tree leaf out: Fieldwork, remote sensing, and warming experiments. International Journal of Biometeorology 58:1251-1257.
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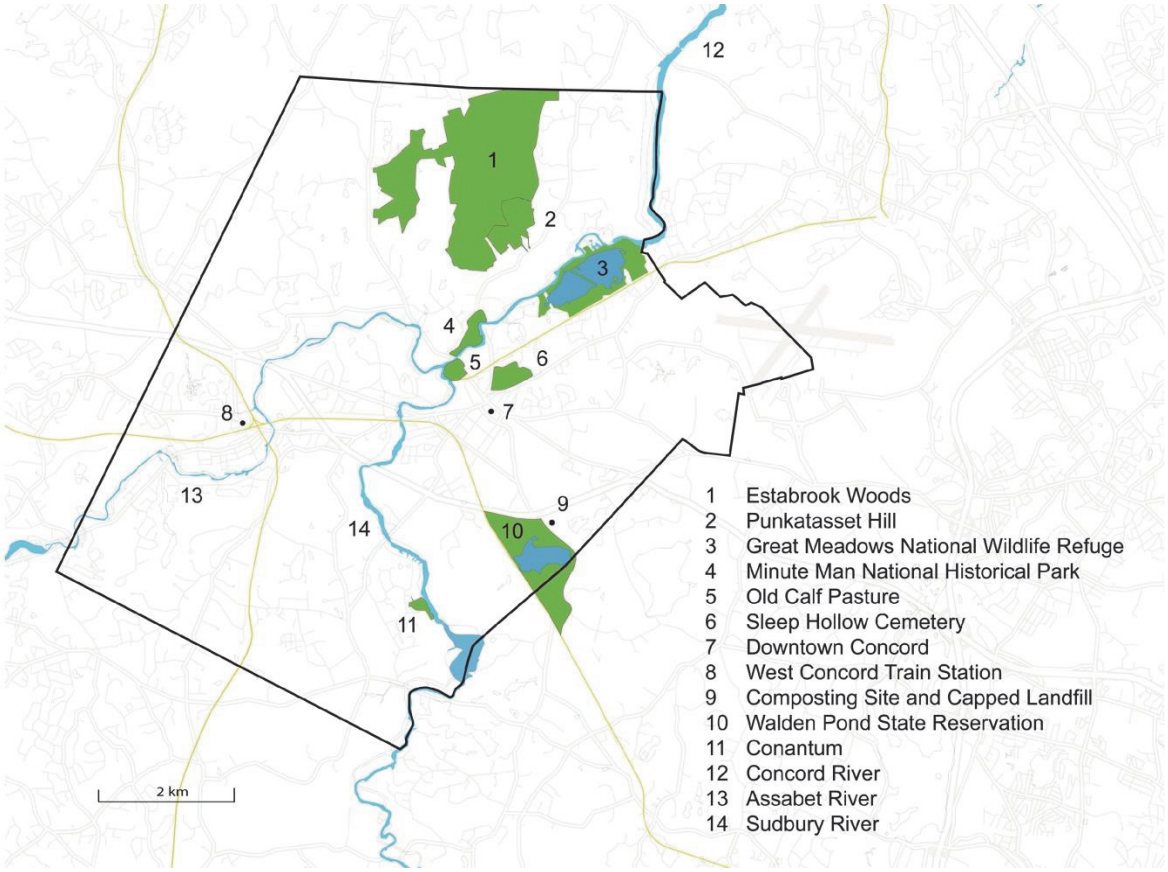

Figure 1. Map of Concord, Massachusetts, United States showing key localities mentioned by Thoreau in his journals (as compiled by Herbert W. Gleason in 1906, and reproduced in Eaton's flora of Concord (1974)) and revisited by subsequent naturalists and contemporary researchers.

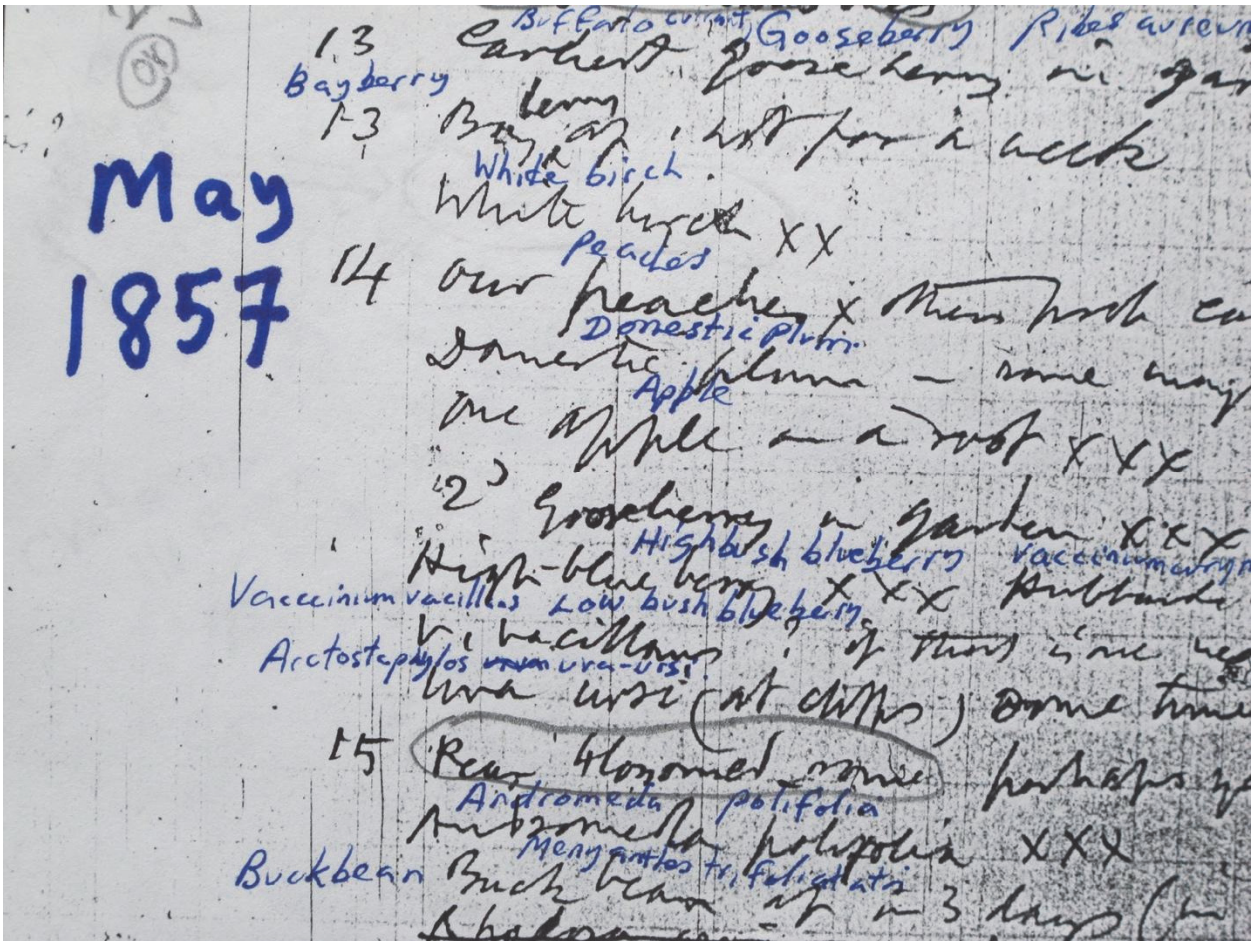

Figure 2. image of a table of phenology observations written by Thoreau (black ink) and his writing interpreted by Primack (blue ink).

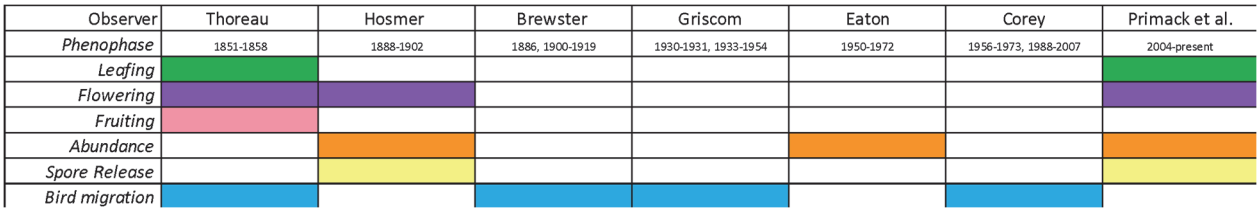

Figure 3. From 1851 to the present, a variety of phenophases were recorded in Concord by several different researchers. These time series provide an unprecedented and invaluable look at phenology in a single location.

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