The Wilson Journal of Ornithology

ISSN: 1559-4491 (Print) 1938-5447 (Online) Journal homepage: www.tandfonline.com/journals/uwjo20

Integrating historical records and citizen science data to understand bird responses to climate change in Concord, Massachusetts: Thoreau to eBird

Amanda S. Gallinat, Abraham J. Miller-Rushing, Trevor L. Lloyd-Evans, Elizabeth R. Ellwood, Corey T. Callaghan & Richard B. Primack

THE WILSON JOURNAL OF ORNITHOLOGY
https://doi.org/10.1080/15594491.2025.2583566

Integrating historical records and citizen science data to understand bird responses to climate change in Concord, Massachusetts: Thoreau to eBird

Amanda S. Gallinat[a], Abraham J. Miller-Rushing[b], Trevor L. Lloyd-Evans[c], Elizabeth R. Ellwood[d], Corey T. Callaghan[e], and Richard B. Primack[f]

[a]Department of Environmental Studies, Colby College, Waterville, ME, USA; [b]US National Park Service, Acadia National Park, Bar Harbor, ME, USA; [c]Manomet Conservation Sciences, Manomet, MA, USA; [d]Florida Museum of Natural History, iDigBio, University of Florida, Gainesville, FL, USA; [e]Department of Wildlife Ecology and Conservation, Fort Lauderdale Research and Education Center, University of Florida, Davie, FL, USA; [f]Department of Biology, Boston University, Boston, MA, USA

ABSTRACT

Extending historical records into the present offers a powerful opportunity to examine how bird phenology is shifting in response to warming temperatures and whether those responses are consistent over time. In Concord, Massachusetts (USA), a uniquely rich record of bird migration phenology dates back to the mid-19th century, beginning with observations made by the American philosopher Henry David Thoreau (1851–1854), and continuing with well-known ornithologists William Brewster (-1886–1919) and Ludlow Griscom (1930–1954), and schoolteacher Rosita Corey (1956–2007). A previous analysis of these records had shown that on average migratory birds were not changing their arrival times over this 156 year period, contrasting with rapid changes in plant phenology. To extend these bird arrival records and assess recent changes, we combined historical observations of first arrival dates for 18 bird species with observations submitted to the online platform eBird between 2013–2024 in Concord, Massachusetts. Using a subset of eBird data to approximate historical sampling effort, we found that, on average, birds are arriving about 7 days earlier now than in the past, reflecting a stronger response to warming temperatures and shifts in the phenology of more species than observed in our previous study. The rate of change in bird phenology appears to be catching up to changes in plant leaf-out and flowering phenology observed in Concord (~10–14 days earlier now than in Thoreau's time). This study shows that the rate of phenological response to climate change can vary over time and demonstrates methods for combining historical data with modern citizen science data to assess these changes and their potential ecological impacts.

KEYWORDS
Big data; data synthesis; global warming; migration; phenology; volunteer

PALABRAS CLAVE
Calentamiento global; fenología; síntesis de datos; migración; voluntarios

Address correspondence to Amanda S. Gallinat. E-mail: amandagallinat@gmail.com
Editor-in-Chief: Ernesto Ruelas Inzunza
Supplemental data for this article can be accessed online at https://doi.org/10.1080/15594491.2025.2583566.

Integrando registros históricos y datos de ciencia ciudadana para entender la respuesta de las aves al cambio climático en Concord, Massachusetts: de Thoreau a eBird

RESUMEN
Extender los registros históricos hasta el presente ofrece una oportunidad poderosa para examinar cómo la fenología de las aves está cambiando en respuesta a temperaturas más cálidas y si esas respuestas son consistentes a lo largo del tiempo. En Concord, Massachusetts (EE.UU.), existe un récord especialmente rico de datos de fenología de la migración que inició desde mediados del siglo XIX, comenzando con las observaciones del filósofo norteamericano Henry David Thoreau (1851–1854), continuando con los bien conocidos ornitólogos William Brewster (1886–1919) y Ludlow Griscom (1930–1954), y la maestra escolar Rosita Corey (1956–2007). Un análisis previo de estos registros mostró que en promedio las aves migratorias no estaban cambiando sus fechas de arribo a lo largo de este periodo de 156 años, en contraste con los rápidos cambios en la fenología de las plantas. Para extender estos registros de arribos de aves, combinamos observaciones históricas para 18 especies de aves con observaciones enviadas a la plataforma en línea eBird entre 2013–2024 en Concord, Massachusetts. Usando un subconjunto de los datos de eBird para aproximar el esfuerzo histórico de muestreo, encontramos que, en promedio, las aves están llegando unos 7 días más temprano que en el pasado, reflejando una respuesta más fuerte a temperaturas más cálidas y cambios en la fenología de más especies que lo observado en nuestro estudio previo. La tasa de cambio en la fenología de las aves parece estar alineándose a cambios en la fecha en que emergen las hojas de los árboles y la fenología de la floración en Concord (~10–14 días más temprano que en los tiempos de Thoreau). Este estudio muestra que la tasa de respuesta fenológica al cambio climático puede variar a lo largo del tiempo y demuestra los métodos para combinar datos históricos con ciencia ciudadana moderna para determinar dichos cambios y sus impactos ecológicos potenciales.

One of the most effective ways to investigate long-term effects of climate change on plant and animal species is the use of historical records to determine how species are responding to varied temperatures over long time periods (Primack and Miller-Rushing 2012; Vitasse et al. 2022). Every year, an increased number of these records are discovered, analyzed, and made available online, providing insights into long-term changes for a wide variety of species (Willis et al. 2017; Meineke et al. 2018; Primack RB, Miller TK, et al. 2023). Historical records can be made more valuable when extended into the present-day with modern observations to produce longer time series (Tingley and Beissinger 2009; Primack and Miller-Rushing 2012; Miller et al. 2019). Long-term phenology data can then allow researchers to test if recent responses to climate change differ from those in the past, whether because the responses are nonlinear, because of interactions between factors that can influence phenology (e.g., temperature, precipitation, land use, nutrient pollution, ecological interactions), or because of evolutionary responses (Moritz et al. 2008; Tingley et al. 2009; Jochner et al. 2016; Wolkovich et al. 2017).

To combine new data with older data there are two main options. First, researchers can use information from old journals and protocols to design new studies that replicate older methods, making it relatively easy to integrate old and new data (Tingley and Beissinger 2009; Ellwood et al. 2013, 2022; Fidino et al. 2022). Alternatively, researchers could use existing present-day observations to extend historical datasets (Fuccillo Battle et al. 2022; Primack RB, Miller TK, et al. 2023). Datasets collected by volunteers through platforms such as the USA National Phenology Network's Nature's Notebook (Denny et al. 2014) and Cornell Lab of Ornithology's eBird (Sullivan et al. 2009) contain billions of phenology observations. These records are increasingly used to advance phenological research, for instance by estimating changes in migration phenology across species ranges and migration pathways (Zaifman et al. 2017; Supp et al. 2021). On their own, these citizen science datasets represent time-series on the order of just one or two decades, limiting the ability to advance understanding of how phenology is changing over longer time periods.

Because of their broad geographic and taxonomic extents, large citizen science projects like Nature's Notebook and eBird often overlap in location and species with local historical datasets, creating opportunities to combine historical and new observations to generate ongoing long-term datasets. Many protected areas and research sites, in particular, have historical datasets and currently use the methodologies of Nature's Notebook, eBird, and other similar programs to monitor phenology (Crimmins et al. 2022). Techniques to combine historical and new data could improve our understanding of responses to climate change in these key locations around the world (Tingley and Beissinger 2009; Primack and Miller-Rushing 2012; Miller et al. 2019).

Differences in the number of observers, sampling days, and area sampled represented in old and new data, however, can make it difficult to combine data (Miller-Rushing AJ, Primack RB, et al. 2008; Primack RB, Gallinat AS, et al. 2023). The difference in sampling effort is particularly large when the new data are from broad-scale citizen science datasets, which engage many observers, contrasting with historical datasets which usually include observations from one or a few observers. Researchers combining historical data with modern citizen science data must account for differences in effort.

In this study, we compared recent eBird observations to historical migratory bird arrival data from Concord, Massachusetts. Concord has one of the oldest and most detailed phenological records in North America, started by the famous environmental philosopher, Henry David Thoreau and continued by later observers. The town also has a large modern community of eBird observers. A previous study (Ellwood et al. 2010) analyzed observations from 1851–2007 and found that, on average, birds did not change their arrival times over the study period, despite significant warming in the region over that time. The lack of change in arrival dates suggested the possibility of mismatches with leaf-out and flowering phenology of plants, which are important for habitat and food resources during breeding seasons. Plant phenology is changing relatively rapidly in Concord: on average leaf-out is occurring 14 days earlier now than in Thoreau's time, and flowering is occurring 10 days earlier (Ellwood et al. 2013; Polgar et al. 2014). With new data from eBird, we investigate whether this lack of change in bird phenology has continued since the previous study or if bird arrival dates are beginning to shift as temperatures continue to warm in recent years.

Methods

Concord, Massachusetts, USA

Concord is a town located 30 km northwest of Boston covering a 64 km^2 total area, with protected areas covering approximately 40% of that area (Ellwood et al. 2010, 2022). The climate is temperate, and the landscape has rivers, lakes and other wetlands, forests, and fields. During Thoreau's time (1850s), Concord was primarily agricultural with forests covering 10% of the area; now, Concord is mainly suburban with forests covering around 50% of the landscape (Primack et al. 2009). Correspondingly, the area of fields and grasslands has substantially declined from 50% of Concord's landscape in the 1850s to around 4% now (Primack et al. 2009; Ellwood et al. 2010). At the same time as these changes in Concord, land use has changed dramatically along the entire east coast of North America and on the non-breeding grounds of Neotropical migrants. These land use changes have resulted in a substantial loss of habitat that has impacted the abundance of bird species. We have addressed this as best we could in this study by investigating changes in the phenology of abundant species, none of which are grassland species that have experienced large habitat losses in Concord.

Temperature records

Following Ellwood et al. (2010), we used temperature records extending back to 1851 from Blue Hill Meteorological Observatory in East Milton, Massachusetts, located 33 km southeast of Concord. This allowed us to maximize the historical coverage, as temperatures at Blue Hill are strongly correlated with those in Concord (Miller-Rushing and Primack 2008). Average monthly air temperature data for January, February, March, and April were available from 1851–2024. These local average temperatures from Blue Hill are also highly correlated with regional temperature along the east coast of North America as far south as Wilmington, North Carolina (Miller-Rushing AJ, Lloyd-Evans TL, et al. 2008).

Bird arrival records

Records of spring first arrival dates of migratory birds in Concord from 1851–2007 are described in detail by Ellwood et al. (2010) and more recently by Ellwood et al. (2022); all historical observations are made available in Ellwood et al. (2022). In Ellwood et al. (2010), species were included if they had at least 22 years of first arrival dates, resulting in the inclusion of 22 migratory passerine bird species. This collection of records includes five separate sets of observations recorded by Henry David Thoreau (1851–1854), well-known ornithologists William Brewster (1886 and 1900–1919) and Ludlow Griscom (1930–1931 and 1933–1954), and schoolteacher Rosita Corey (1956–1973 and 1988–2007). While Thoreau's and Corey's records reflect individual observers, who perhaps communicated with fellow observers, Brewster's and Griscom's records likely represent a small community of observers in Concord (Griscom 2013, 2014). For the most part, the location information accompanying these observations indicated they were made in Concord but did not include more specific details about exactly where within the town each observation was made. Over the past few years, we searched for individuals in Concord and surrounding towns who might be making observations of the first arrival dates of migratory birds in a way that is similar to Thoreau, Brewster, Griscom, and Corey, but we were unable to locate such individuals.

Modern day records from eBird

To compare the historical records with more recent observations, we accessed observations collected by volunteers through eBird (http://www.ebird.org). Volunteer observations come primarily from experienced birders (Rosenblatt et al. 2022) and are thoroughly vetted for quality before being included in the eBird database (Sullivan et al. 2009, 2014; Gilfedder et al. 2019). We downloaded all observations from within the geographic bounds of Concord, Massachusetts, for the years 2013–2024 for the 22 species in Ellwood et al. (2010). We used both complete and incomplete eBird checklists to approximate historical reporting practices, focusing on first seasonal detections that depend only on presence records.

To omit extremely early observations, such as rare individuals that may have over-wintered and do not represent the migratory behavior of the species, we excluded all observations before 15 March (and for Eastern Phoebes *Sayornis phoebe*, before 1 March, based on their relatively early first arrival dates). There were few such observations (146/ 108,738 observations, less than 0.2%, which involved only seven species). In the historical datasets, there were no such extremely early individuals recorded. We then limited our focal species to those common species with at least 50 observations recorded in each year in order to avoid sampling bias associated with rare and declining species (Miller-Rushing AJ, Lloyd-Evans TL, et al. 2008). This resulted in the removal of Bank Swallows *(Riparia riparia)*, Brown Thrashers (*Toxostoma rufum)*, Bobolinks *(Dolichonyx oryzivorus)*, and Indigo Buntings *(Passerina cyanea)*.

Finally, we removed any records occurring past 15 June (the end of the spring season), resulting in a total of 58,977 observations, submitted in 11,479 checklists, from 1,323 observers, for 18 species (Table 1). These observations are distributed throughout Concord and include the most heavily and consistently birded sites in the area, such as Great Meadows National Wildlife Refuge, Walden Pond, and Concord Town Center (Fig. 1). Although we have information on the locations of the modern observations in Concord, we lack this information for the historical observations and, therefore, were unable to make detailed spatiotemporal comparisons between modern and historical observers.

Increased effort resulting from a larger number of observers in the eBird data, compared to single-observer and small-group historical data, required careful consideration of how effort might impact our detection of first arrival dates. We first confirmed that increasing the number of observers leads to earlier detection in the Concord eBird data (Supplemental Fig. S1). This relationship highlights the necessity to consider sampling effort to estimate arrival dates from the eBird records that are most comparable to the effort reflected in the historical data. The observations of Thoreau, Brewster, Griscom, and Corey were made deliberately to detect the first arrival dates of migratory bird species. However, an inspection of eBird records and communication with local birders made it clear that frequent eBird observers were not solely or deliberately targeting first arrival dates; rather, observers were going out singly and in groups throughout the spring and most were recording every bird

Table 1. Comparison of first arrival dates across historical observers and eBird observers, and shifts in first arrival dates with temperature over the full study period (1851–2024) in Concord, MA for 18 migratory bird species, and all species combined.

	Average first arrival dates[a]			Shifts over time[b]					Shifts with temperature[c]			
Species	T,CE	CL	eBird	df	*F*	T,CE—CL (within historical) *P*-value[d]	T,CE—eBird (oldest vs current) *P*-value	CL—eBird (recent historical vs. current) *P*-value	Temperature months	Slope	R^2	*P*-value
Eastern Wood-Pewee (*Contopus virens*)	22-May	23-May	15-May	52	8.47	0.804	0.001	0.008	Mar–Apr	−1.560	0.120	0.007
Eastern Phoebe (*Sayornis phoebe*)	2-Apr	30-Mar	24-Mar	82	3.31	0.362	0.036	0.370	Feb–Mar	− 0.750	0.010	0.241
Eastern Kingbird (*Tyrannus tyrannus*)	7-May	5-May	2-May	76	8.52	0.095	<0.001	0.259	Mar–Apr	−0.630	0.020	0.091
Warbling Vireo (*Vireo gilvus*)	13-May	4-May	2-May	56	17.76	<0.001	<0.001	0.733	Mar–Apr	−2.340	0.140	0.002
Red-eyed Vireo (*Vireo olivaceus*)	14-May	15-May	10-May	42	5.13	0.579	0.012	0.096	Mar–Apr	−0.280	−0.020	0.550
Barn Swallow (*Hirundo rustica*)	22-Apr	1-May	12-Apr	65	21.35	<0.001	<0.001	<0.001	Feb–Mar	−0.860	0.010	0.183
Wood Thrush (*Hylocichla mustelina*)	7-May	12-May	4-May	46	6.51	0.026	0.105	0.002	Mar–Apr	0.730	0.020	0.181
Gray Catbird (*Dumetella carolinensis*)	6-May	4-May	23-Apr	31	5.34	0.069	0.009	0.107	Mar–Apr	−2.550	0.040	0.133
Yellow Warbler (*Setophaga petechia*)	6-May	2-May	28-Apr	86	25.73	<0.001	<0.001	0.004	Mar–Apr	−1.340	0.160	<0.001
Yellow-rumped Warbler (*Setophaga coronata*)	24-Apr	18-Apr	11-Apr	37	12.56	0.230	<0.001	0.370	Feb–Mar	− 2.740	0.240	0.001
Pine Warbler (*Setophaga pinus*)	16-Apr	16-Apr	1-Apr	57	8.81	0.968	<0.001	0.010	Feb–Mar	−2.400	0.140	0.002
Black-and-white Warbler (*Mniotilta varia*)	1-May	3-May	26-Apr	64	7.69	0.127	0.004	0.002	Feb–Mar	−0.690	0.050	0.029
Ovenbird (*Seiurus aurocapilla*)	6-May	14-May	29-Apr	65	27.06	0.001	<0.001	<0.001	Mar–Apr	−1.010	0.090	0.007
Common Yellowthroat (*Geothlypis trichas*)	10-May	NA	1-May	45	21.05	–	<0.001	–	Mar–Apr	−1.940	0.160	0.003

(*Continued*)

Table 1. (Continued).

	Average first arrival dates[a]			Shifts over time[b]					Shifts with temperature[c]			
Species	T,CE	CL	eBird	df	*F*	T,CE—CL (within historical) *P*-value[d]	T,CE—eBird (oldest vs current) *P*-value	CL—eBird (recent historical vs. current) *P*-value	Temperature months	Slope	R^2	*P*-value
Chipping Sparrow (*Spizella passerina*)	21-Apr	18-Apr	5-Apr	59	17.76	0.147	<0.001	<0.001	Feb–Mar	−2.510	0.170	0.001
Scarlet Tanager (*Piranga olivacea*)	12-May	13-May	5-May	55	10.52	0.759	<0.001	0.010	Mar–Apr	−1.370	0.110	0.007
Rose-breasted Grosbeak (*Pheucticus ludovicianus*)	9-May	6-May	30-Apr	51	14.45	0.265	<0.001	0.007	Mar–Apr	−2.160	0.230	<0.001
Baltimore Oriole (*Icterus galbula*)	8-May	6-May	1-May	72	29.16	0.027	<0.001	<0.001	Mar–Apr	−1.000	0.120	0.001
All species	4-May	2-May	25-Apr	91	39.40	0.096	<0.001	<0.001	Mar–Apr	−1.4440	0.251	<0.001

[a]Time periods compared to assess shifts over time include Thoreau (T) through Corey early (CE) from 1851–1973, Corey late (CL) from 1988–2007, and eBird from 2013–2024. The eBird data represent the earliest first day of observation across just the top five observers in each year.
[b]P-values are the result of analysis of variance (ANOVA) and Tukey HSD tests and reflect statistical differences in first arrival dates among sampling time periods for each species.
[c]Shifts with temperature reflect linear regression results for 18 species of migratory birds' annual first arrival dates with mean spring temperatures, for individual species and all species combined. Temperatures were averaged from the 2 months prior to the species' mean first arrival date across all years.
[d]Statistically significant relationships ($P < 0.0028$) are shaded.

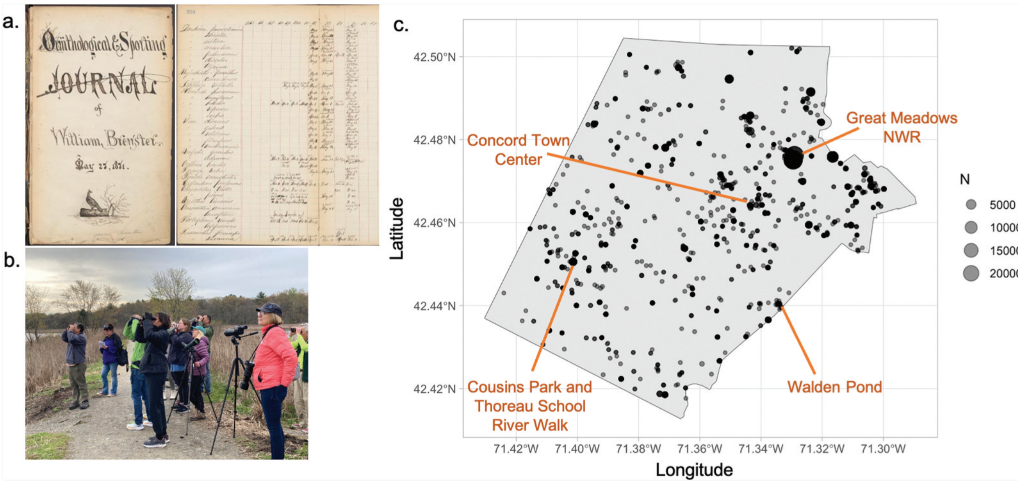

Figure 1. Methods and locations of bird observations in Concord, Massachusetts. (a) The journal of William Brewster, 1871–1919, featuring first bird arrival dates for Concord from 1886–1919 used in this study; images courtesy of the Biodiversity heritage library (www.biodiversitylibrary.org.). (b) a group of eBird observers at Great Meadows National Wildlife Refuge (NWR) in 2023. (c) Locations and counts of eBird observations across Concord from 2013–2024 ($n = 58{,}977$). Observation counts reflect single bird observations of the eighteen target species, during the spring migration season (see Methods section).

they detected and submitting the list of observations to eBird each day that they made observations.

Considering this difference in methodology, we used the earliest detection date for each of 18 bird species for each year using the five most active eBird observers in a particular year, that is, the five observers with the most checklists in a particular year. This subsampling of the eBird data reasonably mirrored the sampling effort of historical observers. For example, the historical observations and the five most active eBirders in any 1 year involved small groups of people detecting first arrivals in Concord. In contrast, using all eBird observers would not be comparable to the historical observers because the sampling intensity in any 1 year would be far greater than in the historical data set in terms of both numbers of people looking for birds and the amount of area covered. We compare three different methods for subsampling eBird observations in the Supplemental Materials (Tables S1–S2 and Figs. S2–S6).

We also considered other methods to calculate and estimate first arrival dates, but most did not adequately address changes in sampling effort between historical observers and eBird data. For example, we used a smoothing/estimating tool that uses presence-only data to calculate when the first 5% of birds had been observed for each species in each year (Belitz et al. 2020) and found that it provides strongly correlated values ($r = 0.89$, $df = 154$, $P < 0.001$) to the first observation dates by the top five observers, but fails to address our concern of combining data sets with differences in effort. For the remainder of this article, we refer to the earliest detection of a bird species by the top five eBird observers in any year as the eBird data.

Statistical analyses

All statistical analyses and figures were performed using R version 4.2.1 (R Core Team 2021). To assess changes in migratory bird arrivals over time and across observers, we compared eBird records to the historical first arrival dates. We divided Corey's observations into "Corey early" (1956–1973) and "Corey late" (1988–2007). We chose this separation because temperatures began warming considerably faster after 1980 compared to prior to 1980 (IPCC 2007; Supplemental Fig. S7), and because there was a 15 year gap between the two time periods. This division of Corey's observations also follows the methods used by Ellwood et al. (2010). Thus, when we compared all observers separately, we compared six "observers" or datasets: Thoreau, Brewster, Griscom, Corey early, Corey late, and eBird.

To compare sampling methods and effort among these observers, we first compared the number of first observation dates and number of species observed in each year. Observers or datasets missing first arrival dates for some species in some years were presumed to reflect lower effort. Second, we tested each of the six observers or datasets for tendencies to record first arrival dates more on weekends compared to weekdays (using chi-squared analysis), a known bias in some citizen science data (Courter et al. 2013) that could reflect the frequency of observation and influence the timing of detection.

Among the historical observers, not all species were observed in all years; thus, for the community-level analysis, we first transformed all species-level data points to reflect anomalies relative to the mean arrival date across all species and years, as described in Ellwood et al. (2010). This involved subtracting the mean first arrival date for each species from the mean first arrival date across all species (with bird data combined from 1851–2024), then adding the resulting species-level anomaly value to each annual first arrival date for the species. This transformation resulted in later arrival dates for earlier-arriving species and earlier arrival dates for later-arriving species, and removed the community-level statistical impact of a single species being absent in any particular year. We used the transformed dates in all further analysis involving the average values of all species combined. An extended rationale and explanation for this approach is given in Ellwood et al. (2010).

To test apparent changes in arrival dates over time, we divided the data into three groups reflecting three broader periods of environmental change: (1) Thoreau, Brewster, Griscom, and Corey early (1851–1973), (2) Corey late (1988–2007), and (3) eBird (2013–2024). For the community-level arrival dates as well as for each species individually, we used analysis of variance (ANOVA) to determine if the three groups were significantly different from one another.

To determine if and how arrival dates have shifted with temperature, in a way comparable to Ellwood et al. (2010), we fit a linear regression with mean spring (March–April) temperature as the predictor variable and community-level annual mean first arrival dates as the response variable, for the eBird dataset. To support this analysis, we also used a linear mixed effect model to estimate the effect of mean spring (March–April) temperature on annual first arrival dates with species as a random effect, using the "lmer" function from the *lme4* package (Bates et al. 2015) and "ANOVA" from the *car* package (Fox and Weisberg 2011). We then conducted linear regression analyses for each individual species, using the mean temperature in the 2 months prior to each species' average arrival date to incorporate the temperatures most likely to impact their migration (Table 1). Given the inflated likelihood of Type 1 error, we applied Bonferroni corrections to all species level analyses; the baseline of $P < 0.05$ adjusted for $n = 18$ species resulted in a threshold of $P < 0.0028$ for statistical significance.

Results

Comparing historical and eBird data for completeness and bias

The six sets of observations of first arrival dates in Concord (Thoreau, Brewster, Griscom, Corey early, Corey late, and the eBird-derived dataset) varied in the mean number of the 18 bird species seen per year. As expected, the eBird data were the most complete with individuals in the top five observers of each year recording an average of 17 of the 18 species. In contrast, there were only seven species per year seen in the Corey late dataset and nine in the Brewster dataset. The lower number in the Corey late dataset reflects the fact that she sometimes visited other sites in Massachusetts to record first arrival dates and did not record first arrivals in Concord if she had seen them elsewhere. Thoreau, Griscom, and Corey early recorded intermediate numbers of species on average per year (11, 10, and 13 species, respectively).

Across the Thoreau and Brewster datasets, there was a tendency for observers to monitor fairly equally on weekdays (Monday–Friday) and weekend days (Saturday and Sunday) ($\chi^2 = 1.884$, df = 1, $P = 0.170$, and $\chi^2 = 0.558$, df = 1, $P = 0.455$, respectively), while the Griscom dataset showed a slight tendency toward greater sampling on weekdays ($\chi^2 = 5.248$, df = 1, $P = 0.022$). In contrast, 65% of Corey's early observations (1956–1973, when she was working full-time) and 36% of her late observations were made on the weekends, significantly different from the expected value of 29% (2/7) and expected distribution ($\chi^2 = 125.339$, df = 1, $P < 0.001$; $\chi^2 = 4.126$, df = 1, $P = 0.042$, respectively). The eBird dataset was also biased toward weekends, with 42% of observations from the top five observers in each year collected during the weekend ($\chi^2 = 18.150$, df = 1, $P < 0.001$).

Changes over time

Using all six data sets, we found trends toward significantly earlier community-level arrival dates over time (Fig. 2). The average first migration date for Thoreau through Corey early was 4 May, and for Corey late was 2 May, while the earliest first detection using the eBird data showed an average first arrival date of 25 April, more than 1 week earlier than the historic average (ANOVA; $F = 39.40$, df = 91, $P < 0.001$, Table 1).

Using the full range of data from Thoreau's data to the eBird data, 15 species are arriving significantly earlier (Table 1)—all but Eastern Phoebes, Red-eyed Vireos (*Vireo olivaceus*), and Gray Catbirds (*Dumetella carolinensis*). These trends are driven primarily by earlier first arrival dates in the eBird records.

Changes with temperature

Mean spring (March and April) temperatures in Concord during the time period of this study (1851–2024) have warmed at an average rate of 0.02°C per year ($r^2 = 0.23$, df = 91, $P < 0.001$; Supplemental Fig. S7). The combined historical observations of annual first arrival dates from 1851–2007 (before the eBird extension) have

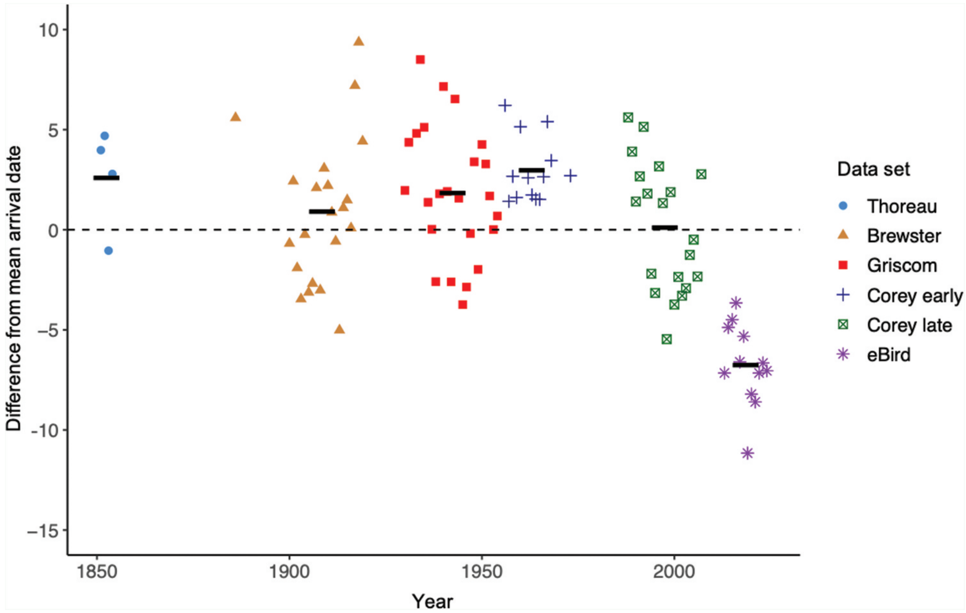

Figure 2. Differences in the average annual first arrival dates across five historical data sets and eBird data, for 18 migratory bird species. Arrival dates are expressed as anomaly values compared to the historical average across all species in all years (2 May), and bars represents the mean value for each set of observations across years.

a significant negative relationship with mean spring temperature; for every 1°C increase in temperature, arrivals occur, on average, 0.77 days earlier (as reported in Ellwood et al. 2010). When we include the eBird data using community-level first arrival dates, this relationship holds, with first arrival dates occurring 1.4 days earlier for each 1°C increase in temperature (slope = − 1.44 days/°C, $r^2 = 0.251$, $P < 0.001$; Figure 3). A linear mixed effect model examining the response of species-level first arrival dates to temperature with species as a random effect showed a similar result (slope = − 1.71 days/°C, $P < 0.001$). This sensitivity to temperature is twice as strong as the relationship detected using historical data alone.

Looking at responsiveness to temperature for the 18 species individually, conservatively, seven species are shifting their first arrivals significantly earlier with warming temperatures, with these shifts varying from 1 to 2.7 days earlier for each 1°C increase (Table 1). At a relaxed significance of $P < 0.05$, twelve species shifted earlier. Species with the strongest responses to temperature include Yellow-rumped Warblers (*Setophaga coronata*), Warbling Vireos (*Vireo gilvus*), and Chipping Sparrows (*Spizella passerina*). None of the species arrived later with warming temperatures.

Discussion

Changes over time

Combining historical and modern data sets allows us to update our understanding of changes in bird migrations in Concord, Massachusetts. The historical observations of first

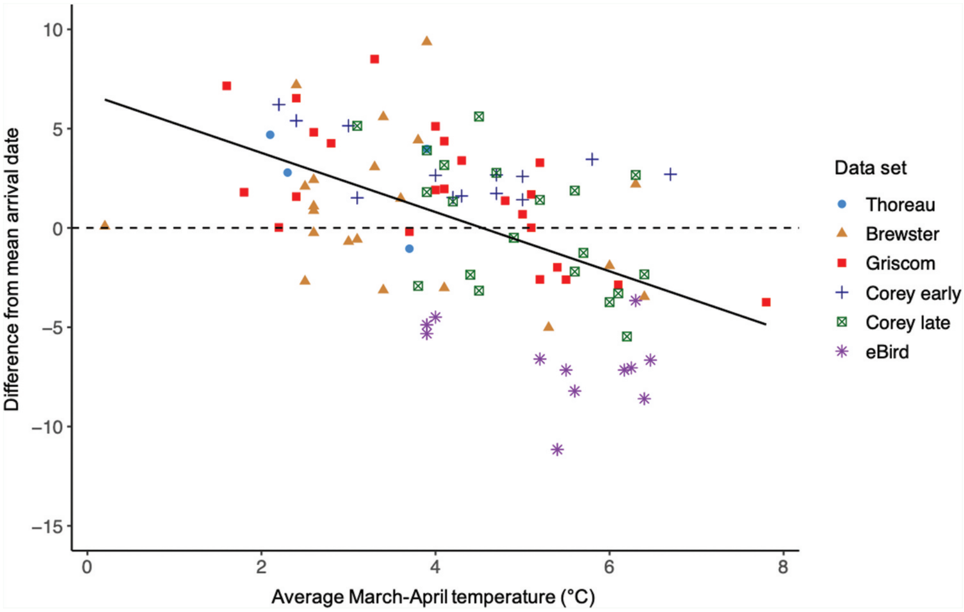

Figure 3. The relationship between mean spring (March–April) temperature and average annual first arrival dates across 18 migratory bird species. Arrival dates are expressed as anomaly values compared to the historical average across all species in all years (2 May). Arrival dates are advancing significantly with mean spring temperatures at a rate of −1.4 days/°C ($R^2 = 0.25$, $P < 0.001$).

arrival dates of birds in Concord from 1851–2007 demonstrated that, on average, bird arrival times were not changing over time. This finding created concerns about the potential for ecological mismatches, because trees in Concord are leafing out 2 weeks earlier than in Thoreau's time, and wildflowers are flowering about 1 week earlier (Miller-Rushing and Primack 2008; Polgar et al. 2014). These prior results suggested that birds might become separated in time from their typical insect food resources, fail to adequately feed themselves and their young, and face population decline (Renner and Zohner 2018; Youngflesh et al. 2023).

In the new results reported here, we see significant shifts in arrival times between the historical records and more recent data collected by eBird observers. This compels us to reevaluate the earlier findings reported by Ellwood et al. (2010), and suggests that on average bird phenology is now changing over time at approximately the same rate as wildflowers, though at a somewhat slower rate than trees.

The historical data alone show two out of 18 species arriving earlier—Warbling Vireos and Yellow Warblers (*Setophaga petechia*)—and two species arriving later—Barn Swallows (*Hirundo rustica*) and Ovenbirds (*Seiurus aurocapilla*). We note that in Ellwood et al. (2010), which used a non-adjusted threshold of $P < 0.05$ for these same data, three species shifted earlier and four shifted later. When adding more recent data, we find that, conservatively, 6 of 18 species, including Barn Swallows and Ovenbirds, are arriving earlier in 2013–2024 compared to the next most recent data set from Rosita Corey in 1988–2007. Overall, individual bird species are showing stronger changes toward earlier arrivals than historical data alone had indicated.

Changes with temperature

In addition, we now see stronger effects of temperature on bird arrival times. The historical records alone show that birds arrive in Concord, on average, 0.77 days earlier with every 1°C increase in temperature (Ellwood et al. 2010). This previous study suggested that first bird arrivals were less sensitive to temperature than flowering (3.1 days/°C; Miller-Rushing and Primack 2008) and leafing out (5.0 days/°C; Polgar et al. 2014) in Concord, and butterfly flight times (5.5 days/°C; Polgar et al. 2013) in Massachusetts more broadly. Our new analysis with eBird data now shows first bird arrival dates occurring 1.4 days earlier for each 1°C increase in temperature. This new value shows bird arrival times as being about twice as sensitive to temperature as had been indicated by the previous study of historical data alone (Ellwood et al. 2010), but still less sensitive to temperature than to the timing of wildflower flowering, tree leaf out, and insect first flight.

The species showing significantly earlier arrival times with increasing temperature were consistent when analyzing historical data alone (Ellwood et al. 2010) as well as when considering more recent observations. Warbling Vireos, Yellow Warblers, Yellow-rumped Warblers, Chipping Sparrows, Baltimore Orioles (*Icterus galbula*), and Rose-breasted Grosbeaks (*Pheucticus ludovicianus*) are all arriving earlier in warmer years.

It is worth noting that among the species significantly advancing their arrivals with warming temperatures, the three most sensitive species—Yellow-rumped Warblers, Pine Warblers (*Setophaga pinus*), and Chipping Sparrows, with slopes ranging from −2.4 to −2.7 days/°C, migrate shorter distances between their non-breeding and breeding grounds compared to less sensitive species like Baltimore Orioles (−1.0 days/°C). This is consistent with previous findings from around the world demonstrating that short-distance migrants are more responsive to temperature than long-distance migrants, which may be constrained primarily by photoperiod (Gordo 2007; Miller-Rushing AJ, Lloyd-Evans TL, et al. 2008). This may put long-distance migrants at greater risk of ecological mismatch. In fact, one study using eBird data found that an extreme warming event in 2012 corresponded with earlier sightings of short-distance migrants during the spring months, and fewer sightings of long-distance migrants during the summer months (La Sorte et al. 2016).

Considering sampling effort when combining historical records and eBird data

As shown in our study, combining historical data sets with more recent phenological observations can provide important ecological insights. However, if researchers fail to account for sampling differences when combining data sets, they may get misleading results. For example, without accounting for sampling and including all eBird observers in all years, birds appear to be arriving 9 days earlier now than they did in the past, suggesting that birds are responding strongly to increasing temperature associated with climate change (Supplemental Table S1).

However, using just the earliest date of the top five eBird observers in each year—a sampling effort analogous to historical observers and the one we used in this study—birds appear to be arriving 7 days earlier than the historical data. This difference between the two approaches reflects the power of sampling effects. If we assume that the high sampling intensity of using all eBird observers results in observing the true first day of arrival of bird species in Concord, then the top five observers in any 1 year detect a species around 2.6 days after it first appears in Concord.

Other researchers have developed methods that can help with differences in sampling methods, depending on the specifics of the data sets and research questions involved. For example, the *R* package *phenesse* uses Weibull-informed estimators to model the complete distribution of phenological phases (e.g., flowering, leaf-out, and bird arrivals) when provided presence-only data sets, which are common in historical and modern phenological data (Belitz et al. 2020). Likewise, Youngflesh et al. (2021) developed a modeling pipeline that accounts for varying effort and uncertainty in eBird data. These approaches generally provide similar results to the approach that we used. For example, we found a strong correlation between estimated onset dates and the earliest detections from our subsample of the top five eBird observers ($r = 0.89$, $df = 154$, $P < 0.001$) showing that the inter-species differences are well-approximated. But such approaches do not directly address the challenge of reconciling differences in sampling effort and intensity between historical single-observer datasets and modern multi-observer citizen science data. Our approach is meant to provide a more conservative and interpretable estimate of first arrival dates while still approximating results consistent with those from more complex modeling tools.

In addition to sampling intensity, changing population sizes can also influence the timing of first observations of species over time (Miller-Rushing AJ, Lloyd-Evans TL, et al. 2008; Stegman et al. 2017). Long-term population declines, such as the steep declines observed in the Wood Thrush (*Hylocichla mustelina*; Sauer et al. 2013) due to a variety of factors including habitat loss, pollution, and brood parasitism (Hoover et al. 1995; Hames et al. 2002), can obscure the effects of climate change on the spring arrival times of birds. In Ellwood et al. (2010)'s analysis of the historical records alone, in fact, the Wood Thrush was reported as shifting its arrival later over time and with warming temperatures. As species which take advantage of grasslands and open habitats, Eastern Kingbirds (*Tyrannus tyrannus*), Barn Swallows, Chipping Sparrows, and Common Yellowthroats (*Geothlypis trichas*), may be at higher risk for population decline due to a loss of these features on the northeastern landscape. It may, therefore, be the case that we are *underestimating* the responsiveness of these species toward earlier phenology with warming temperatures. Conversely, if a population is increasing over time, this can appear as if a population is responding strongly to climate change when no such effect exists. Because of these issues, we limited our analyses to species that were common in the eBird data set.

Future extensions of historical data

Here, we highlight the utility of combining modern-day eBird records with historical data to assess changes in bird arrival dates. We suggest other researchers could do the same for other study systems using additional citizen science records, such as leaf-out and flowering records from the USA National Phenology Network (Crimmins et al. 2022) or iNaturalist (Reeb et al. 2022). Furthermore, recent digitization of historical records, including museum specimens and associated media containing phenological data (Willis et al. 2017; Meineke et al. 2018), offer researchers increasing opportunities to synthesize modern and historical datasets (Primack RB, Miller TK, et al. 2023). With each new type of phenological character under study comes additional challenges of determining issues of sampling and data bias.

In this study, the journals of past observers indicated that they were recording the first sighting of each species, and comprehensive eBird records from Concord, Massachusetts allowed us to estimate dates for the equivalent phenological stage for recent years. While we have suggested a robust approach to compiling and analyzing these data for use in this study, each dataset will have its own challenges in deciding how to proceed in tackling these methodological and sampling issues. Despite these challenges, the growing availability of volunteer-collected big data, and the thoughtful combination of them with historical datasets, creates exciting opportunities for researchers to extend the geographic, environmental, temporal, and taxonomic scope of bird phenology research in the face of climate change (Dickinson et al. 2010; La Sorte et al. 2018; Gallinat et al. 2021).

Acknowledgments

We thank Cris van Dyke, Kathy Dia, Peter Alden, and David Swaine for sharing insights into bird observations in Concord; Carina Terry and Emily Dang for help with statistical analysis; and Kris Cafaro, Benjamin R. Lee, Michael Reed, Michael Stemkovski, and two anonymous reviewers for comments on the manuscript. We are deeply indebted to eBird for providing us with access to their records, including both the volunteer eBirders as well as the volunteer reviewers.

Author contributions

A.S. Gallinat, E.R. Ellwood, and R.B. Primack conceived the idea and design. A.S. Gallinat and C.T. Callaghan analyzed the data. A.S. Gallinat, A.J. Miller-Rushing, and R.B. Primack wrote the paper. All authors contributed substantial edits. Generative AI was not used in the production of this manuscript. All data and R scripts to reproduce the analyses in this manuscript are available on Open Science Framework (https://osf.io/tnpmf).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the National Science Foundation [1950447] and [DBI-2027654].

Research ethics declarations

The findings and conclusions presented in this paper are those of the authors and do not necessarily reflect those of the US Government or the US Department of the Interior.

Literature cited

Bates D, Mächler M, Bolker B, Walker S. 2015. Fitting linear mixed-effects models using lme4. J Stat Soft. 67(1):1–48. https://doi.org/10.18637/jss.v067.i01

Belitz MW, Larsen EA, Ries L, Guralnick RP. 2020. The accuracy of phenology estimators for use with sparsely sampled presence-only observations. Methods Ecol Evol. 11(10):1273–1285. https://doi.org/10.1111/2041-210X.13448

Courter JR, Johnson RJ, Stuyck CM, Lang BA, Kaiser EW. 2013. Weekend bias in citizen science data reporting: implications for phenology studies. Int J Biometeorol. 57(5):715–720. https://doi.org/10.1007/s00484-012-0598-7

Crimmins T et al. 2022. Science and management advancements made possible by the USA National Phenology Network's Nature's Notebook platform. BioScience. 72(9):908–920. https://doi.org/10.1093/biosci/biac061

Denny EG et al. 2014. Standardized phenology monitoring methods to track plant and animal activity for science and resource management applications. Int J Biometeorol. 58(4):591–601. https://doi.org/10.1007/s00484-014-0789-5

Dickinson JL, Zuckerberg B, Bonter DN. 2010. Citizen science as an ecological research tool: challenges and benefits. Annu Rev Ecol Evol Syst. 41(1):149–172. https://doi.org/10.1146/annurev-ecolsys-102209-144636

Ellwood ER et al. 2022. Plant and bird phenology and plant occurrence from 1851 to 2020 (non-continuous) in Thoreau's Concord, Massachusetts. Ecology. 103(5):e3646. https://doi.org/10.1002/ecy.3646

Ellwood ER, Primack RB, Talmadge ML. 2010. Effects of climate change on spring arrival times of birds in Thoreau's Concord from 1851 to 2007. Condor. 112(4):754–762. https://doi.org/10.1525/cond.2010.100006

Ellwood ER, Temple SA, Primack RB, Bradley NL, Davis CC. 2013. Record-breaking early flowering in the eastern United States. PLOS ONE. 8:e53788. https://doi.org/10.1371/journal.pone.0053788

Fidino M, Limbrick K, Bender J, Gallo T, Magle SB. 2022. Strolling through a century: replicating historical bird surveys to explore 100 years of change in an urban bird community. Am Naturalist. 199(1):159–167. https://doi.org/10.1086/717052

Fox J, Weisberg S. 2011. Multivariate linear models in R. An R companion to applied regression. Thousand Oaks.

Fuccillo Battle K et al. 2022. Citizen science across two centuries reveals phenological change among plant species and functional groups in the Northeastern US. J Ecol. 110(8):1757–1774. https://doi.org/10.1111/1365-2745.13926

Gallinat AS et al. 2021. Macrophenology: insights into the broad-scale patterns, drivers, and consequences of phenology. Am J Botany. 108(11):2112–2126. https://doi.org/10.1002/ajb2.1793

Gilfedder M et al. 2019. Brokering trust in citizen science. Soc Nat Resour. 32(3):292–302. https://doi.org/10.1080/08941920.2018.1518507

Gordo O. 2007. Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology. Clim Res. 35:37–58. https://doi.org/10.3354/cr00713

Griscom L. 2013. Modern bird study. Harvard University Press.

Griscom L. 2014. The birds of Concord: a study in population trends. Harvard University Press.

Hames RS, Rosenberg KV, Lowe JD, Barker SE, Dhondt AA. 2002. Adverse effects of acid rain on the distribution of the wood thrush *Hylocichla mustelina* in North America. Proc Natl Acad Sci USA. 99(17):11235–11240. https://doi.org/10.1073/pnas.172700199

Hoover JP, Brittingham MC, Goodrich LJ. 1995. Effects of forest patch size on nesting success of wood thrushes. Auk. 112:146–155. https://doi.org/10.2307/4088774

Jochner S, Sparks TH, Laube J, Menzel A. 2016. Can we detect a nonlinear response to temperature in European plant phenology? Int J Biometeorol. 60(10):1551–1561. https://doi.org/10.1007/s00484-016-1146-7

La Sorte FA et al. 2018. Opportunities and challenges for big data ornithology. Condor. 120:414–426. https://doi.org/10.1650/CONDOR-17-206.1

La Sorte FA, Hochachka WM, Farnsworth A, Dhondt AA, Sheldon D. 2016. The implications of mid-latitude climate extremes for North American migratory bird populations. Ecosphere. 7:e01261. https://doi.org/10.1002/ecs2.1261

Meineke EK, Davis CC, Davies TJ. 2018. The unrealized potential of herbaria for global change biology. Ecol Monogr. 88:505–525. https://doi.org/10.1002/ecm.1307

Miller DA, Pacifici K, Sanderlin JS, Reich BJ. 2019. The recent past and promising future for data integration methods to estimate species' distributions. Methods Ecol Evol. 10(1):22–37. https://doi.org/10.1111/2041-210X.13110

Miller-Rushing AJ, Lloyd-Evans TL, Primack RB, Satzinger P. 2008. Bird migration times, climate change, and changing population sizes. Global Change Biol. 14:1959–1972. https://doi.org/10.1111/j.1365-2486.2008.01619.x

Miller-Rushing AJ, Primack RB. 2008. Global warming and flowering times in Thoreau's Concord: a community perspective. Ecology. 89(2):332–341. https://doi.org/10.1890/07-0068.1

Miller-Rushing AJ, Primack RB, Stymeist R. 2008. Interpreting variation in bird migration times as observed by volunteers. Auk. 125:565–573. https://doi.org/10.1525/auk.2008.07005

Moritz C et al. 2008. Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. Science. 322(5899):261–264. https://doi.org/10.1126/science.1163428

Polgar CA, Primack RB, Williams EH, Stichter S, Hitchcock C. 2013. Climate effects on the flight period of lycaenid butterflies in Massachusetts. Biol Conserv. 160:25–31. https://doi.org/10.1016/j.biocon.2012.12.024

Polgar C, Gallinat A, Primack RB. 2014. Drivers of leaf-out phenology and their implications for species invasions: insights from Thoreau's Concord. New Phytol. 202(1):106–115. https://doi.org/10.1111/nph.12647

Primack RB et al. 2023. Ten best practices for effective phenological research. Int J Biometeorol. 67(10):1509–1522. https://doi.org/10.1007/s00484-023-02502-7

Primack RB, Miller TK, Miller-Rushing AJ. 2023. Generating ecological insights from historical data. Front Ecol Environ. 21(5):216–217. https://doi.org/10.1002/fee.2641

Primack RB, Miller-Rushing AJ. 2012. Uncovering, collecting, and analyzing records to investigate the ecological impacts of climate change: a template from Thoreau's Concord. BioScience. 62(2):170–181. https://doi.org/10.1525/bio.2012.62.2.10

Primack RB, Miller-Rushing AJ, Dharaneeswaran K. 2009. Changes in the flora of Thoreau's Concord. biol conserv. 142(3):500–508.

R Core Team. 2021. R: a language and environment for statistical computing. R Foundation for Statistical Computing. http://www.R-project.org/

Reeb RA et al. 2022. Using convolutional neural networks to efficiently extract immense phenological data from community science images. Front Plant Sci. 12. https://doi.org/10.3389/fpls.2021.787407

Renner SS, Zohner CM. 2018. Climate change and phenological mismatch in trophic interactions among plants, insects, and vertebrates. Annu Rev Ecol Evol Syst. 49(1):165–182. https://doi.org/10.1146/annurev-ecolsys-110617-062535

Rosenblatt CJ et al. 2022. Highly specialized recreationists contribute the most to the citizen science project eBird. Ornithol Appl. 124(2):duac008. https://doi.org/10.1093/ornithapp/duac008

Sauer JR, Link WA, Fallon JE, Pardieck KL, Ziolkowski DJ Jr Jr. 2013. The North American breeding bird survey 1966–2011: summary analysis and species accounts. N Am Fauna. 79:1–32.

Stegman LS, Primack RB, Gallinat AS, Lloyd-Evans TL, Ellwood ER. 2017. Reduced sampling frequency can still detect changes in abundance and phenology of migratory landbirds. Biol Conserv. 210:107–115. https://doi.org/10.1016/j.biocon.2017.04.004

Sullivan BL et al. 2009. eBird: a citizen-based bird observation network in the biological sciences. Biol Conserv. 142(10):2282–2292. https://doi.org/10.1016/j.biocon.2009.05.006

Sullivan BL et al. 2014. The eBird enterprise: an integrated approach to development and application of citizen science. Biol Conserv. 169:31–40. https://doi.org/10.1016/j.biocon.2013.11.003

Supp SR, Bohrer G, Fieberg J, La Sorte FA. 2021. Estimating the movements of terrestrial animal populations using broad-scale occurrence data. Mov Ecol. 9(1):60. https://doi.org/10.1186/s40462-021-00294-2

Tingley MW, Beissinger SR. 2009. Detecting range shifts from historical species occurrences: new perspectives on old data. Trends Ecol Evol. 24(11):625–633. https://doi.org/10.1016/j.tree.2009.05.009

Tingley MW, Monahan WB, Beissinger SR, Moritz C. 2009. Birds track their Grinnellian niche through a century of climate change. Proc Natl Acad Sci USA. 106(suppl. 2):19637–19643. https://doi.org/10.1073/pnas.0901562106

Vitasse Y et al. 2022. The great acceleration of plant phenological shifts. Nat Clim Chang. 12(4):300–302. https://doi.org/10.1038/s41558-022-01283-y

Willis CG et al. 2017. Old plants, new tricks: phenological research using herbarium specimens. Trends Ecol Evol. 32:531–546.

Wolkovich EM, Burge DO, Walker MA, Nicholas KA. 2017. Phenological diversity provides opportunities for climate change adaptation in winegrapes. J Ecol. 105:905–912. https://doi.org/10.1111/1365-2745.12786

Youngflesh C et al. 2021. Migratory strategy drives species-level variation in bird sensitivity to vegetation green-up. Nat Ecol Evol. 5(7):987–994. https://doi.org/10.1038/s41559-021-01442-y

Youngflesh C et al. 2023. Demographic consequences of phenological asynchrony for North American songbirds. Proc Natl Acad Sci USA. 120(28):e2221961120. https://doi.org/10.1073/pnas.2221961120

Zaifman J, Shan D, Ay A, Jimenez AG. 2017. Shifts in bird migration timing in North American long-distance and short-distance migrants are associated with climate change. Int J Zool. 2017: e6025646. https://doi.org/10.1155/2017/6025646