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LETTER

Large-scale citizen science programs can support ecological and climate change assessments

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Abstract

Large-scale citizen science programs have the potential to support national climate and ecosystem assessments by providing data useful in estimating both status and trends in key phenomena. In this study, we demonstrate how opportunistic, unbalanced observations of biological phenomena contributed through a national-scale citizen science program can be used to (a) identify and evaluate candidate biotic climate change indicators and (b) generate yearly estimates of status of selected indicators. Using observations of plant phenology contributed to *Nature's Notebook*, the USA National Phenology Network's citizen science program, we demonstrate a procedure for identifying biotic indicators as well as several approaches leveraging these opportunistically-sampled data points to generate yearly status measures. Because the period of record for this dataset is relatively short and inconsistently sampled (13 yr), we focus on estimates of status, though over time, these measurements could be leveraged to also estimate trends. We first applied various spatial, seasonal, and biological criteria to narrow down the list of candidate indicators. We then constructed latitude-elevation models for individual species-phenophase events using all observations. This allowed us to visualize differences between predicted and reported phenophase onset dates in a year as anomalies, with the expectation that these anomalies—representing earlier or later activity in the species of interest—reflect plant response to local springtime temperatures. Plotting yearly anomalies revealed regions with geographic coherence as well as outliers. We also show how yearly anomaly values can be reduced to a single measure to characterize the early or late nature of phenological activity in a particular year. Finally, we demonstrate how the latitude-elevation models can be leveraged to characterize the pace at which phenological transitions occur along latitude gradients on a year-by-year basis.

1. Introduction

Climate change indicators offer critical information regarding the status and trends in Earth's abiotic and biotic components. To be useful in decision-making contexts, indicators should capture key components of a system and communicate complex information clearly to a wide range of audiences (Kenney *et al* 2016). In addition, climate change indicators should have a clear relationship to changing climate, illustrate change over time, and cover a broad geographic area (US Global Change Research Program 2022). To date, climate change indicators tracked in the United States are primarily abiotic in nature, including measures of air or sea surface temperature, Arctic ice extent, snowpack, and sea level (US Global Change Research Program 2022). Comparatively few biotic indicators have been identified for inclusion in national-scale climate change assessments in the United States, primarily due to a lack of long-term, sustained monitoring across species' ranges (Weltzin *et al* 2020, US Environmental Protection Agency 2021).

Large-scale citizen science programs have the potential to support the identification of potential biotic climate change indicators. Many national- or international-scale citizen science programs welcome reports across many species. The broad taxonomic and spatial representation and temporal depth in the datasets amassed by programs such as eBird (ebird.org) and iNaturalist (inaturalist.org) offer great opportunity to be quantitatively evaluated to identify candidate biotic indicators of climate change. Further, these programs offer strong potential to yield observations in support of selected indicators, generating data that can offer insight into large-scale status and trend in biological parameters.

One such large-scale citizen science program with the potential to support national assessments by yielding indicators is *Nature's Notebook*, the USA National Phenology Network (NPN)'s plant and animal phenology observation program (Rosemartin *et al* 2014). Phenology—the timing of biological events such as leaf-out, flowering, migration, and egg hatch—has been repeatedly identified as a simple and direct biological response to climate change (Parmesan and Yohe 2003, Root *et al* 2003, Parry *et al* 2007, Pachauri *et al* 2014, Cohen *et al* 2018, Renner and Zohner 2018, Iler *et al* 2021). Further, the timing of seasonal events in plants and animals directly affects nutrient and water cycling, ecosystem structure and functioning, agriculture, and human health (Bonan 2015, Kenney and Janetos 2020).

Since *Nature's Notebook* launched in 2009, professional and citizen scientists have contributed nearly 30 M records of phenological status at nearly 20 000 sites across the United States. Driven by the challenges of engaging and sustaining volunteer participants, data collection has primarily been shaped by local-scale questions and applications, resulting in a dataset that is unbalanced across geography and species and characterized by inconsistent sampling frequency and duration, as is common in volunteer-collected datasets (Callaghan *et al* 2019, Low *et al* 2021). Further, because the majority of *Nature's Notebook* participants are volunteers, long-term participation is generally low, and at most sites, observations have been contributed in 5 or fewer years. Even so, this dataset has the potential to reveal valuable information about how species are responding to changing climate conditions, and accordingly, the species and phenological events that are best suited to serve as large-scale biotic indicators.

In this analysis, we evaluate the 13 yr of phenology observations that have been contributed to the USA NPN's phenology observation program, *Nature's Notebook*, with the aim of identifying candidate indicators of direct biological response to current and changing climate conditions. This reflection on the data that have been contributed to the program to-date can help to identify opportunities for adapting the USA-NPN's approach to data collection to more effectively yield robust estimates of status and trends. We also demonstrate some ways that we might capitalize on the unbalanced data that are contributed to the program to ascertain estimates of status. This approach of examining the data that have been contributed to a program to-date to identify potential biotic indicators could extend to other citizen science programs to identify biological phenomena with the greatest potential to reveal large-scale insights.

2. Methods

Status and trends monitoring is intended to generate 'timely and robust estimates' of a system or indicator's state (Gregory *et al* 2005, Isaac *et al* 2014). In this analysis, our focus is to document the status in phenological transitions. Because of the relatively short period of record present in the dataset and the low degree of repeated measures, the data are not yet well-suited to estimating trends, though this effort lays groundwork for eventual trends assessments.

Presently, over 1600 species of plants and animals are tracked in *Nature's Notebook*, and for each species, between three and ten distinct phenological events (i.e. breaking leaf buds, open flowers, colored leaves, egg hatch) are tracked (Denny *et al* 2014). Our initial step was to apply several filters to reduce the pool of candidate indicators considered here for simplicity's sake, as the aim of this analysis was to demonstrate potential, rather than recommend indicators. We narrowed down the indicators—unique species-phenophase combinations—considered here, using several qualitative criteria. First, we narrowed our focus to species occurring in temperate systems of the eastern United States (<100° W longitude and <50° N latitude) and spring-season phenophases, which are primarily temperature-driven (Sparks and Carey 1995). Further, because plant observations make up approximately 70% of observations contributed to *Nature's Notebook*, we narrowed our focus to perennial plants, with emphasis on deciduous species. We also eliminated species with narrow geographic ranges, given our intent to identify large-scale indicators.

2.1. Latitude-elevation models

To generate the most robust estimates of yearly spring status using the opportunistically sampled *Nature's Notebook* phenology observations that exhibit a low degree of repeated measures, we focused on species-phenophases with comparatively large numbers of observations and broad spatial distribution of observations encompassing much of the species' range.

We further placed emphasis on phenophases that are highly visible and strongly representative of the onset of biological activity in deciduous plants: 'breaking leaf buds', 'leaves', and 'open flowers'. We downloaded all 'site-level phenometrics data' (Rosemartin *et al* 2018, USA National Phenology Network 2022) for 2009–2021 from the USA-NPN database using the *rnpn* R package. We retained only the first instance of a 'yes' report in the calendar year for a phenophase at a site, and records where the first report of 'yes' was preceded by a report of 'no' for the phenophase within 15 d. We also excluded observations after 1 July, as our focus was on spring-season events.

To depict yearly spring status in the timing of an event event in a species, we constructed linear latitude-elevation models (day of year ∼ latitude + elevation) for individual species-phenophase events using all observations contributed in all years (2009–2021) for species-phenophases with at least 100 site × year observations. In the northern hemisphere, the arrival of spring warmth progresses following latitude as sun angle increases (Stine *et al* 2009). As a result, individual plants of the same species situated across a large region will undergo phenological transitions over a duration of many weeks (Chmura *et al* 2019). Because of the adiabatic lapse rate, elevation has a similar influence on phenology. Our aim was to remove the effects of latitude and elevation on the expected timing of the phenological transition. To demonstrate this visually, we constructed a map depicting the day of year that 'open flowers' is expected to occur in flowering dogwood (*Cornus dogwood*) using the latitude-elevation model established following the steps described above. Elevation data used were 90 m Shuttle Radar Topography Mission (NASA SRTM 2013) downloaded using the *raster* R package (v 3.15-15).

The residuals from each species-phenophase model in a particular year reflect the deviation of the observation at a site from the mean progression of spring based on latitude and elevation and should reflect local and recent temperature conditions. This approach of predicting when phenological events are expected to occur based on a site's latitude and elevation provides context for the observations contributed by program volunteers. Without a sense of when an event typically occurs at a location, the timing of the event in a given year cannot be evaluated as early, late, or average.

Once we had constructed latitude-elevation models for individual species-phenophase events, we calculated model residuals at each location for which observations had been reported in each year. These residuals reflect the difference between when the event was expected to occur, based on the plant's latitude and elevation, and when it was reported to occur. Because the latitude-elevation models were constructed using observations from all years for an individual species-phenophase event, the prediction for an event at a location would be the same in each of the years under consideration.

We mapped model residuals, which allowed us to explore geographic coherence in residuals potentially driven by large-scale temperature anomalies that may have emerged during the spring season. We further examined the patterns in model residuals by tying them to the local 2 month temperature anomaly in the USA-NPN period of record (2009–2021) and full instrumental record (1895–2021) using the NOAA Monthly U.S. Climate Gridded Dataset (Vose *et al* 2014). The 2 month anomaly for an observation was determined by differencing the average temperature of the month encompassing and preceding the event from the long-term average temperature of those same two months in the two periods (2009–2021 and 1895–2021). Comparing the anomalies calculated with the more recent 2009–2021 period to those generated using the full record provides context for assessing whether the more recent USA-NPN sampling period is representative of the full instrumental record.

Next, for each species-phenophase, we calculated the mean residual of the phenophase event in each year, the mean local 2 month climate anomaly, and the relationship between these measures.

2.2. 'Window of spring' estimate

The latitude-elevation model approach can also be leveraged to characterize the pace at which phenological transitions occur along latitude gradients on a year-by-year basis. The timing of onsets, as reported through *Nature's Notebook*, are assumed to reflect springtime temperature conditions at a location, with earlier onsets reported from locations characterized by warmer springtime temperatures. Further, springtime warmth progresses northward in a predictable manner in the eastern United States but can stall due to cold-spells or advance faster than normal due to warm-spells (Crimmins and Crimmins 2019a). The latitude-elevation model calculated for a species-phenophase indicator for a single year can be used to estimate the average date at which the onset of the event occurred at particular latitudes as well as the time lapsed between the event occurring between these two latitudes. A shorter duration of time between the onset at two latitudes as predicted by the latitude-elevation model indicates a more rapid pace of onset for the species-phenophase event of interest along the latitude gradient encompassed, and a compression of onsets across geography in that year. Conversely, a longer duration of time between the onset at two latitudes indicates a slower pace of onset along the latitude gradient.

To assess the rate of spring phenology progression reflected in *Nature's Notebook* observations in each year, we calculated distinct latitude-elevation models in each year for a species-phenophase event. We

Table 1. Candidate springtime phenological status indicators as identified from observations contributed to the USA NPN's phenology observing program, *Nature's Notebook*, with n ⩾ 280 and $R^2 \geqslant 0.40$. A complete list of candidate indicators emerging from this evaluation appear in table S1.

Candidate indicator	Total sample size (site × years)	Latitude range of observations
American beech (*Fagus grandifolia*)-leaves	364	29.7–46.7° N
Red maple (*Acer rubrum*)-open flowers	890	28.0–48.1° N
American beech (*Fagus grandifolia*)-breaking leaf buds	337	29.8–46.7° N
Flowering dogwood (*Cornus florida*)-open flowers	424	29.7–48.9° N
Red maple (*Acer rubrum*)-leaves	1319	28.0–48.0° N
Flowering dogwood (*Cornus florida*)-leaves	485	30.3–48.9° N
Black cherry (*Prunus serotina*)-leaves	289	28.0–48.4° N
Black cherry (*Prunus serotina*)-breaking leaf buds	290	28.0–47.1° N
White oak (*Quercus alba*)-leaves	317	32.3–45.4° N

then used these year-specific models with a fixed elevation of 350 m to predict the date of onset at 35° N and 45° N latitude in that year. We chose this latitude band because it generally encompasses the range of the species evaluated in this study.

3. Results

Several species-phenophase events queried from the USA-NPN database met our criteria of comparatively large sample sizes, sampling across species' ranges, ranges that extend from low to high latitude in the conterminous United States, adequate temporal depth, and significant latitude-elevation models (tables 1 and S1 (available online at stacks.iop.org/ERL/17/065011/mmedia)). All three phenophases evaluated were represented in the top candidate indicators, though models for the phenophases first to appear in the season for a species (i.e. breaking leaf buds) tend to have poorer performance than leaves and open flowers (mean R^2 for breaking leaf buds = 0.27, mean R^2 for open flowers = 0.45, mean R^2 for leaves = 0.41; table S1) The median day of year of onset ranged from day of year 95 (April 5) to day of year 125 (May 5). In subsequent analyses where we demonstrate ways that unbalanced, opportunistic data contributed to *Nature's Notebook* might be leveraged to yield estimates of phenological status in a year, we focus on the flowering dogwood (*Cornus florida*)-open flowers and American beech (*Fagus grandifolia*)-leaves indicators due to their performance, sample sizes, geographic spread, and timing within the season.

A scatterplot of the day of year a phenophase is first reported for a species against latitude reveals the influence of latitude on the transition. As an example, figure 1(a) depicts the day of year first reported for the 'open flowers' phenophase for flowering dogwood (*C. florida*) by latitude over the full period of record

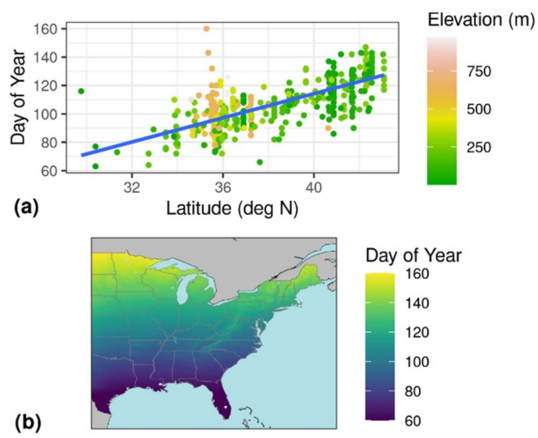

Figure 1. (a) Day of year 'open flowers' was first reported by *Nature's Notebook* observers plotted against latitude of the site for flowering dogwood (*Corunus florida*)-open flowers. (b) Day of year predicted for 'open flowers' in flowering dogwood (*C. florida*) based on the latitude-elevation model established using all observations (2009–2021).

(2009–2021); elevation is depicted by color. In this example, the latitude-elevation model explains 54% of the variance ($R^2 = 0.54$, $p < 0.001$). Onset dates vary by a month or more at many latitudes. This model was then used to indicate the day of year 'open flowers' is predicted to occur across the eastern United States (figure 1(b)).

Yearly maps of the latitude-elevation model residuals—or anomalies—for a species-phenophase event reveal locations where the event was reported to first occur either earlier or later than expected based on the plant's latitude and elevation. This approach for visualizing the timing of transitions reveals coherent regions and years with particularly early or late onsets in this event, which might occur in years with particularly warm or cool conditions. Figure 2(a) shows anomalies—the difference, in days, between the expected onset of the event and the reported

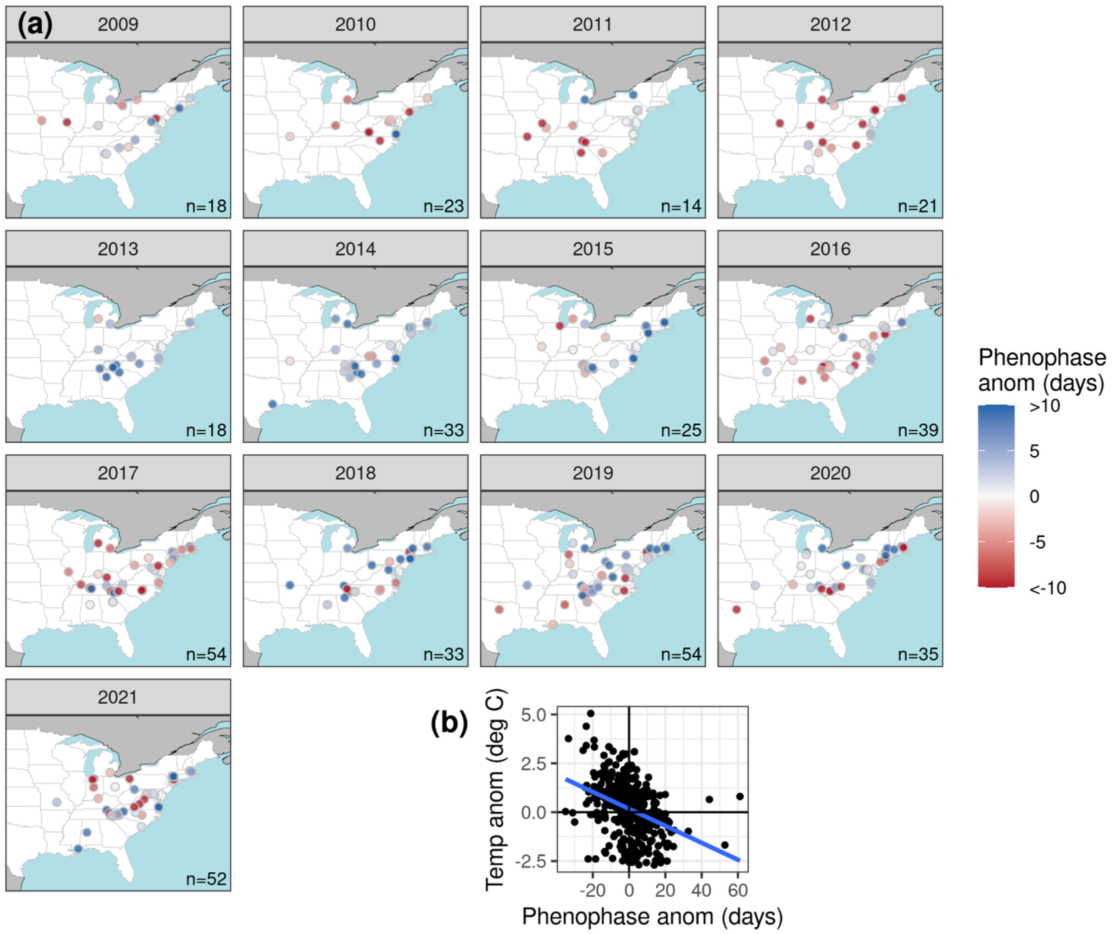

Figure 2. (a) Onset anomalies for flowering dogwood (*C. florida*)-open flowers. (b) Anomalies for the flowering dogwood (*C. florida*)-open flowers observations plotted against the temperature anomaly for the preceding two months, calculatted using the period of record reflected in the USA-NPN dataset (2009–2021).

onset based on the 2009–2021 modeling period—for flowering dogwood (*C. florida*)-open flowers. Open flowers were reported in flowering dogwood (*C. florida*) anomalously early in much of the species' range in 2010, 2012, 2016, and 2017, and later than expected in much of the species' range in 2013, 2014, and 2015. Other years showed more mixed patterns in anomalies. A similar suite of anomaly maps for American beech (*F. grandifolia*)-leaves appear in figure S1.

For phenological events cued primarily by temperature conditions, the average temperature preceding the event can provide context and a richer understanding of anomalies. Figure 2(b) depicts anomalies plotted against the local temperature anomaly for the preceding two months for these locations. This plot shows a significant negative relationship ($r = -0.38$, $p < 0.001$), indicating that open flowers in flowering dogwood (*C. florida*) is typically reported earlier in the year when the preceding two months are warmer than average at a sampling location and later when the local springtime temperatures are cooler than average.

3.1. Yearly mean anomalies

The yearly mean anomalies for flowering dogwood (*C. florida*)-open flowers and the mean of concurrent 2 month local temperature anomalies for flowering dogwood (*C. florida*)-open flowers sampling locations (figure 3) show considerable variation over the record and generally co-vary ($r = -0.85$, $p < 0.001$). Several years with large-scale and persistent springtime temperature anomalies show commensurate anomalies in the onset of open flowers in flowering dogwoods (*C. florida*). For example, consistent with results presented in the anomaly maps (figure 2(a)) the average onset of flowering was much earlier than average in 2012, a year characterized by much warmer than average springtime temperatures at sampling locations; similarly, the onset of flowering was notably delayed in 2013 and 2014, years with much cooler spring temperatures.

The 2 month temperature anomalies calculated using the sampled period of record (2009–2021) are consistently warmer (on average, by 1 °C) than those calculated using the full instrumental record (1985–2021; figure 3).

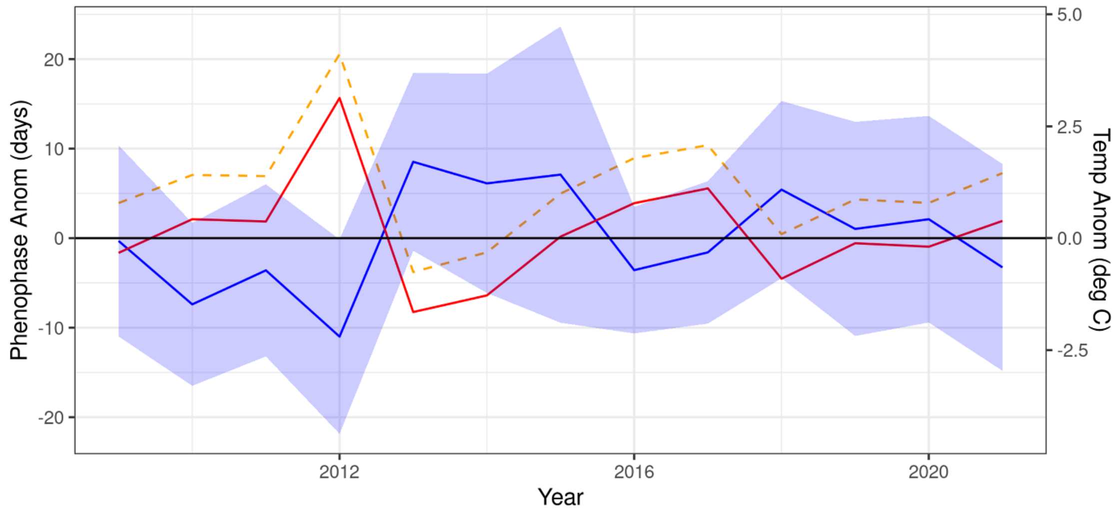

Figure 3. Variability in yearly mean anomalies for flowering dogwood-open flowers (blue line = 2009–2021; shading is ±1SD) and yearly mean of 2 month local temperature anomalies for locations sampled in each year (red line = temperature anomalies based on 2009–2021 period; dashed orange line = anomalies based on 1895–2021 period).

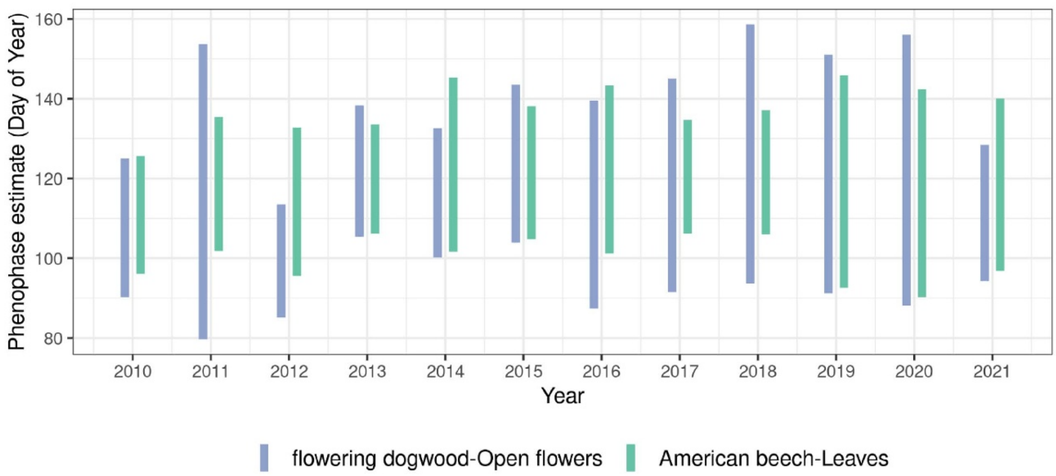

Figure 4. 'Window of spring' measure for flowering dogwood (*C. florida*)-open flowers and American beech (*F. grandifolia*)-leaves (2010–2021; 2009 not shown due to small sample size in American beech). The lower endpoint of an individual bar indicates the day of year the phenophase event is predicted to occur at 35° N latitude by the latitude-elevation model calculated for that year; the upper endpoint indicates the day of year the event is predicted to occur at 45° N latitude.

3.2. 'Window of spring' estimate

The 'window of spring' measure concisely reflects the timing and pace of a species-phenophase event across latitude and elevation gradients in individual years, enabling comparisons in the timing of phenology across space, among years, and among species and phenophase events. To demonstrate the information conferred by this metric, we report spring progression for two candidate indicators, flowering dogwood (*C. florida*)-open flowers and American beech (*F. grandifolia*)-leaves, two events that are typically separated by several weeks at a single location (figure 4).

At 35° N latitude, 'open flowers' in flowering dogwood (*C. florida*) were predicted to occur before 'leaves' in American beech (*F. grandifolia*) in every year of the sampling record (figure 4). In contrast, the two events did not show a clear sequence at 45° N latitude. The onset of 'open flowers' in flowering dogwood (*C. florida*) shows dramatic interannual variability in onset at both latitudes; interannual variability in the timing of onset is more muted for American beech (*F. grandifolia*)-leaves. Further, in some years, such as 2020, the two species-phenophase indicators show coherent behavior, occurring comparatively early at 35° N and late at 45° N; in other years they do not.

4. Discussion

Long-term ecological monitoring provides 'information needed to understand and identify change in natural systems characterized by complexity, variability, and surprises' (Fancy and Bennetts 2012). Citizen science and volunteer-based projects have demonstrated potential to contribute to such monitoring efforts, yielding data that can be used in ecosystem status and trend assessments (Silvertown 2009, Tulloch *et al* 2013). However, volunteer-contributed data are most useful to such assessments when projects and sampling design are instituted with these aims in mind (Tulloch *et al* 2013). In this investigation of the 13 years of data contributed to the USA NPN's plant and animal phenology observing program, *Nature's Notebook*, we identified several species-phenophases with potential to serve as biotic climate change indicators as well as approaches best suited to capitalize on observations that, to-date, have been contributed with no formal sampling design. Such insights could be used to refine or refocus the USA-NPN's approach to data collection in service to supporting national assessments.

Few species-phenophase events that met our qualitative criteria exhibited greater than 300 observations in all years combined. However, of those that did, the latitude-elevation models explained up to 70% of the variance in the date of phenophase onset, suggesting that these events may be worthy of further consideration as formal indicators (tables 1 and S1).

4.1. Making the most of inconsistently sampled observations

The majority of individual plants observed through *Nature's Notebook* are not observed for multiple years, limiting the opportunity for estimating interannual variation, trend, or anomalies in phenology using traditional repeated measures approaches (e.g. Cayan *et al* 2001, US Environmental Protection Agency 2021). Our approach of constructing a latitude-elevation model using all observations collected in all years for a species-phenophase utilizes all observations contributed for the event, regardless of the number of years individual plants have been observed. This type of approach is well-suited for citizen science programs where achieving many years of repeated measurements at a site is difficult.

The motivation behind generating latitude-elevation models is to provide context for the opportunistically contributed observations. Knowing when a particular event is expected to occur at a location enables a determination of the reported value as early, late, or average. The logic underpinning the latitude-elevation model approach is that the difference between when an event is expected to occur based on the latitude and elevation of the site and when the event is reported to occur reflects the local weather conditions of the period preceding the event. The anomalies maps offer a clear visual depiction of the departure from the expected timing for the species-phenophase of interest, showing the constellation of sites sampled in a year as well as the degree of coherence in the departures from expected values across geography. Reducing the anomalies to a single mean anomaly measure for the year, as shown in figure 3, provides an even simpler characterization of the anomalous nature of the year, as captured by the anomalies in the species-phenophase indicator of interest. This simple measure performs best in years characterized by similar springtime conditions across large geographic regions. For example, both the anomalies maps (figure 2(a)) and the yearly mean anomaly measure (figure 3) for flowering dogwood (*C. florida*)-open flowers show anomalously early activity in 2010 and 2012; in both of these years, springtime warmth and the onset of plant activity were dramatically early in the eastern United States (Ault *et al* 2013, Ellwood *et al* 2013). Similarly, the anomalies maps and yearly mean anomaly measure depict 'open flowers' activity in flowering dogwoods (*C. florida*) to be later than average in 2013, 2014, and 2015, all years with cool winter and spring conditions (NOAA National Centers for Environmental Information 2022a, 2022b, 2022c). In contrast, springtime warmth and biological activity occurred exceptionally early across much of the eastern United States in 2017 (Borenstein 2017), though this is not reflected clearly in the yearly mean anomaly measure (figure 3(a)), and the anomaly map shows both early and late anomalies for 'open flowers' in flowering dogwood (*C. florida*; figure 2(a)).

Residual values of unexpected direction or magnitude could arise for several reasons. First, factors other than local temperature could contribute to residual values, including site conditions (e.g. degree of urbanization), individual plant measures (plant size, shade status) or local adaptation (Phillimore *et al* 2013, Li *et al* 2021, Song *et al* 2021). Second, latitude and elevation may not be sufficient to predict phenology in areas with complex topography, where nonlinear relationships between elevation and temperature can occur (Loarie *et al* 2009). Many of the points exhibiting phenological anomalies of unexpected direction and magnitude in 2017 occur in the Appalachian Mountains; the simple latitude-elevation model may be insufficient to account for nonlinear relationships that can occur between elevation and temperature in regions of complex topography. Finally, imprecision in the reports of phenological onsets may contribute substantially to unexpected anomalies. To maximize species-phenophase sample sizes available for model construction, we allowed last reports of 'no' and first reports of 'yes' for a phenophase to be separated by up to 15 d. Such a large window can result in anomalies of the wrong sign of several days, suggesting poor model performance. The mixed signal in 2017 anomalies could also arise from the large window allowed between the last reported 'no' and the first reported 'yes' in this species-phenophase, highlighting the importance of encouraging observers to capture onsets with temporal precision.

With increased observations and additional years of sampling, uncertainty in latitude-elevation models will decrease. The period of record used to estimate the model residuals is relatively short (13 yr). The model residual approach assumes these years are a representative sample of a longer record and that within these years, the observation locations capture the breadth of latitude and elevations well. With additional years and observations, the influence of outliers will decrease. Additionally, sampling through more years of large-scale climatic extremes like 2012, 2013 and 2017 will also test the efficacy of this approach in capturing large-scale biotic responses to climate.

The period of record used to estimate the latitude-elevation models (2009–2021) is approximately 1 °C warmer than the 1895–2021 period (figure 3). The consequence of this difference is that onsets appearing as anomalously late using the recent period of record would not necessarily appear to be late in context of the past 125 yr. The full instrumental record provides important context for the years with phenology data available, which are recent and comparatively warm.

4.2. Tracking spring onset by latitude

Yearly latitude-elevation models for a species-phenophase indicator offer another approach to maximize the observations collected through *Nature's Notebook* in an opportunistic way. As we show, latitude-elevation models calculated for individual years can be used to predict the onset of a phenophase-event at particular latitudes, revealing insights regarding interannual variability for a single species-phenophase event as well as the degree of coherence in the timing and interannual variability among multiple species-phenophase events.

Species undergo transitions such as leaf-out and flowering at different times in the spring season: for example, maples and birches tend to leaf out and flower early in the season in response to smaller amounts of warmth, and oaks and beeches generally undergo phenological transitions later in the season (Lechowicz 1984, Polgar and Primack 2011). A strength of the *Nature's Notebook* dataset is the breadth of species and phenophases monitored; by tracking species undergoing phenological transitions at different stages of the season, differing within-season conditions can be captured over the course of the season. The variable patterns shown in the spring progression measures calculated for flowering dogwood (*C. florida*)-open flowers and American beech (*F. grandifolia*)-leaves (figure 4) demonstrate that species-phenophase indicators occurring at differing times within the spring season do not necessarily exhibit departures from the expected onset of the same magnitude in a year. Over time, tracking spring progression in multiple species-phenophase indicators can reveal whether these changes are occurring in the same way or whether events are becoming more compressed or temporally disjunct in a region (Crimmins and Crimmins 2019b), and could eventually serve as an indicator of trend.

The pace of phenological onset along latitude is predicted to increase under future warming (Jeong *et al* 2013, Wuebbels *et al* 2017, Liu *et al* 2019). Leveraging phenology observations contributed through *Nature's Notebook* to estimate the spring progression measure can yield valuable insight as to how this varies from year to year and how this phenomenon changes over time. The performance of the spring progression approach is expected to improve substantially with more incoming observations, arguing for emphasizing data collection on a small number of species-phenophase indicators to support calculation of this measure.

4.3. Considerations for USA-NPN's data collection emphases

This analysis of 13 years of volunteer-contributed observations of phenological events yielded a small number of candidate indicators (table 1). Additional years of sampling would no doubt yield a larger pool of candidate indicators to be considered for formal adoption.

The insights gained through this exploration could be used by the USA-NPN to select a small number of species-phenophase indicators on which to concentrate data collection efforts, with an eye toward ensuring strong representation along latitudinal gradients and other potentially influential variables such as distance to coast or complex topography. Over ten years' worth of observations have already been amassed for the candidate indicators listed in table 1, providing valuable temporal context for incoming observations. Further, the quantity of data already contributed for these species-phenophases suggests that they are easy to identify and appealing to observers and that participants are likely to continue to observe them. For a small group of species-phenophases selected to serve as indicators, the USA-NPN could strongly encourage a narrower temporal window between the last report of 'no' and the first report of 'yes' to maximize data quality and utility. The USA-NPN might consider imposing a formal spatial sampling design (Stevens and Olsen 2004, Schweiger *et al* 2016) to ensure consistent sampling across latitude and elevation in each year. When considering potential candidate indicators, the USA-NPN should also consider factors such as the known cues to the phenophase under consideration (i.e. accumulated chill, accumulated warmth, daylength; Körner and Basler 2010, Zohner *et al* 2016) to select the most responsive and information-rich phenonema.

The approach implemented here, where we explored the potential to leverage data contributed to a citizen science program to identify both candidate biotic climate change indicators and ways these data can be leveraged to generate broad-scale status assessments, has the potential to be extended to other citizen science programs. The broad taxonomic and spatial representation and temporal depth in the datasets amassed by programs such as eBird (ebird.org) and iNaturalist (inaturalist.org) offer great opportunity to be quantitatively evaluated to identify candidate biotic indicators of climate change. Further, these programs offer strong potential to yield observations in support of selected indicators, generating data that can offer insight into large-scale status and trend in biological parameters.

5. Conclusions

In this study, we demonstrate how volunteer-contributed observations can be used to identify candidate biotic climate change indicators and generate estimates of indicator status. Using observations of plant phenology contributed to *Nature's Notebook*, we prototype an approach for identifying biotic indicators as well as ways to leverage these opportunistically-contributed observations to generate yearly status measures. In this study, we focused on spring-season phenological events; future work could extend this approach to phenological events in other seasons. Additionally, future work could investigate the improvement in model performance with the inclusion of site or individual plant measures as well as the impacts of reducing the window between the last reported 'no' and first reported 'yes' on sample size and latitude-elevation model anomalies.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: doi.org/10.5281/zenodo.5941007.

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Conflict of interest

The authors declare no competing interests.

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