Science and management advancements made possible by the USA National Phenology Network's *Nature's Notebook* program

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Abstract

The USA National Phenology Network was established in 2007 to address the conspicuous absence of widespread, standardized phenology monitoring in the United States. The aims of the Network are to collect, store, and share phenology data and information to support scientific discovery and understanding, decision-making, an appreciation for phenology, and equitable engagement within the Network. To support these aims, the Network launched *Nature's Notebook*, a rigorous plant and animal phenology monitoring program, in 2009.

Since the launch of *Nature's Notebook* 13 years ago, participants in all 50 states and beyond have contributed over 26M records of plant and animal phenology. We review the breadth of scientific studies and applied management decisions that have utilized *Nature's Notebook* and the consequent data and consider how

these findings might shape future efforts by the Network to grow phenology monitoring across the country.

Keywords (up to 5): citizen science, monitoring, climate change, phenology, volunteer science

Introduction

Phenology—the timing of seasonal events in plants and animals, such as leaf-out, flowering, egg hatch, migration, and hibernation—is a key feature of the environment, integrating and reflecting local weather and environmental conditions. For centuries, indigenous peoples and native communities have incorporated a deep and powerful knowledge and practice of phenology into resource management, harvesting and agriculture, and ceremony (Kenote 2020). As well, in various countries around the globe, phenology has been monitored using standardized methods for decades or even centuries (Renner and Chmielewski 2021).

Recent changes in climate conditions, including increases in temperature, have shifted the timing of seasonal events in many species around the globe (Parmesan and Yohe 2003, Root et al. 2003, Cohen et al. 2018). Long-term records of phenology have been crucial for revealing these changes. In the United States, site-specific long-term records have corroborated these patterns (e.g., Inouye 2008, Miller-Rushing and Primack 2008). Widespread, standardized phenology monitoring historically occurred only to a limited extent in the U.S. (Schwartz et al. 2012), yet still reveals clear changes in phenology (Cayan et al. 2001).

Motivated by findings emerging from various forms of phenological monitoring worldwide, a growing appreciation of phenology as a "fingerprint" of climate change (IPCC 2007), and the conspicuous absence of standardized phenology monitoring in the U.S., the USA National Phenology Network (USA-NPN) was established in 2007. The original aims of the Network were to promote understanding of 1) fundamental patterns in plant and animal phenology, 2) the relationships between plant and animal phenology and environmental drivers, and 3) changes in phenology driven by changing environmental conditions (Schwartz et al. 2012), though the Network founders also recognized the utility of phenology information in natural resource management, agriculture, tourism, and carbon and nutrient cycling.

Since the inception of the Network, its aims have evolved beyond understanding phenology as a response to environmental variation. The Network also endeavors to support management decisions, to engender a broader understanding and appreciation for phenology by stakeholders and the public, and most recently, to foster equitable and inclusive engagement opportunities within the Network (USA National Phenology Network 2019). To achieve these aims, the Network launched *Nature's Notebook*, a rigorous plant and animal phenology monitoring program intended for use by both professional and volunteer observers (Rosemartin et al. 2014). As the Network's aims have expanded over the years, the *Nature's Notebook* program and infrastructure have also grown and evolved, shaped in large part by needs expressed by users of the program and the resultant data.

Since the launch of *Nature's Notebook* 13 years ago, participants in all 50 states in the U.S. and beyond have contributed over 26M records of plant and animal phenology (Fig 1). These data have supported the Network's original aims of documenting basic patterns in phenology, determining drivers to phenological transitions, and identifying directional change in the timing of seasonal events. The observations have been used in many additional applications, including natural resource management, human health, and even assisting film producers in planning on-location filming. Great unrealized potential still remains in these data for answering grand challenge science questions, supporting basic scientific discoveries, and documenting patterns and changes within and among species. Moreover, the value of such observations only increases with passing time. In this paper, we summarize the diverse ways that phenology data maintained by the USA-NPN are being used to support science and society and reflect on how these uses align with the aims of the Network.

***Nature's Notebook*: a rigorous and customizable program**

Protocols, infrastructure, and data: distinct and valuable resources

The USA-NPN both offers capacity for collecting phenology data and freely shares phenology observations as a data resource. The USA-NPN phenology observing protocols, the *Nature's Notebook* infrastructure, and the phenology observations contributed to *Nature's Notebook* are distinct resources, all of which can support science and management applications. The USA-NPN's robust phenology observing protocols have been used in dozens of research projects independent of the *Nature's Notebook* program (e.g., Browning et al. 2017, Harrer and Levi 2018, Du et al. 2019, Gallinat et al. 2019), by indigenous groups (e.g., Great Lakes Indian Fish & Wildlife Commission, no date) and by monitoring networks in several other countries.

Rigorous yet approachable protocols

The core of the *Nature's Notebook* program is a set of rigorous, scientifically vetted protocols designed to yield accurate and comprehensive documentation of when plants and animals are expressing various seasonal life cycle stages throughout the year. Different from many phenology observing approaches which place emphasis on documenting the beginning and end of seasonal activity in plants and animals, the USA-NPN protocols embedded in *Nature's Notebook* are "status" protocols, meaning that participants are asked to report on the status of life cycle stages for an individual plant or animal species each time they make an observation and to make observations frequently over the course of the growing season (Denny et al. 2014). Each observation is composed of "yes" or "no" responses to a series of questions pertaining to the state of a plant's leaves, flowers, and fruits, or an animal species' presence and activity, such as feeding, mating, and nesting.

Observations collected using these protocols yield a rich and comprehensive dataset, including a complete picture of when various life stages, or "phenophases," started and ended over the course of a season on individual plants or for animal species at a site (Fig 2). Tracking each phenophase independently in this way reveals instances where the typical progression of events is interrupted, such as when flowers do not lead to fruit development or when unripe fruits are aborted before ripening. Status protocols are also critically important for documenting the "on-off-on-off" cycles in green-up and flowering that frequently occur in water-limited systems (Crimmins et al. 2014) and under "false spring" conditions in temperate environments.

Intensity and abundance estimates are another important feature of the USA-NPN's observation protocols. These measures capture the extent to which a phenophase is being expressed: how many flowers are present on the tree; what percentage of the flowers are open; how many bees are present at the site (Fig 2). This additional information more fully characterizes resource availability and animal activity over the course of the season, offering insights into the impacts of events such as late-spring freezes, capturing large-scale events such as masting years, and supporting the identification of emerging temporal mismatches between dependent species pairs.

Flexible infrastructure and implementation

Unlike other citizen projects where data collection is driven toward answering a single, overarching question (Bonney et al. 2009), participants are invited to collect and submit observations of plant and/or animal phenology for reasons of their own. As such, *Nature's Notebook* can function not only as a "contributory" type of citizen science project, where participants' role is primarily to contribute observations, but also as "collaborative" (Shirk et al. 2012). Local groups adopting *Nature's Notebook* to achieve their own scientific or educational goals, exemplify the collaborative models of participation. In many of these instances, organizations simply use *Nature's Notebook* for data management, but carry out the steps of naming a question, analyzing the data, and sharing the findings independent from USA-NPN.

A unique and important attribute of *Nature's Notebook* is the flexibility in how it can be implemented. Specifically, participants can contribute independently or collectively as a part of an organized effort (Posthumus et al. 2019, Crimmins et al. 2020). Group participation can take multiple forms based on an organization's needs. In one model, members of a pre-existing group, such as students in a classroom or docents at an arboretum, can share the responsibility of collecting observations on the same plants or animals at a site. Alternatively, members of a group, such as members of a Master Gardener chapter or students in a remote learning classroom, can contribute observations from separate sites that are affiliated with their group within the *Nature's Notebook* platform. The various forms of group participation were built into *Nature's Notebook* in the early years of the program's existence, motivated by requests of the program's participants. These instances of group participation are referred to as Local Phenology Programs. Over 500 groups have contributed phenology observations to *Nature's Notebook*, including National Parks and Wildlife Refuges, Audubon chapters, Long-Term Ecological Research (LTER) sites, and botanical gardens and arboretums, nature centers, and universities. In addition, the National Ecological Observatory Network (NEON) tracks plant phenology using USA-NPN protocols and contributes these observations to the USA-NPN database.

The "shape" of the USA-NPN's phenology data resource

The majority of phenology observations contributed to *Nature's Notebook* are made by volunteers, and as a consequence, the resulting dataset exhibits particular strengths. Notably, the observations originate primarily from within or around population centers (Fig 1). Additionally, the number of sites under observation and the temporal record of observation varies conspicuously among the species available for monitoring within the program, with far more records contributed for some species than others (Box 1, Fig 3). Finally, sites are visited more frequently and for more seasons when tracked by Local Phenology Programs compared to individual observers (Box 1, Fig 3).

Scientific advancements emerging from data contributed to *Nature's Notebook*

The distinct "shape" of the phenology data resource maintained by the USA-NPN differs from that originating from traditional intensive studies at individual sites and lends it to certain types of applications. In particular, the data are presently best suited to questions and analyses that require geographic and/or taxonomic breadth as well as those that benefit from observations on the entire suite of phenophases over the growing season. Such applications include identifying patterns and drivers of phenology and ground-truthing remotely sensed imagery. The data have also been used to address some of the questions originally envisioned for the Network, including changes and trends in phenological events in recent years.

Changes, trends and projections in phenology

With 13 years of observations, the phenology dataset contributed through *Nature's Notebook* and maintained by the USA-NPN can play a role in documenting emerging advancements and delays in phenology. For example, using observations contributed by *Nature's Notebook* participants, Howard (2018) demonstrated progressively earlier flowering in common milkweed (*Asclepias syriaca*), an obligate host plant for monarch butterflies (*Danaus plexippus*), under warmer growing season conditions. In a similar vein, Brenskelle et al. (2019) evaluated changes in the timing of flowering in black cherry (*Prunus serotina*) using observations contributed to *Nature's Notebook* and imaged herbarium specimens. The combined observations showed that across North America, black cherry has steadily advanced spring blooming over the past 125 years. Combining phenology data contributed through *Nature's Notebook* with additional sources such as herbarium records, as demonstrated by Brenskelle et al. (2019), is becoming increasingly possible by the development and enhancement of the Plant Phenology Ontology, a tool that facilitates harmonization of phenology datasets originating from different sources (Stucky et al. 2018). Efforts are currently underway to expand the phenology data sources available through a single portal. Because phenology observations derived from other sources can cover a longer temporal record than the *Nature's Notebook* dataset, the ontology can dramatically expand our understanding of how plant phenology has changed over time.

Observations contributed to *Nature's Notebook* have also been instrumental in disentangling reasons for changes in the timing of seasonal events. Consistent with a raft of previous studies, Fu et al. (2015) showed that leaf-out in deciduous trees in the Northern Hemisphere has advanced in recent decades in response to warmer winter and spring temperatures. A surprising and novel finding was that in recent decades, the amount of springtime warmth the trees must experience to trigger budburst also increased during this period, which diminished the advancement in leaf phenology. In a related study taking advantage of *Nature's Notebook* observations, Piao et al. (2015) determined that daytime temperatures play a much larger role than nighttime temperatures in triggering leaf-out.

Phenology also plays a role in determining species ranges. For example, many plants' ranges are limited to the north by a sufficiently long growing season to achieve fruit maturation and to the south by a sufficiently cool season to achieve necessary exposure to chill (Chuine 2010). USA-NPN phenology data can be a valuable resource in understanding the role that phenology plays in limiting species ranges now and into the future, and the geographic extent of the observations for many species makes them especially well-suited for this type of use. Chapman et al. (2014) used observations of ragweed phenology contributed by *Nature's Notebook* observers to predict where ragweed, a highly allergenic plant, will be able to reach reproductive maturity before autumn frost kills the plant under future warming scenarios. Likewise, Prevéy et al. (2020a, b) predicted changes in distribution and the timing of flowering and fruit ripening in culturally important food-producing plants under future warming scenarios using *Nature's Notebook* observations.

Forecasting phenology

The rich and growing USA-NPN phenology data resource has also enabled advancements in understanding the cues to leaf-out, flowering, leaf color change, and more (e.g., Mazer et al. 2015, Melaas et al. 2016, Crimmins et al. 2017). For example, combining USA-NPN data with herbarium records, Park and Mazer (2018) demonstrated the importance of infrequently considered drivers to flowering, including the number of frost-free days and the quantity of precipitation as snow in the seasons preceding flowering. Liang (2018) demonstrated the importance of accounting for varying sensitivity to phenological cues across a species' range, constructing models predicting breaking leaf buds and autumn leaf color using data from *Nature's Notebook* and common gardens. Liang and Wu (2021) expanded on this work and developed an approach to account for local adaptation within species across latitudinal gradients using *Nature's Note-*

book observations of leaf bud break for several tree species.

The USA-NPN phenology data have also facilitated new techniques for predicting the timing of phenological events. For example, Elmendorf et al. (2019) implemented survival analysis to predict the timing of leaf out and leaf color change. This novel approach takes advantage of observations from many species and regions to predict transition states for individual species in specific locations. Taylor and White (2020) developed a system for generating near-term, daily, fine resolution forecasts of budburst, flowers, ripe fruit, and fall colors for 78 plant species using *Nature's Notebook* observations as inputs. Both of these studies shed light on how phenology forecasts might be operationalized.

Finally, *Nature's Notebook* data have been fundamental in recent advances in statistical methods for evaluating phenology. Pearse et al. (2017) demonstrated the use of statistical estimators to improve the accuracy of estimates of phenological onset and end dates, enabling improved ability to estimate changes in phenology over time. Applying this approach to *Nature's Notebook* observations, the authors revealed advancing phenology and increasing variability in the timing of bloom in deciduous trees. In a related effort, Belitz et al. (2020) developed an approach that can provide estimates of phenology for any percentile of a distribution. Developments such as these are invaluable for estimating starts and peaks in phenological events in sparsely sampled species as well as in identifying changes in these measures.

Remote sensing applications

The nuanced measurements of changes in leaf budburst and elongation that result from the USA-NPN plant protocols are especially useful in ground-truthing canopy development measures estimated from remotely-sensed data. Numerous recent studies have used the phenology observations maintained by the USA-NPN to validate and verify information collected by drone-, aircraft-, and satellite-borne sensors (e.g., Browning et al. 2017, Peng et al. 2017, Peng et al. 2018, Bórnez et al. 2020, Chen and Yang 2020, Xin et al. 2020, Zhang et al. 2020, Li et al. 2021, Morisette et al. 2021). Xin et al. (2020) repeatedly emphasized the importance of ground observations such as those offered by the USA-NPN in validating and verifying imagery collected by remote sensors.

To our knowledge, the authors of each of these studies used only the leaf status information logged through *Nature's Notebook* in their comparisons (i.e. presence or absence of leaves). However, the USA-NPN protocols were developed with substantial input from the remote sensing community, with the recognition that refined measurements of canopy development could be highly beneficial in validating remotely sensed data and models. Since 2012, when intensity and abundance measures were added to the USA-NPN protocols, observers have reported percent canopy in ordinal bins (<5%, 5-24%, etc.) in greater than 80% of records, offering a wealth of untapped information.

Though relatively few published studies have utilized the intensity and abundance measures logged as a part of *Nature's Notebook* observations, a few examples exist. Jeong and Medvigy (2014) used *Nature's Notebook* observations to establish the drivers of leaf color change in six deciduous tree species. The intensity information enabled the authors to identify conditions associated with tree canopies nearly completely colored, as opposed to considering conditions associated with any amount of leaves colored. In a recent study in the arid Southwest, phenology intensity measures revealed substantial fluctuations in grass and tree canopy greenness from week to week in response to infrequent rainfall (Morisette et al. 2021).

Relationships across latitudinal gradients

Warmer temperatures in urban and developed areas are known to advance the timing of leaf out and flowering. A study combining phenology observations collected across the U.S. through *Nature's Notebook* with European phenology observations revealed the surprising result that though leaf-out and flowering occurs earlier in urban areas than in rural areas in cool climates, this pattern does not hold for warm climates (Li et al. 2019). Specifically, in New York, a state characterized by cold winters, leaf-out occurs approximately nine days earlier in urban areas than in surrounding rural areas. In contrast, leaf-out in urban areas of Florida is occurring about a day later than in nearby undeveloped areas.

Maynard-Bean et al. (2020) leveraged the capacity of *Nature's Notebook* participants to generate observations across a large geographic area to investigate the impact of extended leaf phenology among invasive understory shrubs across deciduous forests of eastern North America. Earlier leaf emergence and later leaf off in introduced shrubs compared to native shrubs can benefit invasives and negatively affect native plants and animals, though the extent of these impacts across North American forests was previously unknown. Through a collaborative *Nature's Notebook* campaign executed by the USA-NPN and designed to encourage observations on leaf phenology of native and invasive understory shrubs, Maynard-Bean engaged nearly 800 volunteer observers in contributing more than 8,000 observations across the eastern U.S. With these observations, the authors demonstrated that invasives can leaf out months earlier than native shrubs, but that this temporal gap decreases dramatically with increasing latitude.

Fundamental ecological discoveries

Several research teams have made use of the data contributed to *Nature's Notebook* to better understand species interactions and ecosystem functioning. For example, McCormack et al. (2014) evaluated patterns in the timing of leaf and root phenology in deciduous and coniferous trees. A key finding was that root production and bud break are not tightly linked, and that in many species, production of fine roots begins well before production of leaves. Gerst et al. (2017) capitalized on the large number of observations of leaf-out and flowering in several closely related species to demonstrate that these phenophases respond very differently to precipitation and temperature cues in temperate versus arid environments. Finally, Yule and Bronstein (2017) evaluated the timing of flowering and fruiting in desert mistletoe (*Phoradendron californicum*) infecting five host plant species -- desert ironwood, blue palo verde, foothills palo verde, catclaw acacia, and velvet mesquite -- to better understand the reproductive biology of this common desert parasite.

***Nature's Notebook* and rigorously observed phenological events support natural resource management**

Phenology intersects with natural resource management in many ways, and an explicit incorporation of this measure into planning can support achievement of management goals and objectives (Enquist et al. 2014). In particular, an explicit understanding of when key seasonal events take place, such as when ground-nesting birds are brooding, can dictate when management activities such as mowing should occur (Perlut et al. 2011). Similarly, a better appreciation of the phenology of species of interest can guide the timing of treatments such as prescribed burns or thinning to optimize benefits and minimize negative impacts. Phenology monitoring can also comprise a key component of adaptive management, indicating, for example, whether periods of key resource availability are changing and therefore prompting additional adjustments to management actions. For instance, climate-induced shifts in the timing of breeding and rearing young in game species may necessitate adjustments to hunting seasons. Finally, synchronicities in seasonal events among multiple species, when identified, can guide when to take specific actions. For example, through careful tracking of phenology, Herms (2004) established that pine needle scale insects (*Chionaspis pinifoliae*) hatch and are best controlled when common lilacs (*Syringa vulgaris*) reach full bloom; likewise, bronze birch borers (*Agrilus anxius*) trapping is most effective when black locust (*Robinia pseudoacacia*) trees are just beginning to flower. Changing climate conditions can challenge the stability of such synchronies, as well as other symbiotic relationships that exist because of co-evolved phenologies; long-term phenology monitoring can reveal instances where mismatches in species' phenologies are emerging. *Nature's Notebook* is increasingly being implemented as a way to track phenology of species of interest or concern and to guide management activities.

Optimally timing management actions

Multiple land management units and agencies across the country have adopted *Nature's Notebook* to guide the timing of particular management activities in a growing roster of applications. For example, natural resource managers at Midway Atoll National Wildlife Refuge (NWR) used *Nature's Notebook* to track the timing of flowering and seed development in golden crownbeard (*Verbesina encelioides*), an invasive plant, over several years (Taylor et al. 2020). Their observations revealed the window of time available to remove plants between emergence and seed set, and how that window varied between seasons. Similarly, staff at Valle de Oro NWR documented the timing of seed ripening in native Rio Grande cottonwood (*Populus deltoides wislizenii*) and invasive Siberian elm (*Ulmus pumila*) over several years. The information gleaned enabled them to time flooding activities to promote the germination of cottonwoods and avoid germination of elms. Valle de Oro NWR staff also tracked the nesting timing of Cliff and Barn Swallows at an old milk barn at the Refuge to identify when to remove the barn to have the least impact on the birds. Finally, Acadia National Park uses phenology data collected in locations in and around the park to identify species to use in restoration efforts.

The data resource yielded through crowd-sourced observations of plant and animal phenology via *Nature's Notebook* also enables management-relevant discoveries that can guide future planning and actions. For example, researchers used observations of buffelgrass (*Cenchrus ciliare*) phenology, contributed to *Nature's Notebook* by community volunteers, to determine the amount of rain necessary to trigger green-up (Wallace et al. 2016). This invasive grass, rapidly spreading across the Sonoran Desert and causing fire risk to non-fire-adapted communities, must be at least 50% green to be effectively treated with herbicide. Establishing the necessary amount of rainfall required to trigger green-up has enabled the creation of short-term forecasts of buffelgrass greenness, providing managers with the information needed to prioritize where to scout and treat the grass during the summer monsoon season (Gerst et al. under review). In a similar effort, Emery et al. (2020) determined that the critical live fuel moisture threshold of 79% is crossed in chamise (*Adenostoma fasciculatum*), a common and widely distributed plant in chaparral ecosystems in fire-prone California, after the plant has flowered and before fruits have developed. Using this knowledge, managers can readily and inexpensively assess live fuel moisture status in chaparral simply by looking at the flower and fruit status of chamise.

Supporting adaptive management

Shifts in phenological events such as the timing of peak resource availability, can necessitate adjustments to monitoring and management actions. *Nature's Notebook* offers infrastructure and a data resource to support such discoveries. For example, a data collection campaign initiated by the US Fish & Wildlife Service engages volunteers across southern Arizona in tracking the timing and abundance of flowers in key nectar plants of the migratory lesser long-nosed bat (*Leptonycteris yerbabuenae*) as part of the agency's post-delisting monitoring efforts (USFWS 2019). These observations indicate whether food resources are abundant at the critical time when bats are raising their young.

Tracking synchrony among species

The intensity and abundance measures that are a part of USA-NPN protocols also enhance efforts to identify possibly emerging mismatches among dependent species. Volunteers at McDowell Sonoran Conservancy in Phoenix, AZ, are carefully tracking the phenology of migratory white-winged doves and saguaro cacti, which share a mutually beneficial plant-pollinator relationship. During the summer breeding season, doves rely almost exclusively on saguaro for food and water resources. In return, saguaros benefit from the doves' pollination services. Changes in the timing of activity in either of these species could spell trouble for the birds and the cacti. Volunteers at McDowell Sonoran Conservancy have documented strong temporal overlap between bird activity and peaks in saguaro flowers and fruits over the past five years, indicating a stable relationship at present (Holden 2020). These data, and continued monitoring, provide an important baseline and basis for identifying emerging mismatches.

Volunteer-contributed observations of phenology also offer the ability to evaluate the stability and persistence of phenological synchronicities. For example, each spring, up to 16 states in the southeastern U.S. deploy traps to assess the potential for southern pine beetle (*Dendroctonus frontalis*) outbreak and to estimate prevention and suppression needs for the year. The timing of trap deployment has historically been initiated after the start of bloom in dogwood (*Cornus florida*). Thomason et al. (2021) sought to validate the relationship between dogwood bloom and pine beetle dispersal using observations of dogwood flowering contributed by participants in *Nature's Notebook*. Their analysis revealed that dogwoods start to flower three weeks *after* the peak in pine beetle dispersal and that dogwood flowering therefore is not a robust indicator for when to set traps. Whether the start of flowering in dogwoods was historically coincident with beetle dispersal is yet unknown; regardless, this study demonstrated that conditions associated with beetle dispersal might result in more effectively-timed trap deployment.

Reflections and next steps

As evidenced by the growing number and diversity of applications in which the *Nature's Notebook* program and the resultant data being used, the original aims of the USA National Phenology Network -- to improve understanding of patterns in plant and animal phenology, of the relationships between plant and animal phenology and environmental drivers, and of changes in phenology driven by changing environmental conditions -- are being realized. In addition, the program and data are being referenced, analyzed, and applied in many additional ways not initially envisioned, underscoring the necessity of continued -- and expanded -- phenology monitoring. The value of phenology data for revealing changes only increases over time; the potential that is yet to be realized in the U.S. is foreshadowed by the findings emerging from countries where phenology monitoring has been taking place for much longer.

This survey of studies making use of phenology data contributed to *Nature's Notebook* revealed several insights. In particular, the absence of a single, overarching question driving data collection in *Nature's Notebook* has allowed for great flexibility in its application and wide adoption by participants of all skill levels. For example, natural resource managers frequently collect phenology data using *Nature's Notebook* with a particular local-scale question or need in mind, and use the findings emerging from their observations to inform their activities. In a similar fashion, many researchers also use the USA-NPN protocols and/or the *Nature's Notebook* platform to support data collection to answer a particular question. In some cases, researchers actively engage *Nature's Notebook* participants to dramatically expand the data available to answer a particular question (e.g., Elmore et al. 2016, Maynard-Bean et al. 2020). This flexibility is a strength, enabling many and various fundamental science and applied management questions to be asked and answered at scales ranging from local to continental.

One finding revealed by this review is that the lack of an imposed sampling design has resulted in an opportunistically-sampled phenology dataset that is unbalanced across geography and species and characterized by inconsistent sampling frequency and duration. As such, many of the research applications that have used these data are those that capitalize on the taxonomic and geographic breadth of observations, such as evaluations of relationships and patterns across gradients, comparisons involving multiple species, and efforts to identify drivers to phenological transitions.

This review of the outputs and outcomes of the *Nature's Notebook* program sets the stage for a deeper and richer evaluation of the strengths and opportunities for the Network, particularly in the realm of data collection. The scientific community continues to identify unanswered questions and needs, including distinguishing among environmental and organismal drivers of phenological change (Chmura et al. 2018) and addressing spatiotemporal gaps in phenological observations and measurements (Park et al. 2021). Further, as climate conditions continue to change, continued phenology monitoring will be a critically important input to decision-making frameworks such as the Resist, Accept, Direct tool (Schuurman et al. 2020) used by the National Park Service and other U.S. land management agencies. Finally, the Network aims to support the multiple ways of understanding and interacting with phenology that emerge from diverse cultures. A careful assessment of the *Nature's Notebook* program is merited, to ensure the program and the data being generated are as well-suited for these types of applications as possible.

Box 1: *Nature's Notebook* by the numbers

Nature's Notebook is the USA National Phenology Network's plant and animal phenology monitoring program. A major strength of the phenology data contributed through *Nature's Notebook* is the taxonomic diversity present. Nearly 1,500 taxa of plants and animals are available for tracking within the program. Of these, observers have contributed phenology observations for 1,325. Further, over 100,000 observation records have been contributed for more than 60 species, and over 50,000 records have been contributed for 130 species (Figure 3a), indicating that a relatively large pool of data is available for many of these species.

Another strength of the USA-NPN's phenology data resource is the geographic extent of observations. The majority of the species available for monitoring within *Nature's Notebook* have been observed at many locations across the country. Specifically, observations have been contributed at over 1,000 sites for 32 species, and more than 100 species have been observed at over 500 sites (Figure 1). Over 500 species have been observed at 100 or more sites.

The USA-NPN phenology observing protocols available in *Nature's Notebook* yield a record of the status of multiple life cycle events over the course of the growing season. For plants, nearly half of records represent leaf phenophases (Figure 3b; the remaining half of records are fairly equally split among flower and fruit phenophases. Activity, feeding, and reproduction phenophases are relatively equally represented within animal observations (Figure 3c).

Since *Nature's Notebook* launched in 2009, over 21,000 observers have submitted data at over 16,000 sites. The dimensions of the data contributed vary notably between observers that participate in the program independently and by members of a Local Phenology Program. In general, the number of observations contributed to *Nature's Notebook* has increased in each year of the program's existence, and the rate of growth in contributed observations has been much greater for Local Phenology Program participants (Figure 3d). In total, two-thirds of all observations have been contributed by members of Local Phenology Programs. In addition, sites under observation by Local Phenology Networks boast nearly triple the observation frequency than those tracked by individual observers: Local Phenology Program sites are visited 23 days a year on average (±25.8d SD), while sites belonging to individual observers are observed an average of 10 times a year (±19.6d SD; Figure 3f).

Finally, *Nature's Notebook* sites are much more likely to boast a longer period of observation if they are maintained by a Local Phenology Program. Of the more than 13,000 sites monitored by individual participants in *Nature's Notebook*, 16% (2,149) exhibit observations for more than one year (Figure 3f). In contrast, 64% of the nearly 2,000 sites monitored by Local Phenology Programs have data for multiple years, and 26% of these sites boast data for five or more years.

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Biographical narrative

Theresa Crimmins, Ellen Denny, Erin Posthumus, and Alyssa Rosemartin are staff members of the USA National Phenology Network, based in the School of Natural Resources at the University of Arizona. Theresa is the Network director, Ellen is the monitoring design & data coordinator, Erin is the outreach coordinator and USFWS liaison, and Alyssa is the partner & application specialist.

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Figure 1. Phenology observation records contributed to *Nature's Notebook*, 2009-2021.

Figure 2. The USA National Phenology Network's phenology observation protocols reveal the status and abundance of various phenophases on each date organisms are observed. (a) The status of each phenophase on a plant or animal is recorded as occurring (depicted as a colored bar) or not occurring (grey bar) on each observation date, revealing a clear picture of when various phases started, ended, and overlapped over the course of a year. (b) Phenophase intensity or abundance is reported as a count or percent of structures expressing the status, such as number of flowers present or percent of canopy full with leaves, enabling visualization of degree of phenophase expression over the year.

Figure 3. Dimensionality of phenology observations contributed to *Nature's Notebook*. (a) Volume of phenology records contributed by taxon. (b) Distribution of plant phenology records by leaf (green), flower (pink), and fruit (blue) phenophases. (c) Distribution of animal records by phenophase class. (d) Phenology records contributed by individual observers (light green) and by members of Local Phenology Programs (dark green) in each year, 2009-2020. (e) Observation frequency at sites tracked by individual observers (light green) and by members of Local Phenology Programs (dark green) in each year, 2009-2020. (f) Duration of observation (in years) for sites tracked by individual observers (left) and Local Phenology Programs (right).

Figure 1.

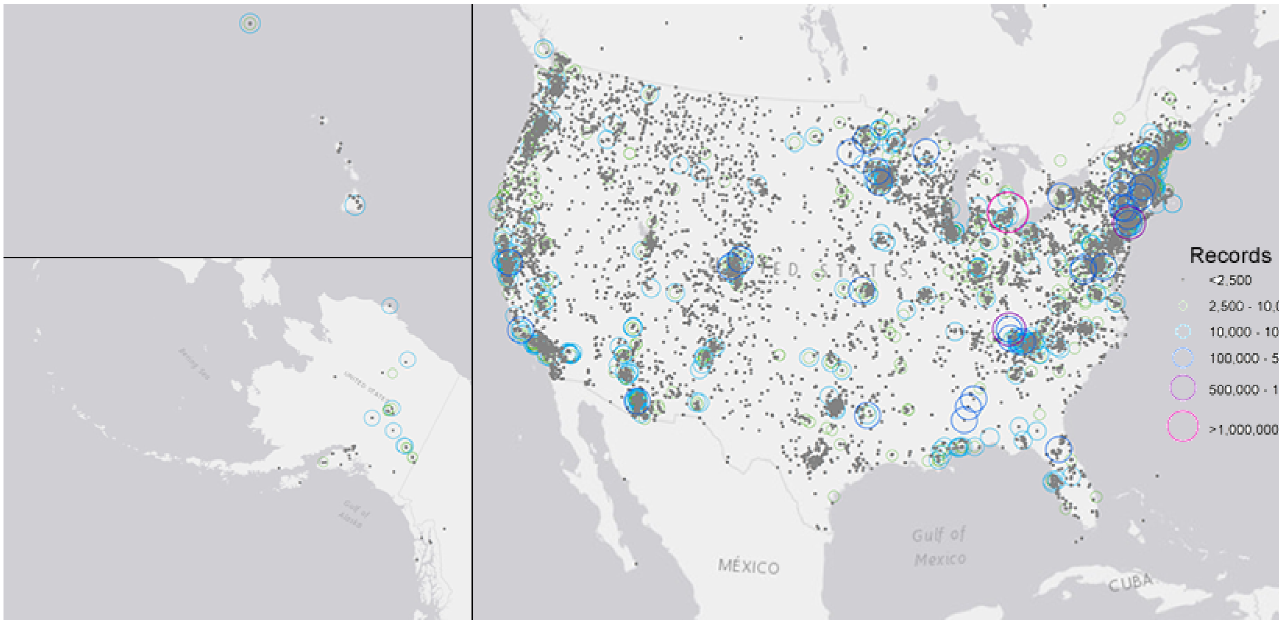

Records
<2,500
2,500 - 10,0
10,000 - 10
100,000 - 5
500,000 - 1
>1,000,000
MÉXICO
Gulf of Mexico
CUBA

Figure 2.

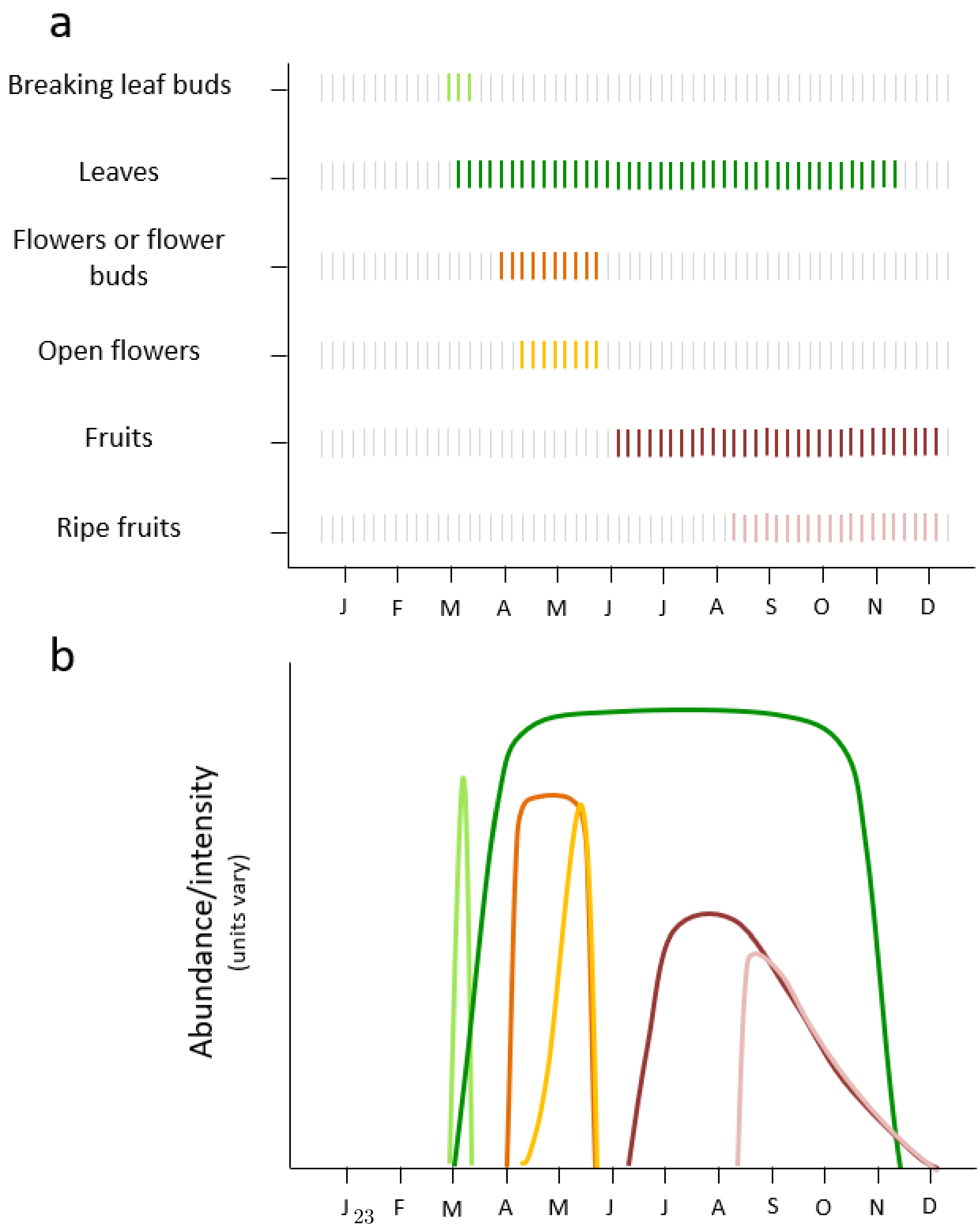
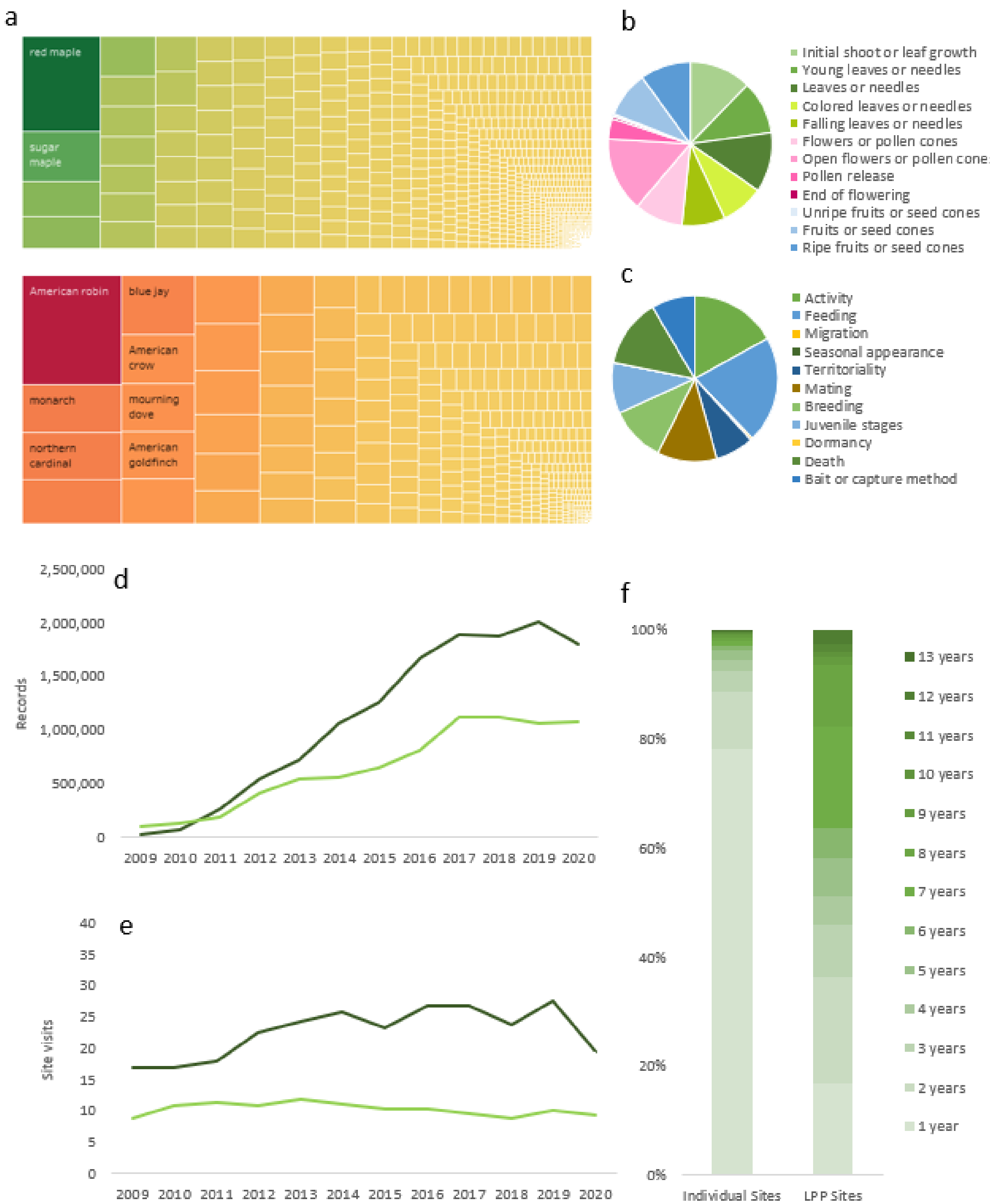

a
Breaking leaf buds
Leaves
Flowers or flower buds
Open flowers
Fruits
Ripe fruits
J F M A M J J A S O N D
b
Abundance/intensity
(units vary)
J F M A M J J A S O N D

Figure 3.



a
red maple
sugar maple
American robin
blue jay
American crow
monarch
mourning dove
northern cardinal
American goldfinch
b
Initial shoot or leaf growth
Young leaves or needles
Leaves or needles
Colored leaves or needles
Falling leaves or needles
Flowers or pollen cones
Open flowers or pollen cones
Pollen release
End of flowering
Unripe fruits or seed cones
Fruits or seed cones
Ripe fruits or seed cones
c
Activity
Feeding
Migration
Seasonal appearance
Territoriality
Mating
Breeding
Juvenile stages
Dormancy
Death
Bait or capture method
d
Records
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
e
Site visits
40
35
30
25
20
15
10
5
0
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
f
100%
80%
60%
40%
20%
0%
Individual Sites
LPP Sites
13 years
12 years
11 years
10 years
9 years
8 years
7 years
6 years
5 years
4 years
3 years
2 years
1 year