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

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Abstract

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

Since the launch of *Nature's Notebook*, participants across the country have contributed over 28M phenology records. Participants range from backyard observers with an interest in nature to researchers and natural resource managers asking specific questions. We survey the breadth of studies and applied decisions that have utilized *Nature's Notebook* and the consequent data. The dimensionality of the dataset maintained by the Network is a function of *Nature's Notebook* users; this insight is key to shaping the Network's future data collection activities.

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— responds strongly to local environmental conditions such as temperature, daylength, and moisture availability (Rathcke and Lacey 1985). In recent decades, the timing of such events has changed -- in some cases dramatically -- in many species in response to increasing temperatures and changing conditions (Parmesan and Yohe 2003, Root et al. 2003, Cohen et al. 2018, United Nations Environment Programme 2022).

Humans have relied on phenological knowledge since the origin of the species for their very survival, recognizing environmental cues that indicate the availability of food and other resources. Many Indigenous peoples continue to incorporate knowledge of phenology into their subsistence lifeways, resource management, planting, harvesting, and ceremony (Kenote 2020, Box 1). However, recent changes in the timing of traditional seasonal indicators is making this knowledge less reliable.

> *"Two weeks before it freezes is when the tullibees hit and they run*

> *until it freezes during that two week time. So, if the climate change makes this two week thing start two months ahead of time, a lot of my people… are going to get messed up big time.” Carmen Butler, Bikoganoogan Ojibwe Elder*

Formally tracking phenology enables a clearer understanding of how the timing of seasonal events are changing in response to changing climate conditions as well as the consequences of these changes (Inouye et al. 2022). Regularly collected observations can support decision making, such as when to treat invasive species, and provide useful information, such as when the allergy season may start or intensify. As time passes, formally recorded phenology observations become increasingly valuable as a historical record (Büntgen et al. 2022).

In various countries around the globe, formal approaches to tracking phenology have been in place for decades or even centuries (Renner and Chmielewski 2021). In the U.S., long-term phenology monitoring has historically occurred to a limited extent and primarily at only a handful of discrete locations (e.g., Inouye 2008, Rafferty et al. 2020). A notable exception is a historical lilac and honeysuckle monitoring effort, established in late 1950s and early 1960s (Schwartz et al. 2013). This program engaged volunteers across the country in leaf and flowering phenology at several hundred sites over nearly four decades. The resultant observations were instrumental in demonstrating clear advancements in leaf-out and flowering across the U.S. (Cayan 2001).

Formalizing phenology monitoring in the United States

Motivated by the changes observed through the lilac and honeysuckle monitoring program in the U.S. and clear advancements in phenology being reported in other countries (e.g., Menzel et al. 2006), researchers representing the US Geological Survey, the University of Wisconsin - Milwaukee, and other institutions established the USA National Phenology Network (USA-NPN) in 2007. At its inception, the Network was a collaborative effort between the US Geological Survey and the University of Arizona; over the years, the Network has been supported by contributions from the National Science Foundation, the US Fish & Wildlife Service, NASA, the National Park Service, NOAA, The Wildlife Society, and several other organizations. Over subsequent years, the Network's aims and activities were shaped by input from an advisory body and many dozens of scientists and natural resource managers (Betancourt et al. 2007, Nolan and Weltzin 2011, Schwartz et al. 2012, Glynn and Owen 2015).

The primary aim of the Network is to document the timing of seasonal events in plants and animals to support scientific understanding, resource management, and a greater understanding of phenology by multiple communities. To achieve these objectives, the Network launched *Nature's Notebook*, a plant and animal phenology monitoring platform in 2009 (Rosemartin et al. 2014). Since the launch of *Nature's Notebook* 13 years ago, participants in all 50 states in the U.S. as well as in Puerto Rico, the Virgin Islands, Canada, and Mexico have contributed over 28M records of plant and animal phenology (Fig 1).

In this paper, we describe the *Nature's Notebook* platform and the various ways it is used by individuals, scientists, educators, and natural resource managers to achieve their goals. We also summarize the diverse ways that phenology data contributed through this platform to support science and society. Finally, we reflect on how the uses of this platform have shaped the phenology data resource offered by the USA-NPN and whether the Network might consider actively driving data collection to support particular high-priority questions and needs.

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

Flexible infrastructure and implementation

The *Nature's Notebook* platform (www.naturesnotebook.org) is highly flexible, designed to be used by professional and volunteer observers, independently or as part of an organized group (Posthumus et al. 2019, Crimmins et al. 2020). The platform consists of standardized observation protocols, a mobile app for data collection, an online interface for submitting and accessing observations, and data visualization and download tools. The Network also offers extensive training materials in multiple formats; emails frequent, information-rich messages to participants; and customizes website content to feature and enhance collaborators' data collection efforts. Platform users can utilize these various features and opportunities to best meet their data collection and engagement needs.

Rigorous yet approachable protocols

The core of *Nature's Notebook* 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. These protocols were developed with input from many researchers and volunteer observers to optimize ease of use by non-scientists and the utility of resulting data. 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," start and end in a season for individual plants and animals under observation (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 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 plant; what percentage of the flowers are open; or 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.

Nature’s Notebook *uses shape the resulting phenology data*

The *Nature’s Notebook* platform is used in a range of ways by various audiences to collect, maintain, visualize, and share phenology observations. Over the 13 years *Nature’s Notebook* has been available, over 23,000 observers have submitted data from over 17,000 sites, and a handful common uses have emerged. The different uses of the platform directly shape the phenology dataset maintained by the USA-NPN (Table 1).

A large segment of *Nature’s Notebook* participants are individuals that collect phenology observations independently. Individual *Nature’s Notebook* observers most frequently track phenology for reasons of personal enjoyment, an interest in learning, and a desire to contribute to a valuable, national-scale effort (Goldsmith et al. 2019). Observers that participate as individuals track taxa of personal interest and generally remain active in phenology observing for a single season; only 16% continue observing in a second or subsequent year (Fig 3a). Accordingly, the observations originating from this segment of *Nature’s Notebook* participants represent many species with fewer observations as well as comparatively lower observation frequency and duration (Fig 3b,c).

In a second model, members of a pre-existing group, such as students in a classroom or docents at an arboretum, collectively adopt phenology monitoring using *Nature’s Notebook* to support science, management, or outreach goals articulated by the host institution. Phenology observations collected by these groups – referred to as Local Phenology Programs (LPPs) -- tend to be collected at a high frequency and regularity for species of the group’s choosing (Fig 3b,c). 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, universities, and the National Ecological Observatory Network (NEON). Collectively, these groups contribute two-thirds of the phenology records submitted each year (Fig 3a). Phenology observations contributed by Local Phenology Programs tend to be robust, collected frequently and carefully. However, species selected by these groups may not be widely observed at other locations. As such, LPPs data, while well-sampled, can sometimes have limited applicability.

The *Nature's Notebook* platform has also been adopted by natural resource professionals across the country seeking to answer questions specific to their management units, following the LPP model. The integrated and customizable data collection, management, and access functionalities available through the platform allow managers to establish a data collection effort with relative ease (Taylor et al. 2020). In addition, USA-NPN protocols and infrastructure are compliant with federal policy governing information management, including paperwork reduction, privacy and security, enabling data collection by staff or volunteers on public lands. Use of the *Nature's Notebook* platform by natural resource professionals and their LPPs tends to result in frequent observations for the species of interest on the properties being managed by the organization leading the monitoring. However, the taxa prioritized at individual management units are not always widely observed at locations beyond the management units, resulting in robust but geographically limited observations for the taxa of focus.

Finally, a growing use of the *Nature's Notebook* platform is by researchers and resource managers seeking to increase the volume and geographic extent of phenology observations to answer a specific question. In this model, the project lead and USA-NPN team members collaboratively design and execute a data collection campaign with focus on a limited number of species and phenophases. Data contributors may include individuals already active in tracking phenology using *Nature's Notebook* or participants newly recruited to the program specifically in support of the campaign. Typically, these campaigns involve the project leads communicating directly with *Nature's Notebook* participants over the duration of the effort through webinars and campaign messaging hosted by the USA-NPN. Campaigns tend to result in more individual organisms under observation, increased observation frequency, and longer sustained monitoring (Crimmins et al. 2014), and ultimately lead to scientific and management outputs (e.g., Elmore et al. 2016, Maynard-Bean et al. 2020, USFWS 2019).

Phenology observations originating through these uses of the *Nature's Notebook* platform funnel into a single phenology database maintained by the USA-NPN. The "shape" of this consequent data resource is both taxonomically and spatially unbalanced (Box 2, Fig 4). Even so, the phenology data resource made freely available by the USA-NPN is analyzed and used in a growing number of science and management applications.

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

Phenology is a key aspect of ecosystem functioning, shaping community structure and composition, water and nutrient cycling, and species range and interactions, with clear societal and economic impacts. The phenology data contributed through the *Nature's Notebook* platform and made freely available by the USA-NPN are increasingly central to scientific discoveries. These uses span evaluating shifts in phenology, forecasting phenology, ground-truthing remotely sensed imagery, and investigating fundamental ecological relationships (Table

2).

Changes, trends and projections in phenology

The phenology data maintained by the USA-NPN are, perhaps first and foremost, suited for documenting changes in phenology, especially when they are combined with historical records that extend the temporal period. 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 standardized vocabulary and semantic framework that facilitates harmonization of plant phenology datasets originating from different sources and collected with different methodologies (Stucky et al. 2018). Efforts are currently underway to expand the data sources mapped to the Ontology and make the integrated data easily accessible from a single portal.

Remote sensing applications

The nuanced measurements of leaf budburst and elongation documented with the USA-NPN plant protocols are especially useful in ground-truthing canopy development measures estimated from remotely sensed data. Numerous recent studies have used these data to validate and verify information collected by drone-, aircraft-, and satellite-borne sensors. Xin et al. (2020) evaluated various methods for identifying the start and end of the growing season from satellite imagery using the ground-based observations of leaf-out and leaf-off reported through *Nature's Notebook* as a basis for comparison. In this paper, the authors repeatedly stressed the importance of ground observations such as those offered by the USA-NPN in validating and verifying imagery collected by remotely deployed sensors.

Relationships across gradients

Because of their large spatial extent, the data contributed through *Nature's Notebook* are well suited to addressing questions and documenting patterns at a regional scale and across latitude, elevation, or resource gradients. Li et al. (2019) examined the influence of urbanization on phenology across the U.S. and Europe. The authors documented 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. 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.

Fundamental ecological discoveries

Several research teams have used the data contributed to *Nature's Notebook* to better understand species interactions and ecosystem functioning. For example, 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.

Forecasting phenology

The taxonomic breadth and sheer number of phenology records maintained by the USA-NPN also facilitate innovative investigations. In the first study of this kind, Elmendorf et al. (2019) implemented survival analysis to predict the timing of leaf out and leaf color change across dozens of plant species. This novel approach capitalized on observations from many species and regions to predict transition states for individual species in specific locations. In addition, this analysis sheds light on how iterative phenology forecasts might eventually be operationalized by the USA-NPN.

***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 used to track phenology of species of interest or concern and to guide management activities (Table 3). These uses range from optimally timing management activities to supporting adaptive management to tracking interacting species for potential temporal mismatches.

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, 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. Thomason et al. (2021) used *Nature's Notebook* observations of dogwood (*Cornus florida*) flowering to evaluate whether the timing of this event, which historically has been used as a cue for foresters to deploy southern pine beetle (*Dendroctonus frontalis*), is in fact, a good predictor of pine beetle activity. Their analysis revealed that dogwoods start to flower three weeks *after* the peak in pine beetle dispersal and that dogwood flowering is not a robust indicator of when to set traps.

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 *Nature's Notebook*-based 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, Arizona 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.

Reflections and next steps

The taxonomically rich, geographically extensive phenology observations contributed through the *Nature's Notebook* platform are increasingly used to address information gaps in management and science in the U.S. The data contributed are most well-suited for the applications they were collected to address, whether they be large-scale research questions or local-scale management concerns. The phenology observations are also useful in applications where unbalanced sampling is of lesser concern, such as ground-truthing remotely sensed imagery.

When considered *in toto*, the data contributed to *Nature's Notebook* exhibits particular characteristics and biases. For example, as in many citizen science projects (Dunn et al. 2005, Callaghan et al. 2019), observations contributed to *Nature's Notebook* are concentrated near population centers, where participants tend to reside (Fig 1). Species biases exist as well: common, visible, and sessile species tend to enjoy a higher rate of observation, as do species featured in data collection campaigns. Further, data quality tends to improve as observers persist with the program; the first observations participants make may be of poorer quality. Reporting accuracy and precision are generally lower for the earliest phenophases in a season, such as breaking leaf buds, than events occurring later, such as unfolded leaves and open flowers (Fuccillo et al. 2014, Crimmins et al. 2017), and observers report higher confidence in correctly identifying phenophases in their second and subsequent years of observing. Finally, the data exhibit inconsistent sampling frequency and duration.

These inconsistencies result in a dataset that requires care and attention when used in analyses. USA-NPN staff are aware of these challenges and potential barriers to data use and are actively developing tools and guidance to support data cleaning and proper use in analysis. These include enhancing the Network's R package, *rnpn*; improving discoverability of site conditions reported by observers; and flagging data that appear suspect. To minimize erroneous reports, USA-NPN staff continue to refine training materials and support and are developing functionality to allow observers to visualize and correct their observations.

Outstanding potential and next steps

Rigorously documented phenology observations collected across geography and many taxa have the potential to contribute meaningfully to many outstanding science questions and societal needs. For example, asynchronies among interacting species tend to be short-lived and are therefore difficult to identify (Renner and Zohner 2018); robust and widespread phenology data collection has the potential to better capture such ephemeral and important phenomena. Additionally, increased observations of leaf-on and leaf-off can address gaps in estimates of forest carbon uptake and storage (Keenan et al. 2014, Piao et al. 2018) as well as feedbacks between vegetation and the atmosphere (Piao et al. 2018). Richer and denser phenology observations can also fill knowledge gaps by distinguishing among environmental and organismal drivers of phenological change (Chmura et al. 2018). Finally, dense spatial and temporal observations of flowering can address a major gap in pollen and allergen mapping and forecasting (Asrar et al. 2020), with substantial positive impact to allergy sufferers. The phenology data maintained by the USA-NPN to-date have not been utilized in many of these applications.

Unbalanced, biased data are not uncommon in citizen science programs, especially when programs were not set up to address particular questions necessitating data of a particular "shape" (Dunn et al. 2005). To generate data better-suited to address particular topical areas, the USA-NPN may wish to consider shifting to a more structured approach to data collection, whereby observers are encouraged or directed to collect observations at specific locations and with greater temporal regularity (Callaghan et al. 2019). However, driving volunteer data collection in particular directions is not easy (Crimmins et al. 2014, 2020). As such, such a shift in focus should be carefully considered, and merits thorough consideration of the questions and needs that might take priority and the spatial, temporal, and taxonomic dimensionality of observations needed to answer these questions. The USA-NPN might also consider potential tradeoffs of placing major emphasis on data collection to support certain high-priority aims, such as whether current volunteers or Local Phenology Program participants might feel alienated by such a shift or whether focusing data collection more narrowly could result in the inadvertent loss of data that could prove valuable at a later date.

An additional area of opportunity for the USA-NPN is to better meet the needs of various *Nature's Notebook* user groups, especially Indigenous peoples. Publicly available data, such as that contributed to *Nature's Notebook*, is not appropriate in some Indigenous contexts, as tribes hold sovereignty over data related to the species and lands they care about. The locations of plants or knowledge of their timing may be sensitive, and it is important to be transparent about what data can be protected and defer to Indigenous partners on what is appropriate to share (Box 1; Carroll et al. 2021). As the USA-NPN grows a national-scale phenology dataset, the organization can support efforts to understand phenological events that are important to Indigenous peoples and to protect the privacy of phenology data they may wish to contribute to *Nature's Notebook*.

This reflection revealed that the *Nature's Notebook* platform is well-suited for collecting data in support of particular questions and applications. The reflection also shows that the data that result from participant-driven monitoring is not necessarily well-suited for questions not envisioned at the outset of data collection, and suggests that directed data collection activities are needed to answer particular questions. The USA National Phenology Network is well-positioned to drive phenology data collection across the country to support particular knowledge gaps. A next step for the Network is a thorough consideration of the highest priority climate change or science questions or societal needs that might drive data collection and the spatial, temporal, and seasonal density of observations required to support these analyses. These specifications should be considered in conjunction with the USA-NPN's capacity for engaging and sustaining participants in data collection. This effort would be best achieved by engaging experts in a diversity of relevant scientific disciplines and applied fields as well as representatives of Indigenous communities. The outcomes of this effort could shape the USA-NPN's activities and priorities in the coming years, driving the Network to collect and offer data best suited to addressing the country's most pressing phenology-related questions and needs.

Box 1: Reconciling data sovereignty and culture: the GLIFWC phenology study

Indigenous people are the original phenologists on the lands currently known as North America. Countless generations of the eleven Ojibwe bands served by the Great Lakes Indian Fish and Wildlife Commission (GLIFWC) have survived and thrived in the often harsh climate of the northern Great Lakes. Historically, they utilized and managed a large land base, traveling seasonally to different areas where they set up temporary camps. When and where they traveled was determined by the location and availability of harvestable resources upon which they depended for spiritual, ceremonial, medicinal, subsistence, and economic needs in order to survive. This way of life led to the development of a deep, place-based understanding of the connection between seasonal changes and the life cycles of the resources in the Great Lakes region.

> *"As soon as the popple leaves got as big as a quarter, that was the sign for them, everybody would go down, the suckers would come up by the thousands and thousands, we used to go catch them." - Joey Duffyban, Gaa-miskwaabikaang Ojibwe Elder*

Much of this gikendaasowin (knowledge) was incorporated into their lives and culture and is passed from generation to generation through oral tradition. Today, many Ojibwe band members live within ceded territories, predominantly on and around their reservations, and continue to maintain a close relationship with the natural world, making a living and subsisting on the resources available at various times throughout the year. Today, the Ojibwe people honor their ancestors by continuing to sustain themselves and their culture by maintaining the lifeways preserved for them in treaties with the United States.

Since 2016, GLIFWC has conducted a plant phenology study at two sites in northern Wisconsin on land ceded to the US in the treaty of 1842. The project methods are largely based on USA-NPN protocols, though some metrics are modified to better capture cultural indicators and to accommodate beings (species) for which USA-NPN protocols are not yet developed. The plant relatives teaching us about the impact of climate change on their life cycles include ten culturally important beings used by Ojibwe people for ceremonial, subsistence, medicinal, and utilitarian purposes. Plant beings are monitored once or twice a week during the growing season. Based on guidance from elders, plant relatives were feasted at the start of the project and are offered asemaa (tobacco) at each visit in recognition of the gifts they provide and in exchange for all that they teach us.

Since the time of colonization, tribal knowledge has been exploited and used without permission to the detriment of the tribes and the beings on which they rely. According to the principles of Free Prior and Informed Consent (Food and Agriculture Organization of the United Nations 2016), anyone interested in using tribal knowledge must first inform the owners of their intention and ask permission to use data in advance. The elders, band members, and staff who informed this project made it clear that they wanted the location of the individual beings protected. Through a series of conversations, GLIFWC and USA-NPN staff evaluated the risk of sensitive data becoming publicly available if housed in *Nature's Notebook*, primarily due to exposure through the Freedom of Information Act. As a result of these conversations, GLIFWC phenology data remain housed on private servers to maintain tribal data sovereignty and ensure that focal beings in this study are not exploited. It is important to note that tribal data sovereignty concerns are not unique to GLIFWC, and different Indigenous communities will have their own approaches and policies.

Box 2: Dimensionality of the *Nature's Notebook* dataset: taxa, geography, and phenophases

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, more than 60 species have over 100,000 observation records each, and 130 other species have over 50,000 records (Fig 4a), 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, 32 species have been observed at over 1,000 sites, and more than 100 species have been observed at over 500 sites. 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 (Fig 4b; the remaining half of records are fairly equally split among flower and fruit phenophases). Within animal observations, activity, feeding, and reproduction phenophases are relatively equally represented (Fig 4c).

The taxonomic diversity, spatial density, and phenological depth present in this dataset are unique to the U.S. and enable users to explore a growing diversity of questions.

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Biographical narrative

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Table 1. Common uses of the *Nature's Notebook* phenology observing platform and "shape" of the contributed phenology observations.

	Motivation(s) or phenomena shaping
Backyard observer	Personal question or curiosity; altruism
Local Phenology Program	Host institution's science, management, an
Researcher or natural resource manager with a specific question	Research or management question

Table 2. Examples of scientific uses of phenology data contributed through *Nature's Notebook*.

Type of use	**Application**
Changes, trends, projections in phenology	Shift in flowering timing of common milkweed (*Asclepias syriaca*
Changes, trends, projections in phenology	Impacts of future warming on culturally important plants
Changes, trends, projections in phenology	Influence of day and nighttime temperatures on leaf out
Changes, trends, projections in phenology	Impact of future warming on invasive plants
Modeling and forecasting phenology	Understanding of climate drivers to phenology
Modeling and forecasting phenology	Development of an automated system for predicting timing of sea

Type of use	Application
Modeling and forecasting phenology	Using statistical methods to improve estimates of phenology onse
Remote sensing applications	Ground truthing of canopy development measures
Relationships across latitudinal gradients	Identification of climate drivers while accounting for variation ove
Relationships across latitudinal gradients	Leaf phenology in native and invasive species
Fundamental ecological discoveries	Understanding of species interactions and ecosystem functioning

Table 3. Example management applications of phenology observations contributed through *Nature's Notebook*.

Type of use	Application
Risk Assessment	Wildfire risk assessment
Selecting species for restoration	Ecosystem restoration activities at Acadia NP
Timing Management Actions	Golden crownbeard (*Verbesina encelioides*) control at Midway Atoll NWR
Timing Management Actions	Maintenance activities at Valle de Oro NWR
Timing Management Actions	Buffelgrass (*Pennisetum ciliare*) treatment in southern Arizona

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

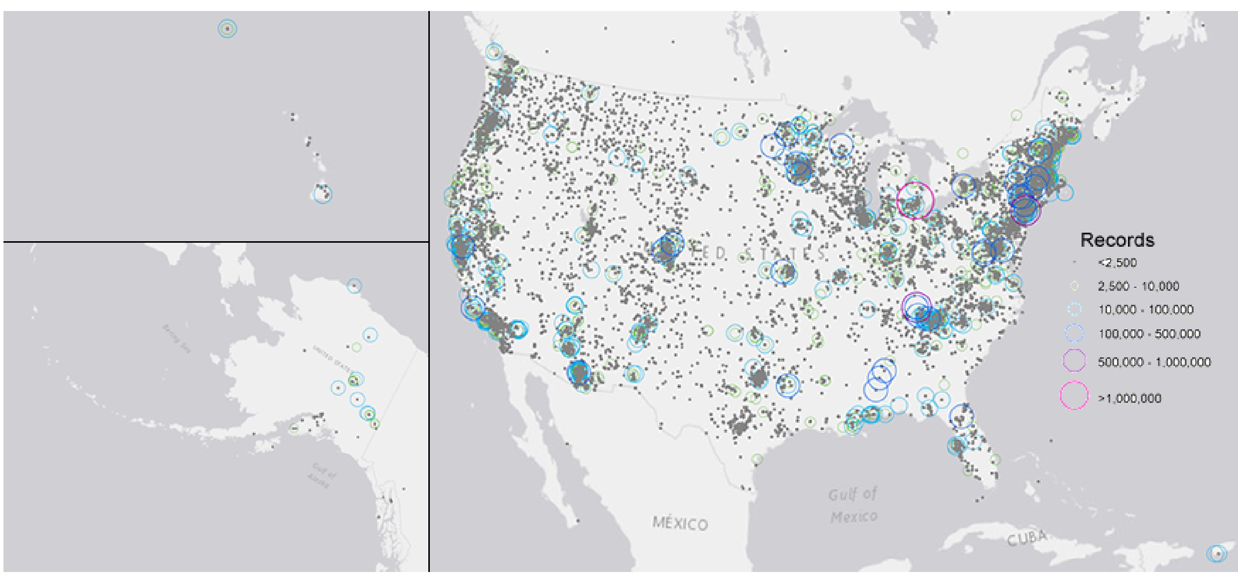


Figure 2. The USA National Phenology Network's phenology observation protocols reveal the status and intensity or abundance of various phenophases on each date organisms are observed. (a) The status of each phenophase on an individual plant is recorded as present (depicted as a colored bar) or absent (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) The intensity of each phenophase is reported as a count or percent of structures that were present on each observation date in (a), such as number of fruits present (pink curve) and percent of fruits that are ripe (dark red curve), enabling visualization of the degree of phenophase expression over the year, and yielding a more complete picture than presence/absence alone.

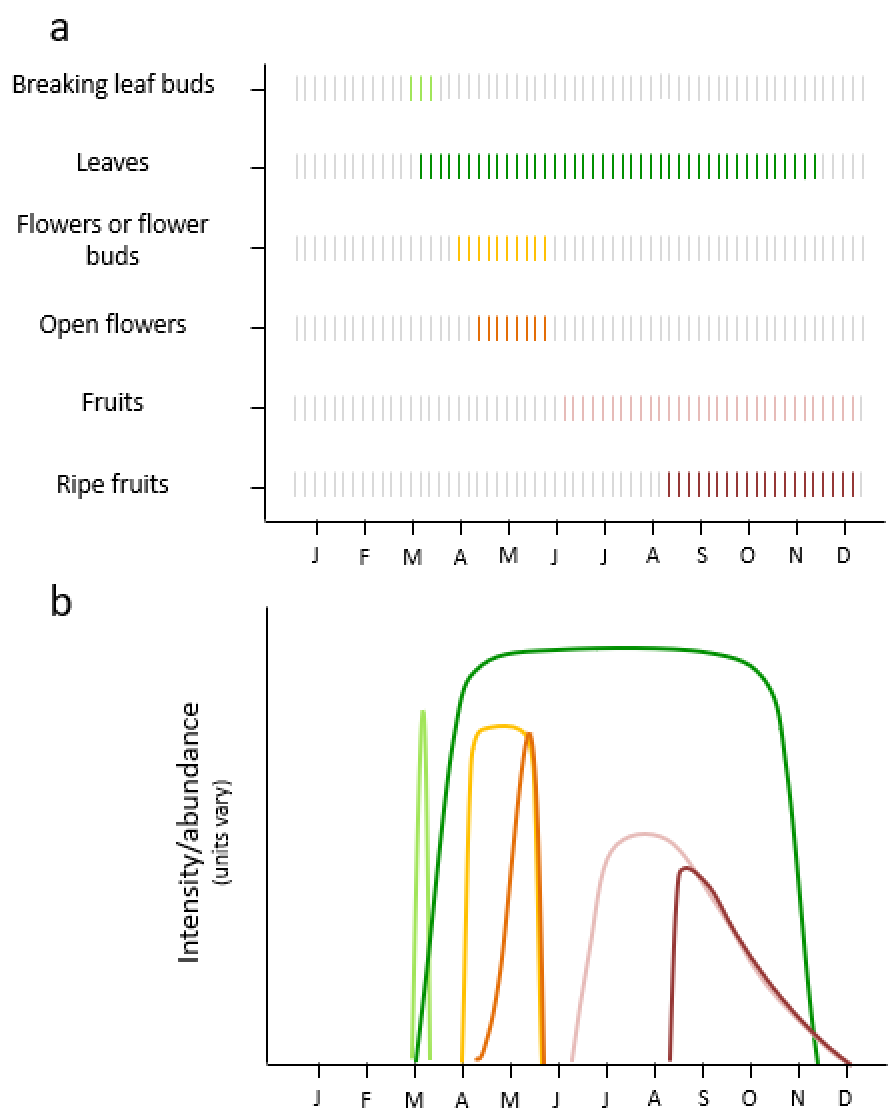


Figure 3. (a) Phenology records contributed by individual observers (light green) and by members of Local Phenology Programs (dark green) in each year, 2009-2021. (b) Observation frequency at sites tracked by individual observers (light green) and by members of Local Phenology Programs (dark green) in each year, 2009-2021. (c) Duration of observation (in years) for sites tracked by individual observers (left) and Local Phenology Programs (right). (d) Members of an LPP observing a plant. (e) Individual *Nature's Notebook* observer.

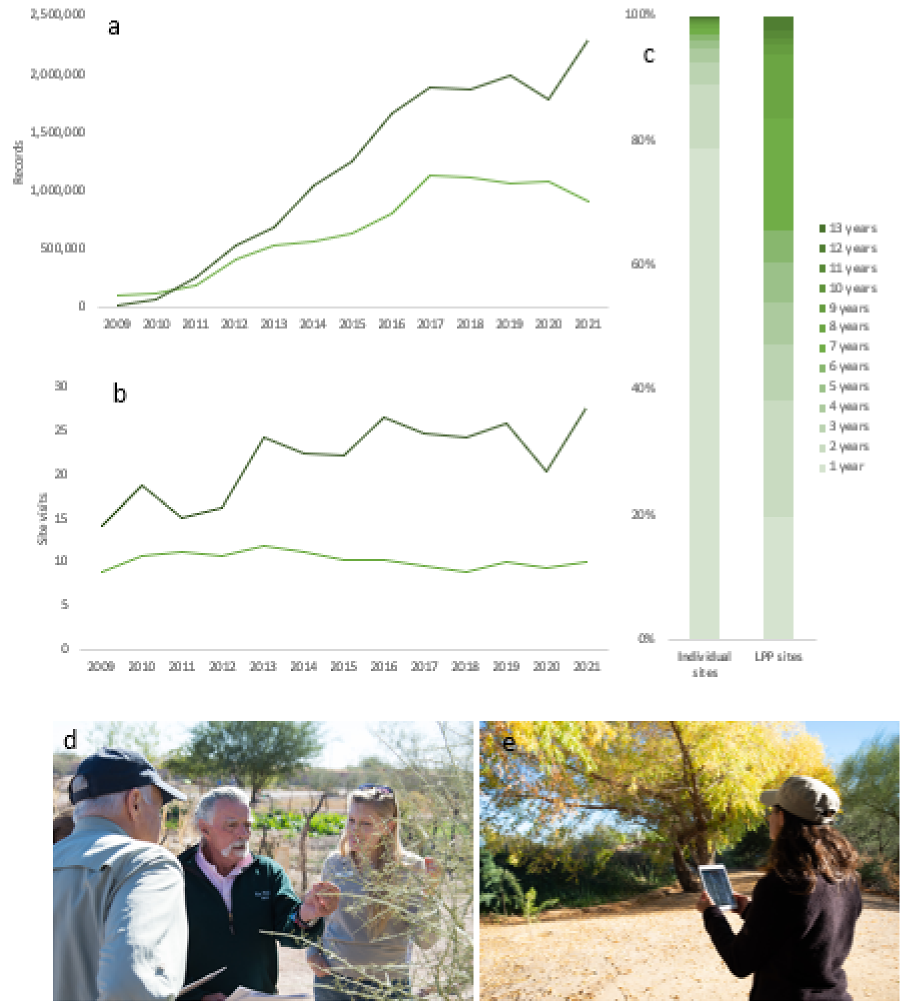
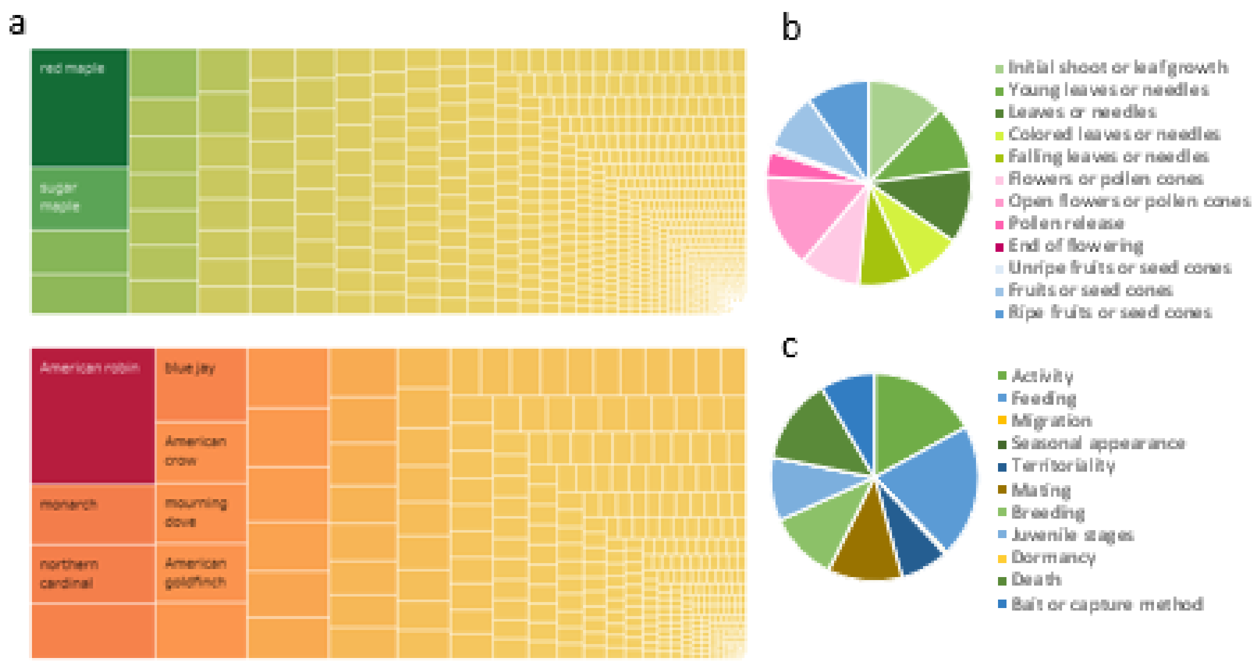


Figure 4. (a) Volume of phenology records contributed to *Nature's Notebook* by taxon. (b) Distribution of plant phenology records by leaf (green), flower (pink), and fruit (blue) phenophases. (c) Distribution of animal records by phenophase class.


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