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Organizing phenological data resources to inform natural resource conservation

Alyssa H. Rosemartin [a,b,*], Theresa M. Crimmins [a,b], Carolyn A.F. Enquist [a,c], Katharine L. Gerst [a,b], Jherime L. Kellermann [a,b], Erin E. Posthumus [a,b], Ellen G. Denny [a,b], Patricia Guertin [a,b], Lee Marsh [a,b], Jake F. Weltzin [a,d]

[a] National Coordinating Office, USA National Phenology Network, 1955 East Sixth Street, Tucson, AZ 85721, United States
[b] School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, United States
[c] The Wildlife Society, 5410 Grosvenor Lane, Suite 200, Bethesda, MD 20816, United States
[d] U.S. Geological Survey, 1955 East Sixth Street, Tucson, AZ 85721, United States

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A B S T R A C T

Changes in the timing of plant and animal life cycle events, in response to climate change, are already happening across the globe. The impacts of these changes may affect biodiversity via disruption to mutualisms, trophic mismatches, invasions and population declines. To understand the nature, causes and consequences of changed, varied or static phenologies, new data resources and tools are being developed across the globe. The USA National Phenology Network is developing a long-term, multi-taxa phenological database, together with a customizable infrastructure, to support conservation and management needs. We present current and potential applications of the infrastructure, across scales and user groups. The approaches described here are congruent with recent trends towards multi-agency, large-scale research and action.

1. Introduction

Global climate change represents one of the greatest contemporary threats to biological conservation not only because its effects are non-homogenous across marine and terrestrial systems (Burrows et al., 2011; Loarie et al., 2009), but also because variation in these effects compounds the differential responses of species, communities and ecosystems (Chen et al., 2011; Sekercioglu et al., 2007). Negative consequences of these effects include changes in species interactions and temporal mismatches (Walther, 2010; Yang and Rudolf, 2009), increased risk of species extinctions (Cahill et al., 2013; Maclean and Wilson, 2011), and loss of critical ecosystem services (Mooney et al., 2009; Thackeray et al., 2010).

An effective conservation response must be broadly coordinated and informed by a range of scientific approaches with diverse data sources (Dawson et al., 2011). Observations of biodiversity taken across spatial and temporal scales are central to this information base, yet the long-term monitoring programs needed to generate these data are typically under-prioritized and underfunded by non-governmental organizations and governmental agencies in the United States (Lovett et al., 2007). Many US federal resource management agencies now require climate response strategies as part of conservation and management planning processes (e.g., US Fish and Wildlife Service, US National Park Service, US Forest Service). Although new guidance aimed at preparing for climate-related changes is appearing with increased regularity in scientific, professional, and web-based outlets (Girvetz et al., 2009; Groves et al., 2012; West et al., 2009), there remains a paucity of climate-relevant, broad-scale, multi-taxa biodiversity data for making well-informed conservation and management decisions.

Changes in plant and animal phenology, such as the timing of flowering, fruiting, breeding, and migration represent a coherent fingerprint of climate change impacts across the globe (Parmesan, 2007; Parmesan and Yohe, 2003; Root et al., 2003). Thus, as a key indicator of the effects of climate change on biodiversity, phenological information is a critical component of the conservation toolkit (Janetos et al., 2012; Parry et al., 2007). For example, vulnerability assessments, in which agencies and organizations evaluate

* Corresponding author at: National Coordinating Office, USA National Phenology Network, 1955 East Sixth Street, Tucson, AZ 85721, United States. Tel.: +1 520 419 2585.
E-mail address: alyssa@usanpn.org (A.H. Rosemartin).

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their conservation goals relative to observed and projected climate impacts, are now part of the recommended practices for responding to climate change (Glick et al., 2011). In this context, phenological data can be used to evaluate whether changes in species' phenology are tracking changes in climate (Cleland et al., 2012; Willis et al., 2008), specifically as a measure of sensitivity and adaptive capacity (e.g., phenotypic plasticity), two of the three variables deemed essential to the vulnerability assessment process (Bagne et al., 2011; Parry et al., 2007; Young et al., 2010). However, existing phenology data resources tend to be limited geographically and taxonomically, and vary substantially in their method of collection (Betancourt et al., 2005; Forrest and Miller-Rushing, 2010).

Phenology has played an important role throughout human history from 16th century European vintners (Maurer et al., 2009) to American naturalists and conservationists such as Henry David Thoreau (Miller-Rushing and Primack, 2008) and Aldo Leopold (Leopold and Jones, 1947). The history and approachability of phenology make it well-suited to public participation (Primack and Miller-Rushing, 2012). Globally, established and nascent national networks engaging both professional scientists and amateur naturalists (e.g., in the United Kingdom, Germany, France, the Netherlands and Turkey) collect, store and share phenological information (Schwartz et al., 2013) . In the United States, a parallel effort, the USA National Phenology Network (USA-NPN, usanpn.org), recently emerged to provide a free, web-based, full-service phenological monitoring program and database (Schwartz et al., 2012). By providing protocols and a data management infrastructure standardized across multiple taxa and bioclimatic regions, the USA-NPN enables climate-informed biodiversity conservation for organizations and land management agencies with limited resources for adaptation. Here, we describe the USA-NPN's online phenological monitoring program and database, collaborative partnerships, and applications of these resources across the country.

2. Organizing and utilizing phenological data resources for conservation in the United States

2.1. The USA national phenology network

The USA National Phenology Network was established in 2007 to collect, store and share historical and contemporary phenological data on a national scale to address the growing needs for this information (Schwartz et al., 2012). The USA-NPN serves science and society by promoting a broad understanding of plant and animal phenology and its relationship with climatic and environmental change. The USA-NPN serves not only as a data repository, but also as a hub of phenology-related activities for researchers, practitioners, decision-makers, and the public. In this way, the USA-NPN aims to foster a phenology "community of practice," facilitating increases in knowledge and understanding specific to phenology through participation, interaction, discourse, and the establishment of best practices (Kania and Kramer, 2011; Lave and Wenger, 1991).

To increase the quantity and quality of phenological data resources in the United States, the USA-NPN developed a comprehensive phenological monitoring infrastructure that includes standardized protocols, an online monitoring program called *Nature's Notebook*, the National Phenology Database (NPDb), and a suite of tools to facilitate use of these resources. This infrastructure accommodates a range of audiences, from individual scientists and trained volunteers ("backyard naturalists" or "citizen scientists") to federal research and management programs such as the National Park Service and the US Global Change Research Program's National Climate Assessment, private organizations such as botanic gardens and conservation groups, and public extension programs, such as Master Gardeners. The overall approach supports regional question-driven research and scientific discovery by providing data resources at the national level and a framework for examining the response of the biosphere to climate variation and change at multiple spatial and temporal scales (Jones et al., 2010).

2.2. Nature's notebook

Nature's notebook (www.nn.usanpn.org) is an online phenological monitoring program that uses standardized status-based protocols developed by the USA-NPN for in-situ monitoring of plants and animals (Denny et al., in preparation). Ground-based organismal data for plants and animals entered through *Nature's Notebook* are stored in the NPDb and integrated with historical phenological data sets (Fig. 1). Data are freely available for download, synthesis and visualization with external data resources (e.g., physical data). *Nature's Notebook* currently supports data collection, storage and use for 243 animal species (including fish, insects, reptiles, amphibians, birds and mammals) and 654 plant species (including coniferous and deciduous trees, shrubs, forbs, grasses and cacti) for the professional scientist, resource manager and naturalist audiences. Over 100 partner groups and 2000 observers have participated in the program since 2009. The following sections describe key components and features of the *Nature's Notebook* information architecture.

2.2.1. Tools for data entry

Participants in *Nature's Notebook* enter data through a browser-based interface or free iPhone or Android mobile applications. The first step to log phenology observations is to register, using a name and a valid email address (anonymous contributions are not accepted). Next, the participant registers a location, or "site" for observing. Participants then register individual plants and/or create a checklist of animal species they will observe at the site. Finally, participants print customized paper datasheets to take into the field for documenting up to 16 days of phenophase status observations (Fig. 2). After making observations, participants transcribe them from the paper datasheets into the online *Nature's Notebook* system. Alternatively, participants may log observations, as well as add new sites, plants and animals, via mobile apps.

2.2.2. Tools for data download and visualization

Once entered into the NPDb, data are accessible instantaneously to the individual collecting and submitting the observations in tabular format, and to the public through advanced data visualization and download tools. The visualization tool allows users to select species, states or a geographic area (by bounding box) and use a time-slider to animate spatiotemporal changes in phenology (Fig. 3). To support exploration of relationships between phenology and climatic patterns, gridded monthly climate data surfaces from PRISM (Parameter-elevation Regressions on Independent Slopes Model; http://www.prism.oregonstate.edu/) can also be displayed in the background (Auer et al., 2011). A three-panel graph allows users to compare the phenology of species or organisms across years or locations. Data and graphics can be downloaded in several formats. A filterable data download tool allows for further customization of output, by partner group, date range, species, location and phenophases. Data may also be entered or accessed dynamically through web services. Metadata (compliant with the Federal Geographic Data Committee's "Content Standard for Digital Geospatial Metadata"), versioning information and supplementary information on sites, organisms and observers are available for each data file.

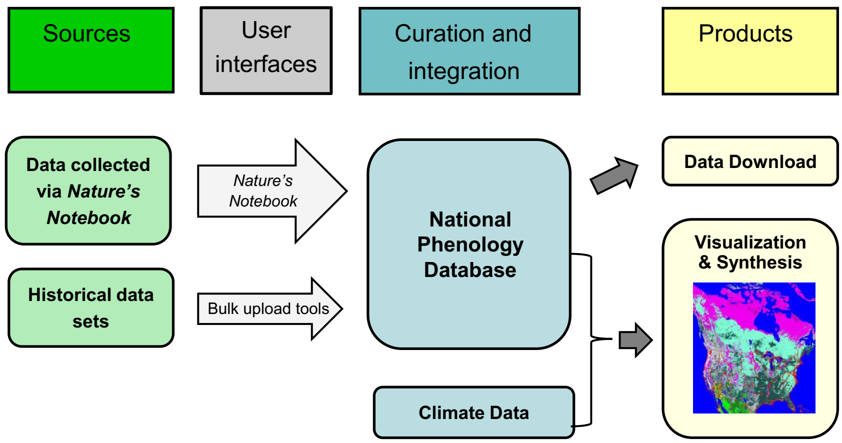
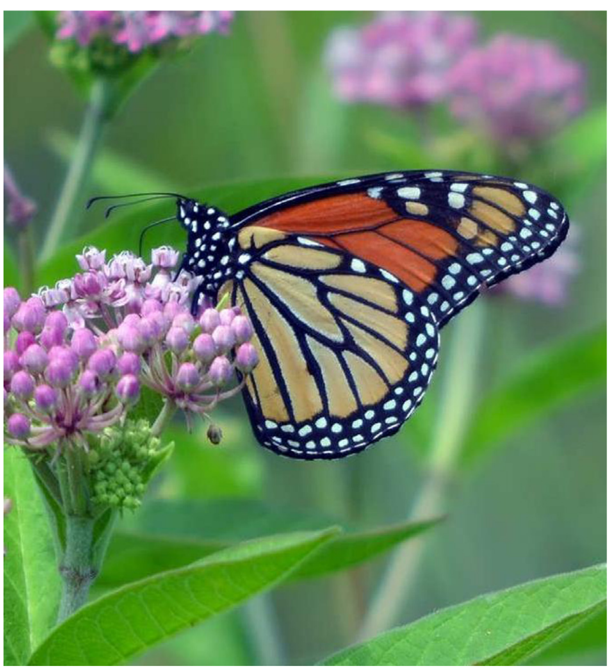


Fig. 1. Information architecture diagram for USA-NPN data resources. Data enters the USA-NPN system from current *Nature's Notebook* participants and historical sources, is stored in the National Phenology Database and is subsequently available for download, and visualization with auxiliary data (unpublished image courtesy of Wim van Leeuwen, University of Arizona, 2010).



Date	07/05/12
Time	4:30 pm
Site	Wilson Park
Plant	Milkweed-3
Observer	Willow Tamias

Milkweed-3: Do you see...?	Status
Initial growth	No
Leaves	Yes
Flowers or flower buds	Yes
Open flowers	Yes
Fruit	No
Ripe fruit	No
Recent fruit or seed drop	No

Monarch: Do you see...?	Status
Active adults	Yes
Flower visitation	Yes
Migrating adults	No
Mating	No
Active caterpillars	No
Caterpillars feeding	No

Fig. 2. Example of data collection instance. In this example, an observer records flowering of her registered common milkweed plant ("milkweed-3") at her "Wilson Park" site, together with observations of an active adult monarch butterfly on July 5, 2012 (photo credit: Howard B. Eskin).

2.2.3. Data storage and integration

All data collected through *Nature's Notebook* are stored in the NPDb, a MySQL relational database (Widenius et al., 2002). The NPDb is also intended to serve as an archive for historical and contemporary phenological datasets collected following protocols other than the standardized protocols developed by the USA-NPN. As a pilot project for historical data integration, the USA-NPN integrated 15 000 event-based records from historic lilac phenology observing efforts, dating back to 1955 (Schwartz et al., 2012).

In the interest of furthering the accessibility, visibility and traceability of the data resources (Arzberger et al., 2004), datasets will be formally published, with unique digital object identifiers (Brase, 2004), and federated with data clearinghouses (e.g., Data-ONE, Knowledge Network for Biocomplexity).

2.3. Public participation in Nature's Notebook and issues of data quality and compliance

Public participation in scientific data collection has dramatically increased recently (Silvertown, 2009); technological advances to support distributed participation in such efforts have shown similar rapid advances (Dickinson et al., 2012). Involving the public in data collection can both reduce costs and increase the spatial and

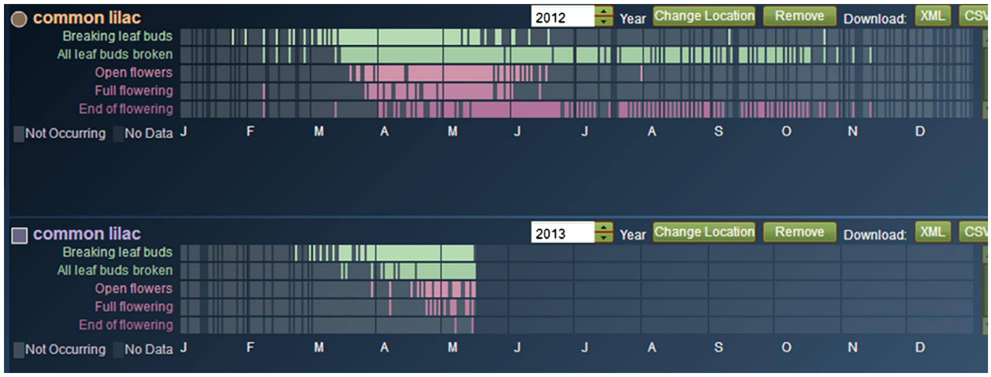


Fig. 3. Screen capture of the USA-NPN visualization tool's graph interface comparing common lilac (*Syringa vulgaris*) leafing and blooming phenophases in 2012 and 2013 across the United States (screen capture on May 16th, 2013). The record-breaking early spring of 2012 can be seen in the earlier leaf and bloom dates for common lilac in the top panel.

temporal coverage of monitoring programs (Devictor et al., 2010). Added benefits of involving the public in scientific data collection include an increased awareness of natural history and the scientific method, as well as increased community engagement among participants (Brossard et al., 2005; Cooper et al., 2007; Cosquer et al., 2012).

While some have expressed concern over quality and reliability in data collected by non-professionals (Foster-Smith and Evans, 2003; Genet and Sargent, 2003), there is growing evidence that citizen science projects provide valuable results (Boudreau and Yan, 2004; Haklay, 2010; Lovell et al., 2009). To rapidly develop a long-term, national scale, multi-taxa data resource, the USA-NPN is recruiting and retaining thousands of volunteer and professional observers to participate in *Nature's Notebook*. Given nationwide public participation in *Nature's Notebook*, the USA-NPN has addressed issues of data quality, data use and attribution, federal compliance, and liability, described below.

2.3.1. Quality assurance and quality control

A number of quality assurance measures have been implemented to minimize the amount of inaccurate data entering the NPDb. For example, when entering data, participants select from lists of predefined values for species, date, phenophase status and intensity, rather than filling in free text fields. Datasheets match the online user interface in terms of color, font, layout and order of species to facilitate accurate transcription. Observers have access to extensive training materials, including resources for species identification and guidance for selecting sites and species. Finally, validation rules in the user interface prevent observations on future dates and illogical values for phenophase status. In addition, post-processing (quality control) measures are in place, such as the provision of site and organism level metadata to enable the identification of outliers by data end-users. Other measures, including flagging species out of range and phenophases out of season are under development.

2.3.2. Policies

Policies to protect individuals and institutions are as important as technological infrastructure to the utility and persistence of data resources. The USA-NPN has developed policies for data use and attribution, as well as policies related to liability (available at www.usanpn.org/terms). Under US law, federal agencies must be cleared by the Office of Management and Budget (OMB) before collecting information from the public. To remove this barrier for federal partners interested in engaging the public in data collection, the USA-NPN obtained OMB clearance (Control #: 1028-0103) for information collection by the public via *Nature's Notebook*.

2.4. Collaborations and partnerships

The USA-NPN engages partners at many levels, understanding that the programs and technologies it provides are supportive of the actions taken by individuals and organizations. *Nature's Notebook* provides a flexible and extensible infrastructure suitable for use by a wide range of organizations, and is a ready-to-use tool for many applications. Organizations, such as nature centers and arboreta, interested in tracking phenology for the purpose of engaging people with the natural world, often use *Nature's Notebook*, to avoid developing their own observation protocols, data archive integration and visualization tools.

Nature's Notebook can also be adapted in a variety of ways to support local to regional conservation and management goals or questions. The USA-NPN works with its partners to provide customizations, which depend on scientific questions of interest, geographic and taxonomic scope, audience, logistics and resources available. These services include: partner affiliation for registered participants, organization-specific data visualization and download, landing pages and project-specific recruitment and retention efforts. Organizations already using this model include university researchers, US National Parks, and state and county Cooperative Extension programs (Table 1; www.usanpn.org/partner/current).

A recent example of a regional collaboration is the California Phenology Project (CPP; www.usanpn.org/cpp), an effort established by universities and National Parks across California, which leverages tools developed by the USA-NPN to understand how climate change is impacting species and ecosystems. California has particularly high species diversity within a wide range of ecosystems, and is expected to have unique and diverse responses to climatic variation and change (Kueppers et al., 2005). For example, precipitation often plays a greater role than temperature in cueing phenological activity in Mediterranean habitats (Peñuelas et al., 2004), and deciduous plants in semi-arid systems frequently exhibit multiple leaf-out cycles in a single season. To capture these potentially diverse responses, phenological monitoring has been underway since 2011 in seven park units that represent three biogeographic regions: mountain, desert, and coastal. The effort aims to establish the influence of environmental factors on phenological metrics, such as onset and duration of flowering. Analyses have focused on the role of precipitation in driving phenological patterns and understanding spatial phenological patterns across broad environmental gradients for widespread species that occupy multiple habitat types. Ultimately, these data will inform management decisions by providing national parks with baseline phenological information on ecologically important species, and will support

Table 1
Phenology data supports applications with societal benefits across geographic scales.

Arborists	Tree phenology data supports effective timing of herbicide and fungicide spraying	Municipal
Saguaro National Park	Buffelgrass and native vegetation phenology inform optimal control windows (Fig. 4)	Municipal
Maine SeaGrant, Signs of the Seasons	*Nature's Notebook* connects the public with climate change research, including experiential learning focused on the local impacts of climate change (Posthumus et al., 2013)	Regional
Natural Resource Managers	Phenology information informs vulnerability assessments in terms of sensitivity and adaptive capacity (Glick et al., 2011; Young et al., 2010)	Regional
Researchers, foresters, arborists	Leaf out data, combined with remotely-sensed phenology data, informs models to predict future atmospheric and ecological conditions (Jeong et al., 2013)	Regional
State Health Departments, commercial allergy medicine distributors	Flowering phenology for allergenic species supports predictions of timing and intensity of allergy seasons (e.g., www.usanpn.org/nn/jpp)	Regional
Western Hummingbird Partnership	Flowering data for hummingbird nectar resource plants across western migratory corridors can be combined with hummingbird presence data to understand potential spatial and temporal mismatch	Regional
Environmental Protection Agency	Lilac leaf and bloom dates (The Spring Indices) have been identified as indicators of climate change impacts (EPA 2012)	National
Natural Resource Managers	Data on phenology and phenotypic plasticity support predictions of species vulnerability to climate change (Cleland et al., 2012; Glick et al., 2011)	National
Pollinator Partnership/NAPPC, farmers	Crop flowering and bee phenology data shed light on temporal mismatch, and can inform valuation of pollination as an ecosystem service	National
USDA Natural Resource Conservation Service, Grassland Reserve Program	Nesting times of protected bird species can inform Grassland Management Plans, allowing participants to comply with the program guidelines and receive federal funding	National
Atmospheric Scientists, Intergovernmental Panel on Climate Change	First leaf and flower data integrated across continents serve to understand and predict atmospheric circulation patterns	Global

planning for the effects of climate change on species activity, interactions, and distributions.

The CPP is typical of the USA-NPN's collaborations in that the partnering organization provides much of the human and social infrastructure, while the USA-NPN provides protocols and tools for data collection, entry, long-term archive, visualization and download. This significantly reduces the cost of developing a phenology project for partners and provides a platform for standardized data collection across diverse and sometimes remote or inaccessible regions such as national parks and wildlife refuges. Continued adoption of *Nature's Notebook* will eventually enable cross-project and cross-site comparisons and synthetic analyses of data collected by many distinct efforts.

2.5. Current data resources

The USA-NPN has developed a taxonomically, spatially and temporally rich data set through the implementation of the tools, policies and collaborations described above. As of May 2013, the database contained 2 064 419 records, reported by 2400 observers at 3500 sites across the nation, on 16 000 organisms. With the completion of the first version of the monitoring and cyber

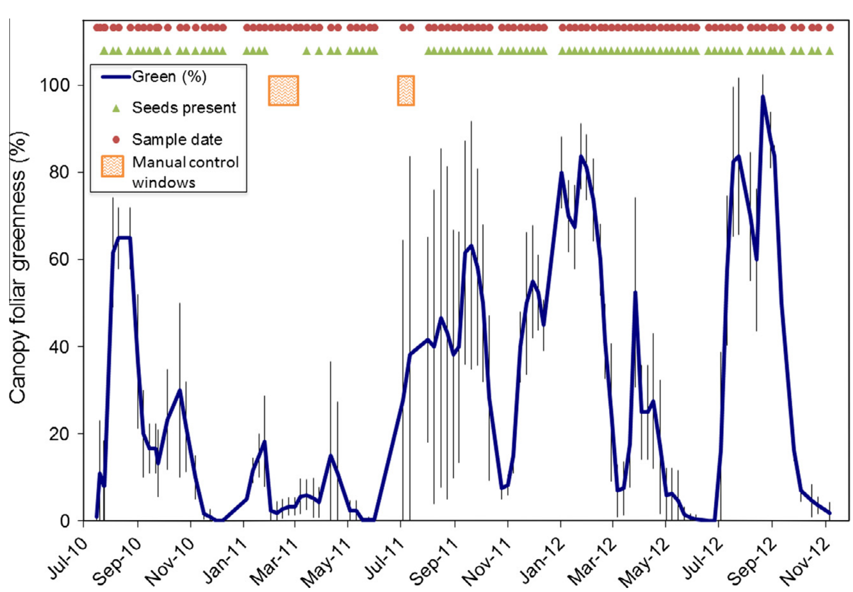


Fig. 4. Buffelgrass phenology near Tucson, Arizona. Canopy foliar greenness (solid line; %; mean ±1 standard deviation) for buffelgrass, *Pennisetum ciliare*, between July 2010 and November 2012 along Pima Canyon trail near Tucson, Arizona, USA. Closed circles represent sampling dates; closed triangles represent the presence of seeds on sampling dates; boxes highlight potential manual control windows. Note that canopy foliar greenness was estimated to the nearest 5%, while the standardized protocols in *Nature's Notebook* provide for reporting canopy greenness in six categorical classes.

infrastructure, and new and increasingly active partnerships, we expect to see sustained growth and expansion of these data resources into the future.

2.6. Applications

A wide range of public agencies and private organizations are partnering with the USA-NPN to build a greater understanding of how phenological information can be used to inform conservation issues related to invasive species, ecosystem services, biogeochemical processes, species vulnerability to climate change, and the efficacy of adaptive management. Here we present an overview of these applications (Table 1) and illustrate the uses of *Nature's Notebook* data in support of invasive species management and predictive modeling of deciduous tree leaf out.

Phenology data inform invasive species management by enabling the identification of reproduction and green-up windows—the two timeframes that are critical for mechanical removal or herbicide application. For example, in desert habitats of the southwestern US, the invasive perennial grass *Pennisetum ciliare* (buffelgrass) is expanding exponentially and threatens biodiversity by disrupting fire and soil moisture regimes (Olsson et al., 2012; Rogstad, 2008; Rutman et al., 2002). Managers seek to minimize inadvertent spread of propagules during mechanical control and to maximize photosynthetic uptake of herbicide during chemical control activities. Thus, to inform future control efforts, researchers collected seed production and canopy foliar greenness data using *Nature's Notebook* for a population of buffelgrass in the foothills of the Santa Catalina Mountains outside of Tucson, Arizona, USA. They found that, because seeds are almost always present on the plants, there are only brief windows of opportunity for mechanical control to minimize seed spread (e.g., July 2011, Fig. 4). Local land managers seek to expand this research, in order to inform the timing of existing invasive abatement treatments.

Phenology data at a much broader scale is important for understanding global biogeochemical cycles and climate change feedbacks, particularly in a predictive framework (Peñuelas and Filella, 2001). Predictive climate models using leaf out data for deciduous trees (collected through *Nature's Notebook*), show leaf budburst across the northeastern United States advancing by up to 17 days by 2100, as well as a swifter spring "green wave" under multiple emission scenarios (Jeong et al., 2013). These changes have implications for migratory birds dependent on foraging for insects among young leaves, as well as global carbon and water budgets (Ewert and Hamas, 1996; Jeong et al., 2013).

3. Discussion

Key climate-relevant biodiversity variables monitoring are required to inform this new era of conservation and management (Pereira et al., 2013). As species vary in their responses to changing climate conditions, the probability of trophic mismatches is expected to increase, often resulting in negative consequences for population dynamics (Conroy et al., 2011; Thackeray et al., 2010; Yang and Rudolf, 2009) that, in turn, may lead to increased risk of species extinctions, non-native species invasions, loss of ecosystem functions, and decreased provision of ecosystem services (Cahill et al., 2013; Schweiger et al., 2008). Long-term, multi-taxa phenological data are critical to support scientists and managers in confronting the uncertainty and variability in species and ecosystem responses to ongoing variation and change.

Over the past five years, building on the efforts of the prior fifty years (Schwartz et al., 2012), the USA-NPN has engaged partners and individuals, from neighborhood organizations to large, complex agencies, in developing a robust data set together with flexible tools and processes that serve stakeholder needs in many contexts (Table 1). As the USA-NPN continues to mature, development will focus on customization of data entry, output and decision-support tools for particular stakeholder groups and conservation needs.

As evidenced by the range of initial applications, the USA-NPN is developing a valuable, national data resource. These data can be used to assess ecosystem services, species interactions, biological invasions, species vulnerability and the efficacy of adaptive management. As parallel advances in data collection, analysis, integration and access take place in the fields of climate modeling, genetics and species distributions, new and exciting avenues of research into the causes and consequences of species phenology, as well as near- to long-term forecasts, will become possible (Pau et al., 2011). In addition, the USA-NPN's *Nature's Notebook* supports community-based monitoring, opening avenues for constituent engagement in confronting climate-related challenges for biodiversity conservation. *Nature's Notebook* can be leveraged as an educational tool to increase scientific literacy and to foster in participants a meaningful, local connection to the abstract and large-scale challenge of climate change.

Moreover, the USA-NPN is a model for international efforts which seek to standardize data collection across species and landscapes. With several well-established and other incipient national-scale efforts to organize phenology research (Schwartz et al., 2013), the USA-NPN is taking steps to share methods and technologies internationally, including the development of protocols that align to the international agricultural standard for phenology data (BBCH; Biologische Bundesanstalt, Bundessortenamt and CHemische Industrie) and support for an emergent version of *Nature's Notebook* in Turkey. Beyond sharing tools and best practices, we also hope to see globally-integrated phenological data resources in the future.

Today's conservation challenges call for an unprecedented standardization and integration of data collection efforts (Reichman et al., 2011). Recent trends towards multi-agency, landscape-level research and action (Austen, 2011; Rickenbach et al., 2011) are enhanced by monitoring tools and approaches, such as those described here, that cross taxonomic, public-private and geographic boundaries. Moreover, advancing, web-enabling and standardizing phenological data resources in the United States holds promise for understanding biological responses to climate impacts.

4. Contributions

AHR led the development of the manuscript; TMC, CAFE, KLG, JLK, EEP and JFW contributed ideas and sections of text. All authors contributed to the development of the data resources, infrastructure and efforts described here.

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