From Caprio's lilacs to the USA National Phenology Network

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Continental-scale monitoring is vital for understanding and adapting to temporal changes in seasonal climate and associated phenological responses. The success of monitoring programs will depend on recruiting, retaining, and managing members of the public to routinely collect phenological observations according to standardized protocols. Here, we trace the development of infrastructure for phenological monitoring in the US, culminating in the USA National Phenology Network, a program that engages scientists and volunteers.

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Changes in the timing of seasonal events – such as flowering, migrations, and breeding – can serve as a "globally coherent fingerprint of climate-change impacts" on organisms (Parmesan 2007). Climate-induced changes in phenology have been linked to shifts in the timing of human allergy seasons and cultural festivals, increases in wildfire activity and pest outbreaks, shifts in species distributions, declines in the abundance of native species, the spread of invasive species, changes in agricultural yield, and changes in carbon cycling in natural ecological systems. Phenological data can also provide critical information needed for understanding important issues, such as agricultural and wild plant species not meeting their requirements for exposure to cold temperatures in winter, timing mismatches for interacting species, and agricultural adaptation. Even in the US, phenological data are limited, and existing long-term datasets tend to be species- or site-specific. Therefore, although climate is a known critical driver of phenological variation of organisms across scales from individuals to landscapes, we are generally unable to answer ecologically and societally important questions, such as: (1) how do phenological variations in time and space affect the abundance, movement, distribution, genetics, and interactions of organisms?; and (2) can we forecast phenological responses to climate variability and change across populations and interacting species in both managed and unmanaged ecosystems?

The future of phenological research, monitoring, and understanding will depend on a coordinated effort to organize and collect phenological and related information (eg climatological and hydrological data) across a variety of spatial and temporal scales. Phenological monitoring activities in the US will be most successful if they are integrated with other ecological science and monitoring networks, remote-sensing products, emerging sensor technologies and data management capabilities, and formal and informal educational opportunities; active participation by members of the general public will also be necessary. The success of these monitoring efforts will depend on how well they inform science, resource management, and policy, as well as the degree to which they empower the public in formulating and facilitating adaptive responses to a changing climate (Figure 1).

Organized phenology monitoring in the US: a brief history

The first spatially extensive phenological observation networks in the US, focused on lilacs and honeysuckles, were initiated by the US Department of Agriculture (USDA) in the late 1950s and early 1960s to characterize seasonal weather patterns and improve predictions of crop growth and development (Schwartz 1994). The volunteer observers included a few thousand cooperative weather service observers, scientists and technicians at agricultural stations, and garden club members, who provided data on leafing and flowering phenology via the US mail. Encouraged by the success of a program established in 1956 by Joseph Caprio (Montana State University) in the western US, similar projects (later merged into a single eastern network) were initiated in the central and northeastern states in 1961 and 1965, respectively. Observations in the western network continued until 1994 (Caprio retired in 1993), while the eastern and central networks were terminated in 1986 after losing funding. Additional details about historical regional phenology networks are presented in WebPanel 1.

Rebirth of the lilac network: an incipient national network

The western US lilac network was reactivated in 1997 by Dan Cayan and Mike Dettinger of the Scripps Institution of Oceanography and the US Geological Survey, respectively, to complement their studies on changes in timing of snowmelt discharge (Cayan *et al.* 2001). Similarly, Mark Schwartz (first author of this paper) reactivated the east-

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ern US lilac network in 1988 for climatological research. Figure 2a provides a synopsis of the spatial and temporal distribution of the historical lilac phenology datasets across the continental US between 1956 and 2008.

In 2002, Schwartz started planning to revitalize and broaden the lilac networks into a national framework, while also extending phenological observations to other native and non-native plant species. Following a workshop to discuss how the incipient National Ecological Observatory Network (NEON) might contribute to monitoring and understanding the ecological impacts of climate change (AIBS 2004), Julio Betancourt (coauthor of this paper), David Breshears of the University of Arizona, and others echoed the idea of continental-scale phenological monitoring. Independent of NEON, in 2005, Schwartz, Betancourt, and colleagues began to develop a national network of phenological observation stations, and existing lilac and honeysuckle observation stations were reorganized to form a prototype Plant Phenology Program for that network.

As proof of concept for a more extensive network, the observations of lilac and honeysuckle phenology made by thousands of volunteers since the 1950s have contributed many useful insights about spring onset variations at regional to continental scales (Schwartz 1994; Cayan *et al.* 2001; McCabe *et al.* 2011). Three examples of inferences made from lilac phenology at the continental scale are provided in Figure 3. There is a high correlation between observed "first leaf" dates and "first bloom" dates (Figure 3a), which is stronger in colder climates and weaker in warmer ones. For species that behave similarly to lilacs, "leaf out" may be a suitable predictor of flowering and conceivably could be used to forecast associated phenomena such as pollen production and allergen loads. Figure 3b shows the North American continent-wide annual average variation (in days) of modeled first leaf dates from weather stations that report daily maximum and minimum temperatures across the continent. These Spring Indices are calibrated and validated with observations of first leaf and first bloom dates for lilac and honeysuckle, and show an abrupt advance in the timing of spring onset in the mid-1980s. The regional risk of an early or late spring, based on positive or negative phases of El Niño Southern Oscillation and the Pacific Decadal Oscillation in the prior October through December, is also estimated (Figure 3c; McCabe *et al.* 2011).

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Figure 1. *Phenology is one of the most sensitive biological responses to climate change, is a critical part of nearly all aspects of ecosystem function, and is relatively easy to observe, requiring little specialized monitoring equipment.*

Development of the contemporary network

The contemporary USA National Phenology Network (USA-NPN; www.usanpn.org) was established in 2007 with support from the US National Science Foundation, the US Geological Survey, and several other agencies and organizations. The USA-NPN is a consortium of individuals and organizations that collect, share, and use phenological data, models, and related information. Its mission is to serve science and society by promoting a broad understanding of plant and animal phenology and its relationship with environmental change. Volunteer observers collect data on hundreds of species, including the common and cloned lilac species observed by network precursors, across the nation (Figure 2b). In turn, USA-NPN makes phenology data, models, and related information freely available to scientists, resource managers, and the public to aid in decision making and adapting to changing climates and environments. Additional details about USA-NPN are presented in WebPanel 2.

Numerous other phenology observation programs in the US operate either independently of or in cooperation with the USA-NPN. Although many were developed within the past 10 years, some of these programs have been operational for several decades; for example, the North American Bird Phenology Program engaged thousands of volunteers to track migratory bird phenology across the continent between 1880 and 1970. The geographic scope of contemporary programs ranges from international (eg eBird, Global Learning and Observations to Benefit the Environment), national (eg FrogWatch USA, Journey North, Project BudBurst), and regional (eg Eastern Pennsylvania Phenology Project, Signs of the Seasons), to state or local (eg Ohio State University Phenology Garden Network, Penn Phen) initiatives. Moreover, contemporary projects have a variety of programmatic missions, including science, education, and/or public engagement. The particular focus may vary, with some programs concentrating on tracking phenology of specific species or taxa, whereas others collect many different types of observations. Coordination and collaboration among the diversity of programs across the nation, while retaining individ-

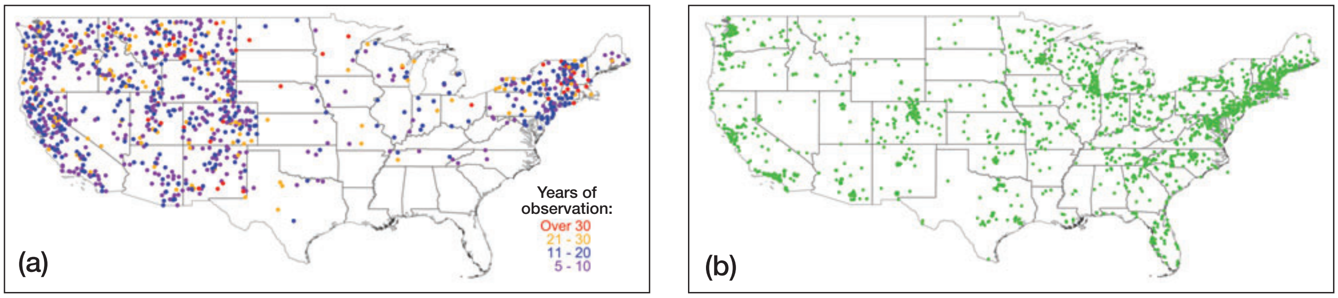

Figure 2. *(a) Years of observations for USA Lilac Phenology Stations, 1956–2008. (b) The multi-taxa phenology monitoring program, Nature's Notebook, has ~4000 registrants at ~5000 sites tracking ~16 000 organisms across the nation (as of October 2011). These sites (shown only for the continental US because of space limitations, and excluding lilac observation stations from panel a) include those maintained by members of the public, local schools and clubs, and neighborhood associations, as well as US National Parks and National Fish and Wildlife Refuges, the National Ecological Observatory Network and the Long Term Ecological Research Network research sites, and nature preserves.*

ual programmatic identity and stakeholder value, will be both a challenge and an opportunity in the coming decades.

Sustaining a national phenology observing system

The reasons for the success or failure of environmental monitoring networks are not always apparent (but see Lovett *et al.* 2007); often, such networks are heroic efforts that wax and wane with their champions, whether individuals or organizations. For example, the Western States Phenological Network lasted from 1956 to 1994, benefiting from Caprio's position as an agricultural meteorologist at Montana State University and generous support from both the USDA and the National Weather Service. But when Caprio retired in 1993, the program faltered because of a lack of personal and institutional interest. A decade or so later, other individuals emerged to develop USA-NPN, an effort much broader in motivation, scope, and interest than its predecessors.

What steps can be taken to ensure the success of networks such as USA-NPN? Support from the US Federal Government will be critical because federal agencies typically outlast individuals, are responsible for long-term and nationwide planning, and are not subject to the lapses in funding faced by academic institutions and non-governmental organizations. Monitoring efforts usually have to strike a balance in scope and avoid trying to satisfy too many diverse objectives. Breadth of scope is usually an advantage early on but can become a liability as a network matures and base funding and participation stabilize. Communication with stakeholders and their changing needs is critical for maintaining the relevance of networks over time.

Two measures of network success will be the number, distribution, and retention of loyal and capable observers and the strategic value of observations across the continent. To focus coverage on national and regional information needs, network expansion will need to evolve beyond attraction of volunteers through mass marketing and toward directed recruitment and management of practiced observers who will record specific phenological events for a focused list of species in targeted locations. For example, the current distribution of USA-NPN observation stations, which grew arbitrarily, is correlated with human

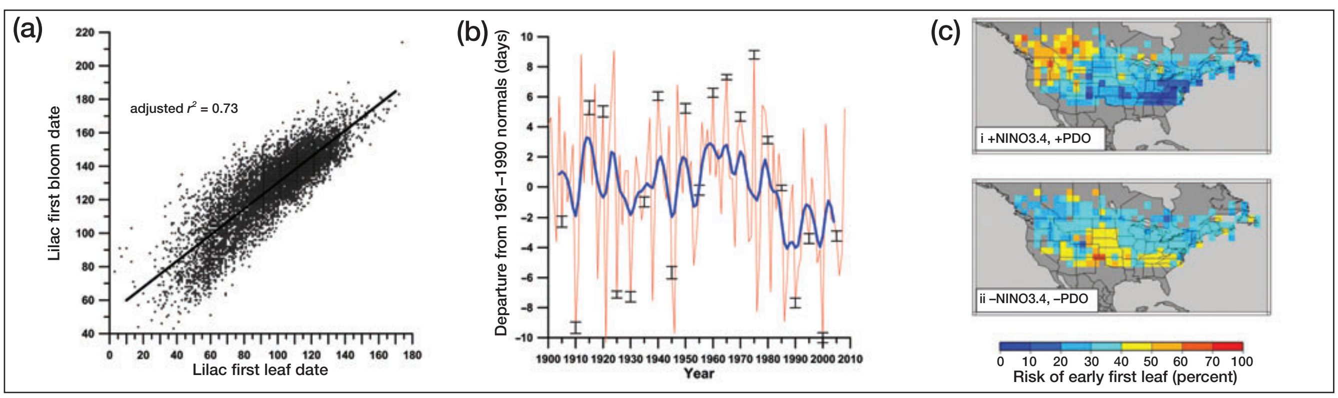

Figure 3. *(a) Relationship of lilac first leaf to first bloom observations in North America. Axis units represent day of the year, with January 1st = 1. (b) Modeled first leaf departures averaged across North America. (c) Risk of early modeled first leaf date for (i) positive October through December (OND) NINO3.4 (a measure of sea surface temperature variations in the central equatorial Pacific, bounded by 120°W–170°W) and positive OND Pacific Decadal Oscillation (PDO) conditions, and (ii) negative OND NINO3.4 and negative OND PDO conditions from 1900 through 2008 (from McCabe* et al. *2011).*

population densities (Figure 2b). To achieve a more homogeneous distribution of stations nationwide and to avoid heat islands and other urban effects, the USA-NPN may have to refocus recruitment and retention activities in rural communities. Also, phenological information becomes optimal when recorded near sites where other environmental variables are monitored, including weather, radiation, biogeochemical fluxes, hydrology (especially soil moisture), and plant and animal demographies. Although uniformity in monitoring is a desired goal at the national level, monitoring efforts should also vary depending on long-term regional trends and projections. For example, over the past 50 years, spring has advanced several days in the Northeast, Upper Midwest, and western US but has been delayed in the Southeast, the result of a so-called "warming hole" that arises from internal Pacific Decadal Oscillation variability and could persist under climate change (Meehl *et al.* 2012). These and other continental-scale differences in historical and predicted climate should be addressed by regional and national campaigns to monitor and study phenology.

Finally, to ensure long-term success, the USA-NPN must consider and balance the needs of: (1) its observers – both volunteer and professional – typically working at local scales; (2) land/resource managers and private enterprise normally operating at landscape to subregional scales; and (3) researchers and policy makers interested in the science and management of global change at all scales. Principles for collaboration among network participants include mutually beneficial activities, shared vision about science and education, realistic demands on the capacities of partners, feedback to improve collaboration, and transparent data and information sharing policies.

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WebPanel 1. The rise and fall of regional phenology networks in the US

The first regional phenological observation network in the US was established in the west by JM Caprio of Montana State University in 1956; the following year, the network was expanded from Montana to 11 western states with the support of both the US Department of Agriculture and regional climatologists (Caprio 1966). Common purple lilac (*Syringa vulgaris*) formed the core of the network with two cloned honeysuckle cultivars (*Lonicera tatarica* "Arnold Red" and *Lonicera korolkowii* "Zabeli") added in 1968, with complementary observations of "headings" for winter wheat. The volunteer observers included a few thousand National Weather Service Cooperative Observer Program (COOP) observers – scientists and technicians at agricultural stations and garden club members – who would mail Caprio their phenophase observations on postcards. In 1967, Caprio began providing the observers with nursery-grown plants, a practice continued today – and extended by the USA National Phenology Network (USA-NPN) to include a cloned cultivar of anthracnose-resistant flowering dogwood (*Cornus florida* "Appalachian Spring") – in collaboration with commercial plant nurseries.

Caprio's Western States Network eventually included volunteer observers distributed throughout 12 western US states. After the initial peak years of participation (1957–1962, with 503 to 665 annual observer reports) and a brief resurgence (1967–1968, with more than 500 annual reports), observer participation began to decline, permanently falling below 300 after 1973, and continuing to shrink until regular observations in the Western States Network ended (after Caprio's 1993 retirement) in 1994.

Encouraged by the success of Caprio's program in the western states, similar projects were started by WL Coville in the central states in 1961 and in the northeastern states in 1965. Both of these networks focused on cloned plants of the lilac cultivar *Syringa chinensis* "Red Rothomagensis" and the same two honeysuckle cultivars used in the western states project. In 1970, the networks of the two eastern states were combined and expanded, reaching peak observer reports (206) in 1973, but these subsequently and gradually declined. Between 1975 and 1986, observations continued under several additional projects, but the eastern network lost funding and was terminated at the end of 1986.

WebPanel 2. Framework of the contemporary USA National Phenology Network

The following sections outline key elements in the structural and operational framework of the contemporary USA National Phenology Network (USA-NPN), and describe how the National Coordinating Office (NCO) works to meet key goals and objectives of the network.

Structural framework

The present structural framework of USA-NPN consists of a NCO, an Advisory Committee, and many partner organizations, including public agencies, non-governmental organizations, specialized networks, American Indian tribes, industry, and academic institutions. As a coordination and resource center that works to advance the mission of the USA-NPN, the NCO maintains a website and data management services, promotes the use of standardized approaches to monitoring phenology, encourages the widespread collection of phenological data, and facilitates communication within and beyond the USA-NPN. The NCO also facilitates basic and applied research on phenology and promotes the development and dissemination of decision-support tools, educational materials, and other information or activities related to phenological research.

National Phenology Information Management System

Data management and information sharing are central to the USA-NPN mission. The NCO develops, implements, and maintains a comprehensive Information Management System (IMS) to serve the data and information sharing needs of the network, including the collection, storage, visualization, and dissemination of phenology data; access to phenology-related information; tools for data interpretation; and general online communication among partners. The IMS includes components for data storage, such as the National Phenology Database, and a variety of online user interfaces to accommodate data entry, data download, data visualization, and catalog searches for phenology-related information. The IMS is governed by a set of standards to ensure security, privacy, data access, and data quality.

The National Phenology Monitoring System

An essential activity of USA-NPN is the collection of contemporary and historical phenology data. The NCO provides and promotes a vetted, well-documented, flexible phenology monitoring system, the National Phenology Monitoring System (NPMS). Implementation of this system in monitoring programs across the nation facilitates the widespread collection of integrated, high-quality ground observations of plants, animals, and (eventually) related biophysical factors. Data collected through this system (or integrated into this system after collection) provide a valuable resource for research, decision support, and educational activities.

A web application called Nature's Notebook, based on the NPMS, has been developed by the NCO. This program is appropriate for scientists and non-scientists alike, and enables individuals or groups to collect and organize phenology-related observations of both plants and animals across the nation. Nature's Notebook provides standardized protocols for phenological status monitoring and data management for more than 500 species and facilitates collection of sampling intensity, absence data, and considerable metadata (from site to observation). Recent functionality includes protocols and tools for recording estimates of animal abundance and plant canopy development. Real-time raw data for plants (from 2009 to present) and animals (from 2010 to present), including metadata and documented methodology, are now available for download from the website (Figure 2b). A data exploration tool that premiered in spring 2010 allows sophisticated graphical visualization of integrated phenological and meteorological data.

Partnerships and collaborations

Effective partnerships are critical to the success of the USA-NPN. The network consists of individual and organizational partnerships within and between communities of researchers, land managers, policy makers, citizen scientists, educators, and others to collect common phenology-related data on a national scale. The NCO coordinates the efforts of partners to efficiently advance the objectives of the USA-NPN.

Education and outreach

The NCO facilitates the development of outreach and education materials to support the network's phenology monitoring efforts, enhance scientific discovery and inquiry, promote the integration of science and education through science and climate literacy, engage observers in outdoor and nature experiences, and teach the importance of accurate data collection. Participants learn about the value of phenology as an indicator of environmental health as well as the benefits of data accuracy related to a high-quality, long-term dataset. Program materials are designed to help observers, including those in underserved audiences, self-select to spend more time in natural settings, increase awareness of self–nature relationships, and experience enhanced quality of life.

Facilitation of research and development of decision-support systems

An important aspect of the USA-NPN is facilitating basic and applied research on all aspects of phenology and on the relationship of phenology to rapidly changing environmental conditions, including climate-related changes. The NCO facilitates communication among researchers, works to identify gaps in our understanding of the role of phenology in natural and managed ecosystems, and supports coordination of research to fill those gaps. A key role of the USA-NPN is to provide quality, timely information on phenology to help decision makers manage critical resources and to develop climate adaptation strategies. Working together, members of the USA-NPN develop and disseminate phenology-related decision-support tools (eg models, visualizations, data summaries, syntheses). These efforts serve to inform decisions made by resource managers, health officials, community and national planners, and others.

■ WebReferences

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