**Title:** The Plant Phenology Monitoring Design for the National Ecological Observatory Network

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**Abstract**

Phenology is an integrative science that comprises the study of recurring biological activities or events. In an era of rapidly changing climate, the relationship between the timing of those events and environmental cues such as temperature, snowmelt, water availability or day length are of particular interest. This article provides an overview of the plant phenology sampling which will be conducted by the National Ecological Observatory Network NEON, the resulting data, and the rationale behind the design. Trained technicians will conduct regular *in situ* observations of plant phenology at all terrestrial NEON sites for the 30-year life of the observatory. Standardized and coordinated data across the network of sites can be used to quantify the direction and magnitude of the relationships between phenology and environmental forcings, as well as the degree to which these relationships vary among sites, among species, among phenophases, and through time. Vegetation at NEON sites will also be monitored with tower-based cameras, satellite remote sensing and annual high-resolution airborne remote sensing. Ground-based measurements can be used to calibrate and improve satellite-derived phenometrics. NEON's phenology monitoring design is complementary to existing phenology research efforts and citizen science initiatives throughout the country and will produce interoperable data. By collocating plant phenology observations with a suite of additional meteorological, biophysical and ecological measurements (e.g., climate, carbon flux, plant productivity, population dynamics of consumers) at 60 terrestrial sites, the NEON design will enable continental-scale inference about the status, trends, causes and ecological consequences of phenological change.

**Key words:** long-term monitoring; NEON; plant phenology; open-source data; sample design

## Introduction

The overarching mission of NEON is to enable understanding and forecasting of the impacts of climate change, land use change, and the introduction of invasive species on ecosystem structure and function (see Thorpe et al., this issue). Tracking the timing of seasonally recurring life cycle events (phenology) is thus a natural focal area of study for the Observatory. Plant phenological transitions may be triggered by a variety of cues, including chilling, spring temperature, growing degree days, and daylight cues (Chuine 2000); many of these factors are likely to shift significantly over the next 30 years (IPCC 2013). Changes in phenology have been observed for many taxa across the earth (Parmesan and Yohe 2003). The onset of spring phenological events advanced at an estimated mean rate of 1.2 days per decade from 1955-2002, across the Northern Hemisphere, likely caused by recent climate warming (Schwartz et al. 2006). Observational and experimental studies indicate that plants flower on average ~5 days earlier per 1°C increase in spring temperature (Wolkovich *et al.* 2012) and current projections indicate that spring phenology could advance by between 1 and 10 days over the planned 30-year lifespan of the NEON observatory (IPCC 2013). Many species, however, delay flowering in response to increases in winter or spring temperatures (Mazer et al. 2013), and there is still much to learn about the causes of variation among species and higher taxa in the direction and magnitude of their phenological responses to both temperature and rainfall (Mazer et al., 2013, 2015).

Beyond providing an indicator of climate change, the timing of phenological transitions is also a potentially important driver of demographic trajectories and biogeographic distributions of individual taxa, and of ecological processes including species interactions and rates of biogeochemical cycling (Morisette et al. 2008).

Phenological traits may physiologically constrain broad-scale distribution patterns of species; phenology is consistently an important predictor in process-based species distributions models (Chuine 2010 and references therein). Phenological plasticity may be a beneficial trait; for example, species whose activity patterns closely track interannual climate variability tend to have improved growth, productivity, or reproductive success than those that do not (Cleland et al. 2012). In other cases, however, early greenup or floral bud development in response to anomalously early arrival of spring can be detrimental. Phenological advancement in response to warm spring temperatures followed by a late frost can have catastrophic effects on fruit and seed production and canopy development (Inouye 2008, Hufkens et al. 2012).

Climate-induced changes in phenology can create feedbacks that alter biogeochemical cycling and species interactions (Melillo et al., 2014). Changes in the timing of leaf budburst and senescence affect surface radiation, near surface temperature, hydrology and carbon cycling (Churkina *et al*. 2005, Bonan 2008, Richardson et al. 2010, Jeong et al. 2012, 2013). An analysis of more than a dozen models included in the North American Carbon Program (NACP) Interim Synthesis indicated across all models, sites, and years of data, for each forest type; errors of up to 25 days in predictions of "spring onset" were common, and errors of up to 50 days were observed (Richardson *et al*. 2012). From the general positive relationship between carbon uptake and season length derived from a synthesis of a range of eddy covariance sites, the largest phenological errors in current models would translate into between ~150 and ~450 g $m^{-2}$ of carbon annually (Churkina et al. 2005). Differential responses to phenological cues between plants, consumers, and/or pollinators can disrupt the overlap in activity periods among

interacting organisms, potentially resulting in changes in species fecundity and cascading effects on the food chain (Strode 2003, McKinney et al. 2012) or local extinction of consumer populations (Singer and Parmesan 2010).

Plant phenology has been studied at a range of geographic and temporal scales and by employing a variety of tools, including: recording *in situ* observations, experimental manipulation of abiotic factors, modeling, remote sensing, and digital photography (Cleland et al. 2007). Understanding and reconciling the information contributed at each scale is challenging (Morisette et al. 2008) and observations at multiple scales are rare (but see Liang et al. 2011). This article provides an overview of the plant phenology sampling that will occur within NEON sites, including observation protocols, the spatial and temporal frequency of monitoring, and the taxa targeted for observations, and the rationale for the sampling regime that was selected (Box 1). The science design, developed by a technical working group of comprised of phenology experts from academic institutions, government and non-profit agencies, reflects current best practices in monitoring terrestrial plant phenology. By providing integrated and multi-scale suites of measurements on the seasonal progression of a diversity of taxa and ecosystem processes at intensively measured sites, data collected by NEON will enable the scientific community to develop mechanistic linkages between the environmental drivers that affect plant phenology, as well as the functional consequences of changing phenology for a range of ecosystem types and processes. The resulting scientific knowledge can inform decision-making processes related to natural resource conservation and management, control of invasive species and infectious disease, and efforts related to societal climate change adaptation (Enquist et al. 2014).

***Box 1:NEON's contribution***

NEON is poised to advance the field of phenology by:

1) Accumulating high quality, long-term, standardized measurements recorded by trained technicians across 20 major ecosystem types found within the US;

2) Observing replicate individuals of select species to quantify intraspecific variation in the timing of phenological events within and across years, facilitating precise population-level estimates of phenology;

3) Observing multiple species to characterize the range of phenological response patterns across species and functional groups and life history strategies;

4) Collocating plant phenological measurements with other terrestrial and atmospheric measurements data, which may be used to understand relationships between climate, phenology, ecosystem processes and biodiversity; and

5) Providing open-access, standardized datasets that easily integrate with other large scale monitoring networks.

***Measurements***

Plant phenology is typically quantified by observing the date of onset and the duration of particular phenophases, which may include both vegetative and reproductive events. Specific phenophase definitions have not been universally adopted across monitoring networks. Without common units, data interoperability becomes a limiting factor in data integration. Consistent with NEON's commitment to use existing

nationally-accepted, vetted and standardized protocols wherever possible, NEON will employ USA-NPN phenophase definitions and protocols (Denny *et al.* 2014).

Advantages of USA-NPN protocols and the reasons for selecting this standard for NEON *in situ* phenology observations include: (1) status-based monitoring, or the practice of reporting the phenological condition of an individual at any time that it is monitored; (2) repeated tracking of marked and georeferenced replicate individual perennials and patches of annual/clonal herbs and, (3) incorporation of both status and 'intensity' definitions for phenophases (Kao *et al.* 2012, Denny *et al.* 2014). Using status-based rather than first-event monitoring is a departure from many historical phenological monitoring protocols, but has the advantage that events (such as leaf emergence in Mediterranean climates, or flowering in many desert species) that may occur multiple times during a single year can be captured. Status-monitoring also allows the explicit quantification of uncertainties in phenophase transition dates (which occur in continuous time) that are introduced by monitoring in discrete temporal bouts, as well quantifying the duration of phenophases rather than just their date of onset. Monitoring marked individuals/small patches ensures that the recorded dates of phenological events, or their duration, are decoupled from population size (Miller-Rushing et al. 2008). The protocols employed include intensity metrics (e.g. percentage of the canopy that is full with leaves) along with phenophase status (e.g. one or more live, unfolded leaves visible). These data can be used to estimate mean population onset and end dates for each phenophase, as well as track the seasonal progression of development throughout the active period. Together, these data should provide better linkages to ecosystem function and remotely sensed phenological data than existing 'first event' phenological datasets,

which typically quantify the phenological status of only the most extreme individuals within a population of unknown size (Miller-Rushing *et al.* 2008). While other phenophase definitions exist (e.g. the BBCH scale, commonly used in agricultural systems, as well as across Europe (Meier 2001; Koch *et al.* 2007)), the USA-NPN scales were selected for interoperability with large-scale distributed monitoring datasets in the continental US. Mapping from USA-NPN definitions to BBCH definitions is feasible for many phenophases.

The phenology protocol includes repeated assessment of phenophase status and intensity on each individual (see section Temporal distribution of sampling, below, for more details), as well as an annual assessment of individual-level covariates that can affect phenology. Due to resource constraints, only a subset of the USA-NPN-defined phenophases (as described by Denny et al. 2014) will be targeted in NEON phenology sampling protocols, with the greatest focus on leaf phenology. The focus on canopy development was selected based on recommendations in the NSF Research Coordination Network Report (2012), to facilitate linkages with NEON's measurements of ecosystem processes such as landscape phenology and carbon cycling. To connect phenological measurements to plant health, productivity and canopy position, NEON will measure the size (stem diameter, % cover, height and canopy dimensions), disease status, health condition and structure of each individual plant or patch once per year. These annual measurements will be consistent with those taken on other plants at NEON sites as part of the vegetation structure and productivity protocol (see Meier and Jones 2015 for details).

***Phased sampling design***

Two priorities were identified for NEON's plant phenology observations: *Phenology of dominants*, which includes estimating the mean and intraspecific variance of phenological timing in dominant species within each site (see Phase I, below), and *Community phenology*, focused on capturing a range of species-specific phenologies that represent the plant community at each NEON site (Phase II). Dominants are targeted specifically to facilitate linkages to ecosystem function based on the assumption that species contribute to ecosystem properties roughly in proportion to their relative abundances (Grime 1998). Sampling of dominant species' phenology will enable linking phenological events and patterns observed above-ground to processes captured at other scales by other NEON measurement systems (including root phenology, ecosystem productivity and respiration, and carbon, water and nutrient cycling) and to the ground-based land-surface phenology signal observed via remote sensing methods. It will also provide critical information on intraspecific variation in phenology patterns, which are poorly captured when monitoring efforts are limited to a census of one to several individuals per site. Sampling of community-level phenology will inform questions regarding interspecific variation in the timing and duration of phenological phases and their sensitivity to climate. The resulting dataset will enable assessment of the degree to which phenological timing and climate sensitivity vary based on functional groups or growth forms (e.g. natives/exotics, overstory/understory, perennial/annual, deciduous/evergreen, herbaceous/woody, early and late-season). These patterns can enable generalizations regarding the likely phenological responses and sensitivities of species beyond those targeted for regular observation.

NEON will implement phenological monitoring in two phases in order to accomplish both inter- and intra-specific sampling goals. During Phase I (Phenology of dominants), implemented during the first three full (i.e., all sites operational) years of sampling, phenological observations will concentrate on intensive monitoring of three dominant species at each of the 60 terrestrial sites.. The NSF Research Coordination Network (RCN) report (2012) recommends a minimum of 5-10 replicate individuals sampled for vegetative phenology per site per species, with an ideal sampling intensity of 20-30 individuals. In the absence of existing data sufficient to statistically determine smaller minimum sample sizes for particular species and sites, NEON will target the higher end of this range in order to quantify intraspecific variation in phenological timing for the three most dominant species at each site (see section 'Temporal distribution of sampling, below, for details of monitoring frequency)**.**

Phase II (community phenology), will follow Phase I and consist of more limited sampling than Phase I in terms of frequency and the number of replicate individuals per species (minimum of 5 individuals per species per site), but will have an increased number of species. The focal shift will alter which individuals are monitored, but keep the total number of plants monitored per site at ~90-100 due to budgetary limitations. Phase II monitoring will commence in the $4^{th}$ year of operational sampling and will continue for the remainder of NEON operations at each site. Species to be monitored in Phase II will include dominant species (the three species studied as part of Phase I at each site) and up to 17 additional species per site that collectively represent a range of functional groups and life history strategies. Phase II will inform both the range of

phenological patterns occurring at a site, as well as predictive models of the sensitivities of particular species based on their traits (Buckley and Kingsolver 2012).

***Spatial distribution of sampling***

A common critique of much of the existing ground-phenology observation data is that observations are limited in space and are reported as points, whereas remote sensing data pixels from commonly used satellite products used to model phenology range from 30m to >1km (Schwartz and Hanes 2010). While some studies have found little spatial autocorrelation in a single plant species' phenological response given uniform temperature over small areas (Schwartz et al. 2013), dispersion of monitored individuals throughout a larger area is important to encompass variation in plant phenology within the sampling area caused by microenvironmental variation, genetic variation, or both. To facilitate repeatable observation of multiple individuals over a relatively large area, while keeping travel time to a minimum, marked individuals will be situated along a fixed, 800-meter square 'loop' transect (200 meters on a side), with the 4 edges oriented in the four cardinal directions. This size is comparable to the ~250m modis pixel size, which is commonly used in satellite-based phenology assessments.

This loop will be situated within or near NEON's flux tower footprint whenever possible. The distance of the transect from the tower will be site specific based on identified exclusion areas around tower instrumentation, and will be placed to facilitate inclusion of individuals located within sampling plots used for NEON's biomass and productivity measurement (see Meier et al. this issue) (Figure 1). Collocation of the phenology transect with the instrument tower will allow meteorological and biophysical data collected by tower-mounted sensors to be used directly in analysis of phenological

data (e.g. how local climate affects phenology) and vice versa (e.g. how leaf status affects daily carbon flux). NEON's tower locations are positioned such that the tower air-shed is situated in a spatially and structurally homogenous area with the goal of a minimum of 80% contribution from the representative ecosystem, ensuring that plants selected for phenological monitoring are also located within a regionally representative habitat type. The assumption is that the intraspecific variation in phenological responses will, in general, be from individuals subject to similar environmental conditions. Even so, microtopographic features may still affect variation in observed phenological response. Additional information such as slope, aspect, community composition, above-ground biomass, and canopy chemistry as derived from NEONs airborne observation system may provide additional insight into the realized environmental heterogeneity of the various sites.

***Temporal distribution of sampling***

A standard sampling frequency for phenology has not been prescribed by the ecological community. Typically, sampling frequency varies by species, environment, sampling objectives, and budgetary and logistical constraints. The ideal frequency of sampling depends on analysis goals (e.g. fitting a thermal forcing model vs. long-term trend detection vs. quantifying intraspecific variation in phenology), as well as the degree of intraspecific and interannual variation in phenology. Mazer *et al.* (2015) found that twice-weekly sampling over a three-year period was sufficient to detect statistically significant associations between winter monthly rainfall and/or mean temperature (and their interactions) and the onset dates of vegetative growth, flowering, and fruiting in four species monitored in California across broad environmental conditions. An NSF

Research Coordination Network (RCN) report on phenology (2012) suggests a sampling interval of 2-4 times per week. Miller-Rushing *et al*. (2008) recommend sampling every 2nd day to ensure a 97% chance of detecting a significant change in flowering date over 10 years of sampling, based on existing long-term flowering data collected in Massachusetts and Colorado. These recommendations assumed realistic anticipated rates of climate warming and interannual variability in temperature, in addition to a sensitivity of flowering date to temperature of 1 day/°C. A more recent synthesis of long-term phenology datasets worldwide (Wolkovich *et al.* 2012), however, suggests that flowering phenology will, on average, shift at a rate of 5-6 days/°C. Therefore less frequent sampling may be adequate for many species for simple trend detection.

Following the RCN recommendations, the first three years of sampling the phenological status of dominant species (Phase I) will be observed 3 times a week during key transition periods (i.e. leaf emergence and senescence, Table 1). Resulting data will be used to inform the sampling intensity necessary to characterize the mean (+/- 3 days S.E.) for leaf phenology transition dates for the 3 dominant species at the site in subsequent years. This target is based on a recent analysis by Jeong *et al.* (2012), who concluded that when observational error in estimating population mean transition days for key phenological events (e.g. budburst) is greater than +/- 3 days, parameterizing phenological forcing models is compromised. During Phase II, the frequency of phenological observations will be reduced to 2 times a week during transitional phases in order to accommodate sampling of a greater number of species.

Phenologically active periods will vary among species both spatially across the continent, and inter-annually at each site. In order to catch the full growing season for all

selected species, NEON will aim to commence weekly sampling three weeks prior to the earliest anticipated onset of the first phenophase (based on the earliest date observed in recent records for the species). This date will be determined using local information, where available (such as at LTER sites where historical phenological data exist, or indicator plants at a nearby, lower elevation site), or from historical MODIS data, in sites where local information is not available to guide sampling. Start of season metrics based on remote sensing data are typically biased towards early dates (White *et al.* 2009; Ganguly *et al.* 2010), so this should provide an 'earliest' outer bound on start of season.

Once bud break or initial growth is observed, the observation frequency will increase from once a week to either three times (Phase I) or two times (Phase II) a week. The intensive sampling stage ends once full-sized leaves have emerged/full canopy has formed, and sampling frequency is reduced to once a week or once every other week to survey for open flowers. Three weeks before the anticipated first date of senescence, based on local and/or MODIS data, sampling frequency will increase again to weekly (if previously reduced to every other week). At the first sign of leaf senescence (i.e. fall color), observation frequency will, once more, increase to 2 times a week sampling until <5% of leaves remain or until three consecutive censuses of no change have been observed.

**S*pecies selection***

Prior to commencing phenology observations at a given site, NEON will conduct quantitative vegetation surveys within 20-30 randomly placed plots within the tower footprint to assess species abundance. Three dominant species will be identified at each

site for Phase I phenology monitoring. The dominant species selected will include the two most abundant canopy species plus the single most abundant understory species for sites with greater than 50% canopy closure, and the two most abundant understory species plus the single most dominant overstory species for sites with less than 50% canopy closure. At sites with no defined woody overstory, e.g. grasslands, all three species will be selected from the herbaceous community. Understory and canopy species frequently occupy discrete temporal niches, with the understory species, or in some cases understory individuals, showing advanced phenology relative to that of canopy-forming individual (Richardson and O'Keefe 2009).

Additional species to be sampled for Phase II will be selected from the whole community of species present within the tower footprint using a random selection procedure, weighted by abundance. Abundance of woody vegetation with stem diameter >1 cm at a height of 130cm along the stem will be determined by biomass, calculated from stem diameters, according to Jenkins (2003) allometric equations per species. Because biomass is more difficult to assess for shrubs and herbaceous species, abundance in these growth forms is assessed based on total areal cover by species (surveyed as percent cover / $m^2$ for herbaceous species and measurement of canopy area within defined survey plots for shrubs). Species are then re-grouped into a single list, ordered by their absolute abundance rank as estimated within the 20-30 plots surveyed. The abundance values will then be used to identify species for targeted selection (Phase I) or to weight species for random selection (Phase II). By stratifying in this way, common species with very low biomass have a greater likelihood of selection than infrequent high biomass individuals.

Exceptions to the randomized selection process will be made to intentionally target species that either contribute to NEON's ability to address grand challenge questions (e.g. invasive species) or contribute to NEON's ability to align data collection with existing national citizen science data collection efforts. Invasive species, USA-NPN campaign taxa and PBB '10 most wanted' species will be preferentially selected from the species list prior to weighted random selection. In order to avoid species that are not present in sufficient quantities to maintain monitoring of replicate individuals, NEON will limit potential community members for monitoring to those species found in more than 10% of the surveyed plots. The weighted random selection procedure should ensure that a diversity of plant growth forms, invasives and natives are selected at sites where they are present, without requiring any *a priori* definition of 'functional group', a concept which is not yet well understood for predicting phenology. It will also serve to concentrate monitoring efforts on species that are relatively common, while also including some rare species.

***Site-specific modifications***

Modifications will be made for sites with growing seasons or species with life histories that differ from the typical temperate deciduous model. For example, sampling may begin earlier than described above to capture flowering phenophases for plants that flower prior to leaf production. Additionally, sampling frequency will need to be modified at sites without a clear seasonal greening pattern (e.g. tropical ecosystems, or Mediterranean climates where species may leaf out or flower multiple times per year in response to episodic rainfall); in these cases, year-round sampling with longer intercensus

intervals will be necessary to capture phenological trends. Modifications will also need to be made for cropped (agricultural) sites. At these sites, NEON will monitor the cultivated species; in most cases, the selected species will vary by year to track crop rotations and will likely not have the diversity to support Phase II sampling. Details of monitoring, including frequency and replication, may be adjusted based on the initial data collected at each site and budgetary constraints. All site specific details including site-specific modifications, species selection and targeted sampling windows will be captured, tracked, and made available to end users as part of the NEON phenology sampling protocol (available through the NEON web portal; www.neoninc.org).

**Applications of phenology data**

NEON plant phenology data will provide foundational information about the variability in plant phenology across populations, communities, and landscapes, which can be used to validate remotely-sensed land surface phenology measures and better inform terrestrial biosphere models. To date, realistic parameterization of phenological models for wild species is limited to the very few species for which relevant data are available (Jeong et al. 2012). NEON will expand the taxonomic representation of phenological data, measuring as many as 20 plant species at each of 60 sites across the continent. Quantifying the range of phenological responses across a diversity of species and sites also will aid in the development of more general phenological forcing models based on species and site characteristics, as well as understanding of the degree to which these models can be used to estimate phenology where direct measurements are not available. Bayesian hierarchical models are a promising avenue forward in community

phenology forecasting (see Ibáñez et al. 2010, Diez et al. 2012 for examples applied to individual sites with multiple taxa, or single taxa measured across multiple sites). Multi-site, multi-species datasets provided by NEON can form the basis of an expanded phenological modeling framework across sites and species. Accurate representation of intra- and inter-annual variability in vegetation phenology is critical for correctly predicting net $CO_2$ uptake (Desai 2010). An evaluation of vegetation phenology in 14 terrestrial biosphere models found that for deciduous forests an early start of season bias of two weeks or more was typical across all models which resulted in a 13% over estimate of gross ecosystem productivity (Richardson et al. 2012). Such misrepresentation of phenology has consequences beyond ecosystem productivity estimates. When terrestrial and atmospheric models are not properly coupled, reductions in temperature associated with the onset of leaf emergence and associated increases in transpiration are often misrepresented (Levis and Bonan 2004). This insufficient coupling during critical phenological stages can lead to errors in modeled microclimate and weather patterns and thus present cascading effects on other model components. High quality, long-term, standardized phenological measurements across major ecosystem types will be critical components for improving model development and accuracy.

The dominant species in all plant communities generally represent key resources for animals that depend on them for food or shelter. Consequently, phenological shifts in the onset, duration, and abundance of vegetative and reproductive resources detected by NEON's phenological monitoring program can alert resource managers of changes that may affect the community composition and population dynamics persistence of insects, pollinators, birds, and mammals at site or regional scales. This goal requires monitoring

of the animals that interact with the focal plant species at NEON sites. In addition to plant phenology observations (the focus of this manuscript), terrestrial protocols that contribute to phenological monitoring at NEON sites include trapping of (1) mosquitoes and (2) small mammals throughout the active growing season; these data may be used to track phenology of mosquito emergence and annual population dynamics and small mammal reproductive periods, respectively (Hoekman *et al.,* this issue, Thibault *et al.*, this issue). Integration of NEON phenology data with surveillance data on other taxa, conducted either by NEON or by PIs working at NEON sites, can help track phenological asynchrony between interacting species and potential consequences to shifts in overlapping activity periods throughout the duration of the observatory.

The development of integrated, interoperable datasets will enhance the utility of data collected by NEON and other programs. A number of other programs (e.g. USA National Phenology Network (https://www.usanpn.org/) , Long Term Ecological Research (LTER) Network sites (http://www.lternet.edu/) , National Parks (http://science.nature.nps.gov/im/monitor/), the Pan European Phenology Project (PEP725; http://www.pep725.eu/)), as well as multiple longterm PI-directed research projects also take phenology measurements. NEON data will augment and compliment these efforts, providing replication and longevity of measurements that are difficult to achieve without a centralized source of funding. Because of NEON's planned infrastructure, its potential to link ground-based measurements, landscape green-up and brown-down metrics, and ecosystem processes is unique (Keller et al. 2008). NEON will also collect biweekly leaf area index (LAI) digital hemispherical photos, landscape images collected multiple times per day using stationary cameras (phenocams), and

carbon flux estimates processed at half-hour intervals. These data streams, augmented with annual sub-meter hyperspectral and LiDAR remote sensing data will be valuable in determining statistical and mechanistic associations between aboveground, belowground and landscape scale seasonal dynamics.

One limitation of the NEON design for phenology is that the financial and logistical commitment required to measure phenology alongside a large suite of other parameters (see Lunch et al. 2014 for the full list of NEON data products) constrains the total number of NEON sites. As a result, NEON sites are spatially sparse compared to continent-wide citizen-science observation efforts, such as the USA National Phenology Network (www.usanpn.org*;* hereafter USA-NPN), Project BudBurst (www.budburst.org; hereafter PBB) and affiliated national and regional monitoring networks. Because NEON uses nationally standardized protocols, however, data from the intensively studied NEON sites can be readily combined with existing and ongoing efforts to facilitate continental-scale analysis and forecasting. By integrating ground-based observations with other North American plant phenological monitoring programs (e.g., USA-NPN), existing datasets (e.g. Wolkovich et al. 2012), the PhenoCam network (http://phenocam.sr.unh.edu/webcam/), satellite imagery (e.g. MODIS land cover dynamics http://modis.gsfc.nasa.gov/data/dataprod/), and/or models (e.g. the Growing Season Index; Jolly et al. 2005), *in situ* phenology observations made by NEON can contribute critical information to an annual 'green wave' (Schwartz 1998; Ault et al *in press*) projection over the continent.

Phenological data can also be used in a number of natural resource management activities (Enquist et al. 2014). Accurate phenological forecasts can aid land managers in

timing controlled burns, mechanical harvesting, pesticide and/or herbicide applications for maximum efficiency in controlling invasive species. Data on seasonal growth and senescence patterns can inform wildfire predictions. Similarly, information on peak flowering and leaf color change dates can help promote and plan for seasonal tourism coincident with wildflower or fall foliage viewing. Last, recent studies theorize that a species' ability to make appropriate phenological adjustments to a changing climate may be predictive of its future success in a changing climate (Willis et al. 2010; Pau et al. 2011). This suggests that an improved understanding of species-specific phenological sensitivities could be used to identify particularly vulnerable native taxa for protection, or prioritize invasive species for removal.

Changes in plant phenology are widely regarded as 'fingerprints of climate change' or 'climate change indicators'(e.g., U.S. Environmental Protection Agency 2014); indeed, plant phenology is an exemplary essential species trait in the ongoing development of Essential Biodiversity Variables (EBV's) targeted for international monitoring (Pereira et al. 2013). Ongoing efforts both nationally (e.g. USA-NPN, Project Budburst) and internationally (e.g. PEP725), will continue to document patterns of plant phenology over large spatial extents. Leveraging data from NEON will enable the extrapolation not only of patterns of plant phenological shifts across the continent (e.g. Jeong et al. 2013, Ault et al. *in press*), but potentially also of the functional consequences of these shifts. Collocated measurements conducted by NEON will elucidate the degree to which plant phenological status is broadly indicative of related ecosystem processes for which continent-wide data are sparse (e.g. below-ground phenology, carbon flux, seasonal biomass accumulation. In turn, the analysis, synthesis, and application of

phenological information will facilitate decision-making related to critical ecological issues that affect societal well-being now and into the future.

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**Table 1. Proposed rule sets for specific growth forms for phenology sampling at sites with a well-defined growing season**

| Growth form | Monitor indicator individual for: | Sample 3x/week until all tagged individuals show: | Sample 1x/week until all tagged individuals show: | Then[2]: | Then: | Sample 2x/week until all individuals show: | Sample 1x/week until: | Then: |
|---|---|---|---|---|---|---|---|---|
| **Cactus** | Breaking flower buds | NA | End sampling season when no more fresh flowers are present | NA | NA | NA | NA | NA |
| **Deciduous broadleaf** | Breaking leaf or flower buds | >50% of canopy is full with leaves or three consecutive bouts of no change | 95% or more of canopy is full with leaves | Commence every-other week monitoring for open flowers | Monitor indicator individuals for one or more colored leaves | One or more colored leaves | <5% of canopy full with green or colored leaves | End sampling season |
| **Deciduous conifer** | Breaking needle buds | >50% of canopy is full with needles or three consecutive bouts of no change | 95% or more of canopy is full with needles | Commence every-other week monitoring for open pollen cones | Monitor indicator individuals for one or more colored needles | One or more colored needles | <5% of canopy full with green or colored needles | End sampling season |
| **Drought deciduous broadleaf** | Breaking leaf buds | Young leaves | No more young leaves | Commence every-other week monitoring for open flowers | Monitor indicator individuals for one or more colored leaves[3] | One or more colored leaves | <5% of canopy full with green or colored leaves | End sampling season |
| **Evergreen Broadleaf** | Breaking leaf buds | Young leaves | No more young leaves | Commence every-other week monitoring for open flowers | End sampling season when no more fresh flowers are present | NA | NA | NA |
| **Evergreen conifer** | Breaking needle buds | Young needles | No more young needles | Commence every-other week monitoring for open pollen cones | End sampling season when no more fresh pollen cones are present | NA | NA | NA |

| Growth form | Monitor indicator individual for: | Sample 3x/week until all tagged individuals show: | Sample 1x/week until all tagged individuals show: | Then[2]: | Then: | Sample 2x/week until all individuals show: | Sample 1x/week until: | Then: |
|---|---|---|---|---|---|---|---|---|
| **Evergreen forb** | Breaking leaf buds | Young leaves | No more young leaves | Commence every-other week monitoring for open flowers | End sampling season when no more fresh flowers are present | NA | NA | NA |
| **Forb** | Initial growth | One or more fully unfolded leaves | NA | Commence every-other week monitoring for flowering phenology | Monitor indicator individuals evidence of senescence | NA | No more full sized leaves are present | End sampling season |
| **Graminoid** | Initial growth | >50% of plant is green or three consecutive bouts of no change | >95% of plant is green | Commence every-other week monitoring for flowering phenology | Monitor indicator individuals for >5% Leaf senescence (i.e. percentage of plant that is green <95%) | <95% green leaves | <5% of plant is green | End sampling season |
| **Pine** | Emerging needles or pollen cone development | Young needles | No young leaves | Commence every-other week monitoring for open cone | End sampling season when no more fresh pollen cones visible | NA | NA | NA |
| **Semi-evergreen broadleaf[4]** | Breaking leaf or flower buds | Young leaves OR >50% of canopy is full with leaves OR three consecutive bouts of no change | No more young leaves OR 95% or more of canopy is full with leaves | Commence every-other week monitoring for open flowers | Monitor indicator individuals for one or more colored leaves[3] | One or more colored leaves | <5% of canopy full with green or colored leaves | End sampling season |

1 This is generally applicable to temperate or boreal systems; sites lacking a distinct growing season where growth occurs year-round or is episodic such that a growing season cannot be defined will be monitored on a weekly basis.

2 If flowering phenology precedes leaf/needle bud break skip the steps outlined in this column and decrease monitoring to watching indicator individuals for fall senescence or end monitoring for the season as specified in the following column.

3 Seasonal monitoring may end at this point if senescence does not occur.

4 Semi-evergreen broadleaf growthform may be used for species in which life history varies with latitude. Monitoring strategy should be driven by phenophase observations.

## Figures

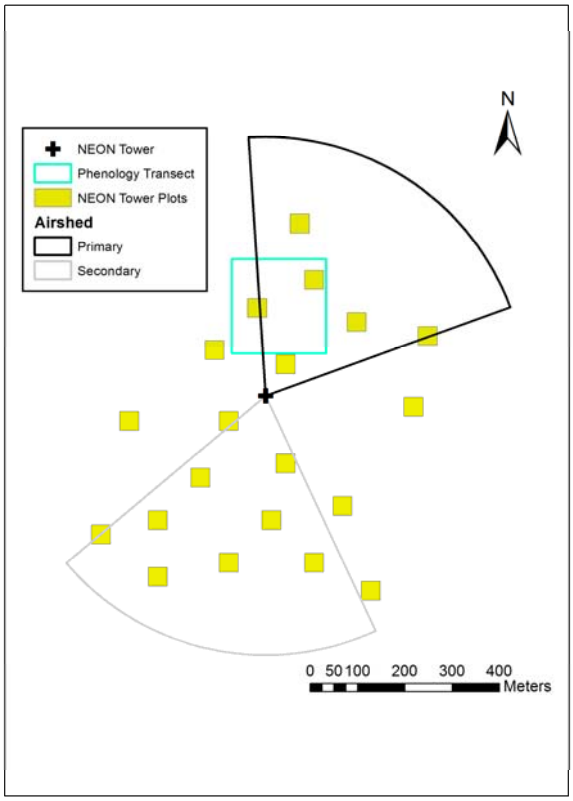


**Figure 1.** Layout of phenology transect (teal square) with respect to the NEON Tower (cross shape), the airshed (wedge shapes) and the Tower Plant Productivity plots (yellow squares) (figure credit: Rachel Krauss, 2015)