TOS SCIENCE DESIGN FOR PLANT PHENOLOGY

PREPARED BY	ORGANIZATION	DATE
Sarah Elmendorf	DPS	07/22/2014
Katherine Jones	FSU	07/22/2014

APPROVALS	ORGANIZATION	APPROVAL DATE
Andrea Thorpe	SCI	03/13/2015
Mike Stewart	SYS	02/23/2015

RELEASED BY	ORGANIZATION	RELEASE DATE
Jennifer DeNicholas	CM	03/13/2015

See configuration management system for approval history.

The National Ecological Observatory Network is a project solely funded by the National Science Foundation and managed under cooperative agreement by NEON, Inc. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	03/13/2015	ECO-02158	Initial release

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1 DESCRIPTION

1.1 Purpose

NEON design documents are required to define the scientific strategy leading to high-level protocols for NEON subsystem components, linking NEON Grand Challenges and science questions to specific measurements. Many NEON *in situ* measurements can be made in specific ways to enable continental-scale science rather than in ways that limit their use to more local or ecosystem-specific questions. NEON strives to make measurements in ways that enable continental-scale science to address the Grand Challenges. Design Documents flow from questions and goals defined in the NEON Science Strategy document, and inform the more detailed procedures described in Level 0 (L0; raw data) protocol and procedure documents, algorithm specifications, and Calibration/Validation (CalVal) and maintenance plans.

1.2 Scope

This document defines the rationale and requirements for Plant Phenology in the NEON Science Design.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

Applicable documents contain information that shall be applied in the current document. Examples are higher level requirements documents, standards, rules and regulations.

AD[01]	NEON.DOC.000001	NEON Observatory Design
AD[02]	NEON.DOC.001282	Introduction to the TOS Science Designs
AD[03]	NEON.DOC.000913	TOS Science Design for Spatial Sampling Design
AD[04]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[05]	NEON.DOC.014040	TOS Protocol and Procedure: Plant Phenology
AD[06]	NEON.DOC.000987	TOS Protocol and Procedure: Measurement of Woody Structure
AD[07]	NEON.DOC.000914	TOS Science Design for Plant Biomass, Productivity, and Leaf Area Index
AD[08]	NEON.DOC.XXXXXX	Areas of Mutual Representativeness and Exclusion around Terrestrial Infrastructure Measurements (TBW)

2.2 Reference Documents

Reference documents contain information complementing, explaining, detailing, or otherwise supporting the information included in the current document.

RD [01]	NEON.DOC.000008	NEON Acronym List
RD [02]	NEON.DOC.000243	NEON Glossary of Terms
RD [03]	NEON.DOC.001025	TOS Protocol and Procedure: Plot Establishment

2.3 External References

External references contain information pertinent to this document, but are not NEON configuration-controlled. Examples include manuals, brochures, technical notes, and external websites.

ER [01]	
ER [02]	
ER [03]	

2.4 Acronyms

Acronym	Definition
NPN	National Phenology Network
PBB	Project Bud Burst
RCN	Research Coordination Network

2.5 Acknowledgments

This document was written with input from the following coauthors:

- Ben Cook, Columbia U.
- Jeff Diez, U.C. Merced
- Carolyn Enquist, National Phenology Network
- Matthew Jones, U. Montana
- Rebecca Kao, Denver Botanical Garden
- Susan Mazer, U.C. Santa Barbara
- Abe Miller-Rushing, Acadia National Park
- David Moore, U. Arizona
- Mark Schwartz, U. Wisconsin Milwaukee
- Jake Weltzin, National Phenology Network

3 INTRODUCTION

3.1 Overview of the Observatory

The National Ecological Observatory Network (NEON) is a continental-scale ecological observation platform for understanding and forecasting the impacts of climate change, land use change, and invasive species on ecology. NEON is designed to enable users, including scientists, planners and policy makers, educators, and the general public, to address the major areas in environmental sciences, known as the Grand Challenges (Figure 1). NEON infrastructure and data products are strategically aimed at those aspects of the Grand Challenges for which a coordinated national program of standardized observations and experiments is particularly effective. The open access approach to the Observatory's data and information products will enable users to explore NEON data in order to map, understand, and predict the effects of humans on the earth and understand and effectively address critical ecological questions and issues. Detailed information on the NEON design can be found in AD[01], AD[02].

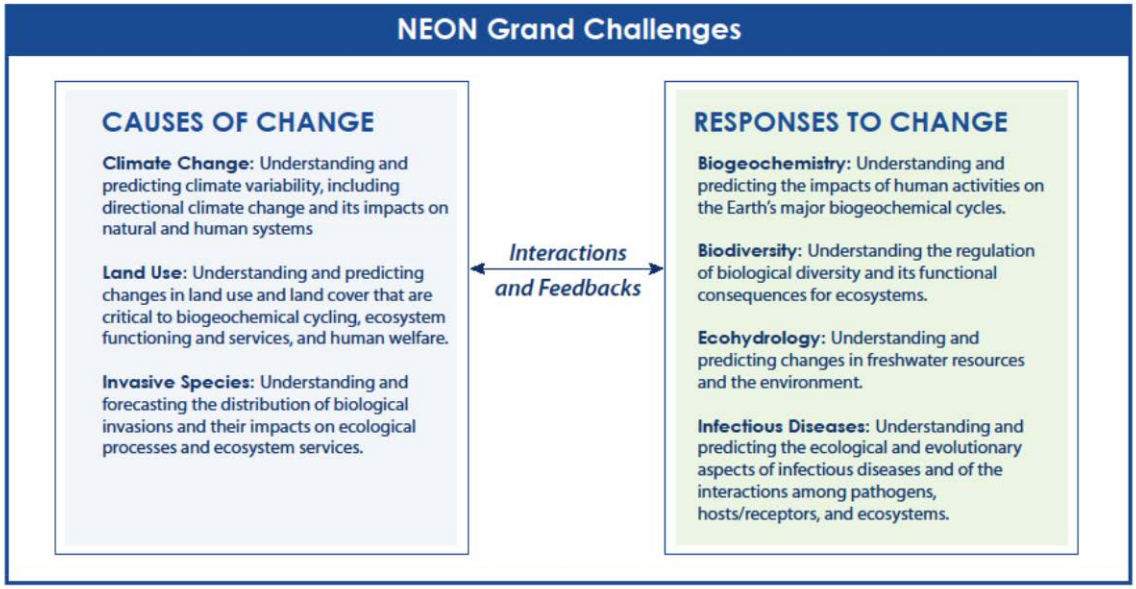

Figure 1. The seven Grand Challenges defined by the National Research Council (2001).

3.2 Components of the Observatory

There are five components of the Observatory: the Airborne Observation Platform (AOP), Terrestrial Instrument System (TIS), Aquatic Observation System (AOS), Aquatic Instrument System (AIS), and Terrestrial Observation System (TOS). Collocation of measurements associated with each of these components will allow for linkage and comparison of data products. For example, remote sensing data provided by the Airborne Observation Platform (AOP) will link diversity and productivity data collected on individual plants and stands by the Terrestrial Observation System (TOS) and flux data captured by instruments on the tower (TIS) to that of satellite-based remote sensing. For additional information on these systems, see Keller et al. (2008), Schimel et al.(2007).

3.3 The Terrestrial Observation System (TOS)

The NEON TOS will quantify the impacts of climate change, land use, and biological invasions on terrestrial populations and processes by sampling key groups of organisms (sentinel taxa), infectious disease, soil, and nutrient fluxes across system interfaces (air, land, and water) (AD[01], AD[02]). The sentinel taxa were selected to include organisms with varying life spans and generation times, and wide geographic distributions to allow for standardized comparisons across the continent. Many of the biological measurements will enable inference at regional and continental scales using statistical or process-based modeling approaches. The TOS sampling design captures heterogeneity representative of each site to facilitate this inference when possible. Plot and organism-scale measurements will also be coordinated with the larger-scale airborne measurements, which provide a set of synergistic biological data products at the regional scale. Details of these design elements and algorithms can be found in individual design documents available through the NEON website (www.NEONinc.org).

The standardization of protocols across all sites is key to the success of NEON (and its novelty) and must be maintained at all sites through time. Thus, although specific techniques may be required at some sites (e.g., due to different vegetation types), protocols have been developed to ensure data comparability. These details can also be found in individual design documents available through the NEON website (www.NEONinc.org).

The TOS Science Designs define the scientific strategies leading to high-level sampling designs for NEON sentinel taxa, terrestrial biogeochemistry, and infectious disease, linking NEON Grand Challenges and science questions to specific measurements (AD[02]). The TOS Spatial Sampling Design document describes the sampling design that collocates observations of the components of the TOS (AD[03]). TOS Science Design documents were developed following input from the scientific community, including module-specific Technical Working Groups, and the National Science Foundation (AD[02]). Science Designs will be reviewed periodically to ensure that the data collected by NEON are those best suited to meet the requirements of the Observatory (AD[01]), are (to the extent possible) consistent with standards used by the scientific community, and fit within the scope of NEON. Additional information on the development and review process can be found in AD[02].

4 INTRODUCTION TO THE PHENOLOGY SAMPLING DESIGN

4.1 Background

Phenology is defined as the seasonal timing of life cycle events. The Intergovernmental Panel on Climate Change IPCC (Solomon et al. 2007) notes that phenology is one of the simplest processes for tracking changes in species' ecology in response to climate change. According to a recent synthesis, the onset of spring phenological events is advancing at a mean rate of 2.3 days per decade worldwide, likely due recent climate warming (Parmesan and Yohe 2003). Plants flower on average ~5 days earlier per °C increase in spring temperature (Wolkovich et al. 2012), so substantial changes in spring phenology are expected over the life of the Observatory.

In addition to being a variable that is sensitive to climate change, phenology is also a potentially important driver of ecological responses ranging from the demographic trajectories of individual taxa to biogeographical distributions to ecosystem processes. For example, species whose phenologies track climate variability tend to have improved growth, productivity, or reproductive success in contrast to those that do not (Cleland et al. 2012) On the other hand, phenologic 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). In either case, a population's phenological sensitivity may be an early indicator of its demographic trajectory. These sensitivities may constrain broad-scale distribution patterns; phenology appears to be a key biological constraint in process-based species distributions models (Chuine 2010 and references therein).

Phenological shifts can themselves create feedbacks that alter species interactions and ecosystem processes. Differential sensitivities to phenological triggers can cause trophic mismatches between interacting organisms (Singer and Parmesan 2010, McKinney et al. 2012). The timing of leaf budburst and senescence can alter surface radiation, temperature, hydrology and carbon cycling (Bonan 2008, Richardson et al. 2010, Jeong et al. 2012, 2013). Phenological transitions may be triggered by a variety of cues, including chilling requirements, spring temperature, and daylight cues (Chuine 2000), but realistic parameterization of phenological models for many wild species has been limited due to the scarcity of relevant data (Jeong et al. 2012).

A number of techniques exist for monitoring and recording the phenological status and progress of plants , including *in situ* observations, modeling, eddy covariance towers, experiments, remote sensing, and digital photography (Cleland et al. 2007). However, formulating linkages between these different approaches to monitoring phenology, and scaling from individual-based monitoring (as implemented in citizen science programs, natural resource monitoring programs, and a variety of site-based long-term ecological studies), to larger scales is an active area of research (Morisette et al. 2008). By providing integrated suites of measurements on the seasonal progression of a diversity of taxa and ecosystem processes at intensively measured sites, NEON data will enable the scientific community to further

develop mechanistic linkages between the environmental drivers that affect plant phenology, as well as the functional consequences of changing phenology for a wide array of ecosystem types.

4.2 NEON's Contribution

NEON is poised to advance the field of phenology due to the combined contributions of the following attributes: 1) The monitoring of replicate individuals per species in order to quantify intraspecific variation in the timing of phenological events and its sensitivity to environmental conditions, and to increase the precision of estimates of the mean phenological trajectories at the population level; 2) Measurements of multiple species to characterize the range of phenological response patterns; 3) Accumulation of high quality, long-term, standardized measurements recorded by trained technicians across 20 major ecosystem types of the continental US; and 4) Collocation of plant phenological measurements with an extensive array of monitoring data from other sentinel taxa as well as meteorological, flux and ecosystem productivity data which may be used to understand linkages between climate, phenology, ecosystem processes and biodiversity. Elements of all of the above are currently being collected by a number of other programs (e.g. Ameriflux, NPN, LTER sites, National Parks) as well as multiple long term PI directed research projects, and both NEON and these allied projects and programs stand to benefit from this integration. For example, the collocation of multiple measurement systems at NEON sites may enable inference of ecosystem processes at an extensive network of spatially distributed sites where only *in situ* observations are feasible.

The phenological data collected by NEON will provide a rich dataset for informing continental-scale phenology over the lifetime of the Observatory, for forecasting future phenological shifts in response to anticipated anthropogenic changes, and for understanding the sensitivity of critical ecosystem processes to phenological change. Quantifying the range of phenological responses across a wide array of species and sites will aid in the development of more general phenological forcing models based on species and site characteristics, as well as understanding of their limitations in forecasting phenology where existing data are sparse. Bayesian hierarchical models are a promising avenue forward in community phenology forecasting (Ibáñez et al. 2010, Diez et al. 2012). To date such models have been limited either to sites with multiple species, or to single species observed over multiple sites; in contrast NEON will provide community-level data with observations on up to 20 species at 60 sites, using common protocols and in association with extensive meteorological information, in sites across the country.

By integrating ground-based observations with other North American phenological monitoring programs throughout the country (e.g., USA National Phenology Network), existing datasets (e.g. (Wolkovich et al. 2012), the PhenoCam network (http://phenocam.sr.unh.edu/webcam/), satellite imagery (e.g. US Remote Sensing Phenology, http://phenology.cr.usgs.gov/; MODIS 12Q2 product https://lpdaac.usgs.gov/products/modis_products_table/mcd12q2; MODIS for NACP http://accweb.nascom.nasa.gov/) , and/or models such as (e.g. Spring Indices (Ault et al. 2011), GSI (Jolly et al. 2005), and a variety of chilling, thermal forcing and photoperiod models (Vitasse et al. 2011) *in situ* phenology observations made by NEON can contribute critical information to an annual 'green

wave' (Schwartz 1998) projection over the continent. Integration of collocated NEON datasets ranging from *in situ* phenology, phenocam, LAI, productivity, eddy flux, along with sub-meter hyperspectral and LiDAR remote sensing data will be particularly valuable in determining both statistical and mechanistic linkages between the multiple components of seasonal cycles.

4.3 Purpose and Scope

The purpose of sampling plant phenology is to capture inter-annual variation in the timing of phenological stages of plants. This document details the approach used to derive a scientifically rigorous, logistically feasible sampling design that meets the goals of NEON.

5 SAMPLING FRAMEWORK

5.1 Science Requirements

This science design is based on Observatory science requirements that reside in NEON's Dynamic Object-Oriented Requirements System (DOORS). Copies of approved science requirements have been exported from DOORS and are available in NEON's document repository, or upon request. Execution of the protocols that stem from this science design procures samples and/or generates raw data satisfying NEON Observatory scientific requirements.

5.2 Data Products

The data resulting from the plant phenology protocols are used to create NEON data products, as outlined in the NEON Scientific Data Products Catalog (AD[04]).

5.3 Priorities and Challenges for Plant Phenology Sampling

Two priorities were identified for NEON's plant phenological sampling: 1) capturing the mean and intraspecific variance of dominant species within each site 2) capturing a range of species-specific phenotypic responses that represent the community at each site. The first (dominant species' phenology) will enable linking phenological patterns observed above-ground to processes captured by other NEON measurement systems, such as root phenology, ecosystem productivity and respiration, carbon, water and nutrient cycling It will also provide critical information on intraspecific variation in phenology patterns, which are poorly captured when monitoring efforts are limited to as census of one to several individuals/site. The second (community phenology), will inform questions regarding inter-specific variation in the timing and duration of phenological phases and their sensitivity to climate. It will provide a rich dataset across a diverse array of plant types (natives/exotics, overstory/understory, perennial/annual, deciduous/evergreen, herbaceous/woody, early and late-season, phylogenetic relatedness) that may permit generalization and predictions regarding the phenologies and sensitivities of other species in these functional groups that are not directly monitored. These priorities stem from those identified by the 2008 Tiger Team report (Davis et al. 2008), which emphasized the importance of

characterizing both 'earliest dates' and within-population variation in phenology. An increasing appreciation of the limitations of first appearance dates as a phenological estimator (Miller-Rushing et al. 2008, Moussus et al. 2010) since the publication of the Tiger Team reports suggested a shift in emphasis away from earliest dates as a focus of data products.

Due to resource limitations at NEON sites, compromises must be made between the number of species, the number of individuals per species to be monitored and the number of phenophases monitored; NEON cannot maximize the measurement of both inter- and intra-specific variation. As a result, NEON will implement its phenology sampling in two phases in order to accomplish both inter- and intra-specific sampling goals. During Phase I, phenological sampling will concentrate on the intensive monitoring of 3 dominant species at each site. Phase II will consist of more limited sampling of up to 20 species/site. Phase I will last for the first 3 years of sampling at each site, after which sampling will transition to Phase II. The procedure for selection of individual species to be monitor at each site is described in section 6.1.1 below)

Both leaf and reproductive phenological events are sensitive to environmental change. However, quantifying with precision the dates of a large set of identifiable phenophases would require frequent sampling throughout the entirety of the growing season. Instead, NEON will dynamically vary the sampling intensity in order to capture the phenology of key leaf transitions with greater precision, with coarser resolution sampling for flowering (see Section 6.5 below). A focus on canopy development was selected in order to facilitate linkages with NEON's measurements of canopy development as captured by tower-mounted sensors such as phenocams and carbon cycling, as well as to provide linkages to remote sensing provided via the Airborne Observation Platform (AOP). Where more precise estimates of flowering or fruiting events for specific taxa are of interest (e.g. to understand resources for particular species interactions) individual PIs may set up additional phenological monitoring in the area by leveraging the baseline phenology data collected by NEON as well as the meteorological measurements.

6 SAMPLING DESIGN FOR PLANT PHENOLOGY

NEON's potential to link ground-based measurements, landscape greening metrics, and ecosystem processes is unique. However, NEON sites are relatively sparse, spatially, compared to continental citizen-science monitoring efforts such as the USA National Phenology Network (www.usanpn.org; hereafter NPN), Project BudBurst (PBB) and affiliated national and regional monitoring networks. Using nationally standardized protocols and leveraging existing and ongoing efforts in other areas will increase the potential for continental-scale analysis and forecasting by direct integration of NEON and other phenology data.

Plant phenology is typically quantified by noting the date of onset and the duration of particular phenophases, which may include both leaf and reproductive events. Without a common definition for specific phenophases, data interoperability becomes a limiting factor in continental-scale analyses, since there is not a 1:1 mapping of phenophase definitions among all monitoring networks. The USA NPN is

the largest and most scientifically rigorous national phenological monitoring program in the U.S., developed with feedback from a large scientific community and natural resource managers. Consistent with NEON's commitment to use existing nationally-accepted, vetted and standardized protocols wherever possible, and following the recommendation of the 2008 Tiger Team report, NEON will employ USA-NPN phenophase definitions (see Appendix A, after Denny *et al*. in revision).

Additional advantages of NPN protocols for NEON include: (1) status- based monitoring; (2) repeated tracking of marked and georeferenced individuals or "patches," rather than simply recording the date of 'first events' over unknown population sizes and (3) incorporation of both status and 'intensity' definitions for phenophases (Denny et al., in revision). Using status- rather than first event monitoring is a departure from many historical phenology 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 as the duration of phenophases rather than just their date of onset. Monitoring marked individuals (or small patches for annuals and clonal plants) ensures that the phenology dates recorded are decoupled from changes in population size (Miller-Rushing et al. 2008). The protocols employed will include 'intensity' metrics (e.g. % of leaves that are green vs. colored) along with phenophase start and end dates. By recording data that will allow the estimation of mean population start and end dates, as well as the intensity of each phenophase, these phenological data should provide better linkages to ecosystem function and landscape or remotely sensed phenologies than existing 'first event' phenology datasets, which quantify the phenological status of only the most extreme individuals.

In order to link phenology measurements to health and productivity, NEON will augment observations of leaf and reproductive phenology with annual status measurements on each individual/patch. These measurements will include size (dbh, % cover, height, and canopy dimensions), disease status, health condition and structure. During annual measurement, plant tissues will also be collected for archival, these samples will be available to the ecological community as part of NEON's research resource collection.

6.1 Sampling Methods

A recent NSF Research Coordination Network Report (2012), recommends tracking leaf phenology for dominant species in order to make linkages to remote sensing data. Such a strategy is also likely to allow the strongest inferences regarding the relationship between phenology and ecosystem processes, with the assumption that species contribute to ecosystem properties roughly in proportion to their relative abundance (Grime 1998). An additional priority is to characterize the community phenology of the site, which includes not only dominant species but subdominants and a range of functional groups and life history strategies. Such a strategy will both inform the range of phenological patterns occurring at a site, as well as predictive models of the sensitivities of particular species based on their traits.

The NSF RCN report (2012) recommends a minimum of 5-10 replicate individuals sampled for leaf phenology per site per species, with an ideal sampling intensity of 20-30 individuals. In the absence of existing data on intraspecific variance which might permit smaller sample sizes for particular species and sites, we will target the higher end of this range in order to quantify intraspecific variation in phenological timing (28-31 individuals/year) for the three most dominant species in each site, during Phase I of phenology sampling. In Phase II (community phenology), a reduction in sampling intensity (reduced measurement frequency and fewer replicates within species) will occur coincident with a shift to sampling of a greater number of species, to better quantify the community phenology. Due to budgetary constraints, it is not possible to monitor the phenology of every species that exists within the tower fetch area at each site. Estimates based on preliminary budget allocation to plant phenology monitoring suggest that NEON should be able to monitor 5 individuals, 2x/week, of approximately 20 species per site during the peak green-up and leaf senescence periods. Therefore, NEON will aim to continue to collect data on the three dominant species at each site during the 'community phenology' phase of the project, as well as an additional ~17 species at each site. The number of additional species to be sampled may be reduced or increased as more accurate estimates of technician time per phenological observation at each site become available.

In 2011 NEON conducted a prototype of the plant phenology sampling protocols at the Domain 10 Core site, Central Plains Experimental Range. Three species, *Atriplex canescens*, *Bouteloua gracilis* and *Bromus tectorum* were selected from the list of species common to the short grass prairie ecosystem. These species were selected 1) because they represent broad phylogenetic diversity, 2) are species with large geographic distributions and therefore are likely present at other NEON sites and 3) represent both native and non-native/invasive species. Thirty individuals/patches from each species were selected for sampling; these individuals/patches were scattered throughout three different sampling areas, none of which was located near the NEON Tower. Leaf and reproductive status of individuals was recorded weekly though phenophase intensity was not recorded. These initial efforts at implementing phenology sampling protocols were valuable more for assessing sampling methods than for the data collected. Changes to the design resulting from these efforts include (1) establishing a sampling transect from which to conduct phenology observations (2) focusing sampling to within the Tower airshed and (3) prioritizing characterization of the vegetation within the Tower airshed prior to selecting species. By restricting individual selection to those located along a 200 m x 200 m transect located near the NEON Tower sampling becomes more streamlined and efficient; traffic through other NEON plots and total travel time per sampling event is reduced by sticking to a single sampling transect. During phenology prototyping, one of the species selected for monitoring (*Bromus tectorum)*, though regionally common in, was not locally abundant; field crews were unable to achieve the intended sample size demonstrating that species selection needs to be based on a quantitative survey *of the intended monitoring area* (i.e. the Tower airshed); additionally, a site-specific survey of species abundance will provide values for the weighted random selection of Phase II species (see section 6.1.1.1 for more details).

A common critique of much of the existing ground-phenology observation is that observations are extremely limited in space, reported as points, whereas remote sensing data pixels from commonly used satellite products used to model phenology are ~250m (Schwartz and Hanes 2010). While some studies have found little spatial autocorrelation in plant phenologies within a homogeneous area (Schwartz in press), dispersion of monitored individuals throughout a larger area is important to capture the relevant (if any) spatial or genetic variation in plant phenology. To address these concerns, as well as those identifies during prototype efforts, marked individuals will be situated along a fixed, 800 meter square 'loop' transect (200 meters on a side) within the tower airshed (Figure 2). The tower airshed has been targeted for phenology sampling for both scientific and logistical reasons. First, to the extent that is possible, the Tower airshed is situated over a relatively homogeneous area in terms of vegetation type (AD[01]), so the intraspecific variation in phenology responses will, in general, be from individuals subjected to equivalent environmental conditions including community composition. Second, environmental data collected by tower-mounted sensors will facilitate identification of drivers of observed phenological trends. Lastly, because of construction and infrastructure requirements, NEON Towers are located near roads and are more accessible than other areas within a site, placing the phenology transects near the Tower minimizes travel-time to and from the transect and facilitates sampling efficiencies.

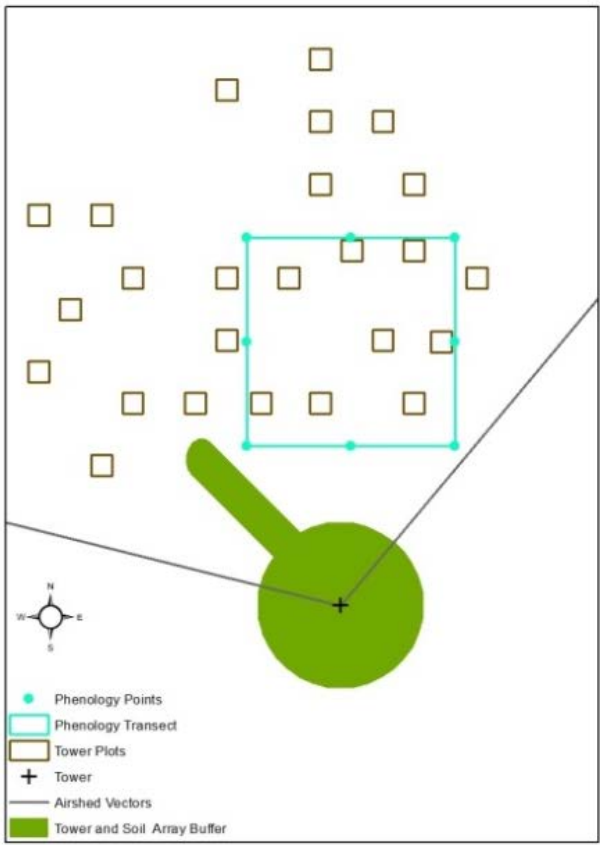

Figure 2. Layout of phenology transect (teal square) with respect to the NEON Tower (cross shape), the instrument buffers (green area), the airshed (black lines) and the Tower Plant Productivity plots (small squares)

It is desirable to have at least a few individuals of the dominant (Phase I) species that are included in both the *in situ* observations and within view of tower-mounted phenocams, which are planned to always be north-facing. This may occur without any additional effort (where airshed is naturally to the north of the tower itself); in other locations, an additional three individuals of each of the dominant species that are visible from the phenocam but offset from the phenology transect will also be monitored. The tower footprint is always contained within the larger (~10x10km area) overflown annually with NEON's airborne observation platform (AD[01], Kampe et al. 2010). Derived data on vegetation type and relative abundance from those remotely sensed data may enable scaling from individual species phenologies to landscape phenologies through relative abundance, using approaches outlined in Liang et al. (2011).

Implementation of the *in situ* plant phenology monitoring at each site will occur in three stages: Characterization, Phase I (dominant species phenology), and Phase II (community phenology). Refer to the Plant Phenology Protocol (AD[05]) for detailed information on how phenophases on marked individuals/patches are observed .

6.1.1 Characterization

Site characterization for phenology sampling will consist of (1) conducting a quantitative survey of vegetation present in the Tower airshed and (2) selection of species to monitor in both phases of phenology monitoring.

Within the tower footprint, prior to operations, a trained botanist familiar with the flora at each site will conduct a quantitative vegetation survey (using standardized methodology) to quantify percent cover by species. The characterization survey will also be used to determine whether the site contains greater than or less than 50% canopy closure. From the resulting species-abundance list, NEON will select three dominant species at each site for Phase I of phenology monitoring. The dominant species 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 over overstory, e.g. grasslands, all three species will be selected from the herbaceous community. Relative dominance is defined the rank order of species-specific cover percentages in the airshed. Stratifying sample species by canopy and understory is desirable because understory and canopy species frequently occupy discrete temporal niches, with the understory species -- or in some cases individuals -- showing advanced phenology compared to canopy emergents (Richardson and O' Keefe 2009).

Additional community species to be sample for Phase II will be selected from the community of the species present within the tower airshed using a random selection procedure, weighted by abundance. In forested systems, because it is difficult to evaluate abundance for all species on a continuous scale ranging from annual herbs to overstory trees, we will stratify species selection by vertical stature. During characterization, each individual surveyed will be categorized as contributing to the top, middle or lower third of the vertical profile in terms of height. For the top third, the tallest individuals, abundance will be ranked and weighted for random selection based on basal area by species. The middle third, shrubs and low stature understory trees, will be ranked according to either basal area or cover area (assessed in 100m^2 quadrats) depending which is most appropriate for a given system. The lower third, primarily made of the herbaceous community, will be ranked according to abundance and frequency as determined by cover estimates in 8, 1m^2 subplots in 20 Tower Plots. By stratifying in this way, common species with very low biomass have a greater likelihood of selection than infrequent high biomass individuals. Once all species have been ranked, they will be re-grouped into a single site-specific species abundance list, for targeted (Phase I) and random (Phase II) selection weighted by rank. Exceptions to the randomized selection process will be made to intentionally target state listed invasive species of concern, NPN calibration species and Project BudBurst (PBB) 10 most wanted species in regions of interest. 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 based on all species that are found in at least 5% of Tower subplots surveyed during the characterization phase. Monitored species at agricultural sites will be dictated by site- and year-specific planting regimes.

6.1.2 Phase I Sampling

For Phase I plant phenology sampling, NEON will target ~30 individuals (or 0.25*0.25 m patches, in the case of annual or clonal species where delineation of individual ramets is problematic) of each of the three dominant species for phenology monitoring at evenly spaced locations around the 800m transect. For annual plants, locations may change slightly from year to year; an effort will be made to retain the same locations interannually but adjustments may be made when plots do not contain any of the target species. Individuals selected will be within 1-10m of the phenology transect and, where possible, span a range of life stages (e.g. include both canopy emergent and understory individuals). In cases where there is not an individual of the desired species within the specific distance at a given sampling point, two individuals from the nearest sampling point(s) will be selected in order to maintain a total of the target number of individuals (28-31) along the transect. In addition, for sites where the tower phenocam does not include at least three individuals of the dominant species at each site, NEON will aim to select and mark an additional 3 individuals of each dominant species within the phenocam view in order to make explicit linkages between phenocam greenness metrics and *in situ* phenophase observations. This additional sampling may not be achievable at all sites, depending on the availability of existing trails or boardwalks permit access to the relevant areas without causing undue disturbance.

6.1.3 Phase II Sampling

For Phase II plant phenology sampling, NEON will select additional species, up to the 20 previously mentioned if site diversity allows. Individuals/patches to sample will be located along the phenology transect. From this list, NEON will use a weighted random sampling procedure to select additional species for monitoring, with weights proportional to the log of relative abundance as determined in the vegetation characterization survey. This procedure should ensure that a diversity of plant growth forms, invasives and natives are selected at sites where they are present, without any a priori definition of 'functional groups', 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. In order to target domain specific questions on invasive species, for domains with an invasive species science theme, the regionally dominant invasive species will be selected as one of the 'community' species in cases where it is present along the sampling transect. NPN calibration taxa and PBB '10 most wanted' species will be similarly targeted.

Individuals/patches monitored will be identified within 1-10m of the phenology transect. Technicians will aim to spread out sampling points for a given species along the transect, but (where possible) collocate individuals of different species at relatively few sampling points to increase sampling efficiencies. The locations of all individuals will be mapped with sub-2m accuracy.

6.2 Spatial Distribution of Sampling

The phenology transect at each site will be oriented in the four cardinal directions. The minimum distance of the basal edge of the transect from the tower will be site specific based on identified exclusion areas around Tower instrumentation (AD[08]). The exact location of the phenology transect will be selected to facilitate inclusion of individuals located within tower plots for sampling (Figure 2).

In order to facilitate linkages between ground-based measurements, landscape greening metrics, NEON's most intensive measurements will occur at the Tower and surrounding airshed. In addition to collocation with the instruments on the tower itself and soil array, this siting will provide general collocation with the majority of the plant productivity plots and LAI measurements, which are concentrated in the tower airshed (AD[06], AD[07]). The targeting of phenological monitoring of plants in this area best leverages NEON's ability to contribute to an understanding of the correlates, causes and consequences of plant phenological change. NEON Core sites are selected be representative of the domain in terms of vegetation, soils/landforms, climate and ecosystem performance with the location of relocatable selected to address specific scientific questions often dealing with land use and connectivity (AD[01]). The placement of instrumented Towers within NEON sites is targeted in the dominant vegetation type at that site. This design allows for extrapolation from identified relationships between ecological drivers and responses made within the tower airshed to regional and continental trends (AD[01]).

An additional advantage of the concentrated placement of plants to be monitored in a relatively centralized location is that it will reduce travel time during monitoring, allowing for greater sampling of species and individual plants. Thus while the monitoring of highly dispersed plants is desirable for some purposes, such as quantifying phenological variation across a localized environmental gradient, the number of observations that could be made over widely dispersed areas would be substantially reduced.

6.3 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, and sampling objectives and resource limitations. 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. Expert scientific opinion, as contained in the 2012 NSF RCN report (2012), suggests a sampling interval of 2-4x/week to capture dominant species phenologies. 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 but 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) suggests that flowering phenologies 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 dominant species (Phase I) phenology status will aim to be recorded 3x/week during key transition periods. These 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), which concluded that when observational error in estimating population mean transition days for key phenological events (e.g. budburst) are greater than +/- 3 days, parameterizing phenological forcing models is compromised. During Phase II, phenological observations will be reduced to 2x/week in order to accommodate sampling of a greater number of species.

During both Phase I and Phase II sampling, the most intensive (2-3x week), for sites with a single, definable pattern of seasonal activity per year (e.g. most of the sites) phenological sampling will occur only during the active transition season for canopy development and senescence. The timing of canopy development periods at each site is not known a priori. In the absence of existing information to determine these transition dates at each NEON site, sampling dates will initially be determined from the analysis of local *in situ* measurements, where available, or remote sensing data when local knowledge is absent (see logistics and adaptability section 6.1.4, below). Sampling at intensive frequencies (2-3x/week) will continue until the full canopy development or leaf greening has been achieved for all

monitored individuals. During the intervening growing season, phenological observations of flowering will occur biweekly; during the intervening dormant season no phenological observations will occur. A second intensive sampling phase will occur coincident with senescence. In sites without a clear seasonality (e.g. Tropical), and/or multiple greenup periods per year, NEON will sample continuously throughout the potentially active season with reduced frequency (targeted weekly, subject to budgetary constraints).

It is difficult to know a priori when to commence intensive sampling periods, since active periods vary both spatially across the continent, and interannually at each site. However, sampling efficiencies dictate that intercensus intervals vary dynamically in order to concentrate observations during periods of rapid change. NEON will aim to commence weekly sampling three weeks prior to the earliest anticipated onset of leaf greening (earliest date observed in recent record). This date will be determined in collaboration with the site managers, using local information, where available (such as at LTER sites where historical phenological data exists, or indicator plants at a nearby, lower elevation sites), or by 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 early (White *et al.* 2009; Ganguly *et al.* 2010), so this should provide an 'earliest' outer bound on start of season. When one individual reaches the 'trigger intensive sampling stage', observation frequency will increase to 3x (Phase I) or 2x (Phase II) weekly sampling.

- Trigger leaf-on intensive sampling stages are as follows:
  - Forb or Grass or Sedge: Initial growth
  - Drought-deciduous Tree/Shrub or Broadleaf Evergreen Tree/Shrub: Breaking leaf buds
  - Evergreen (non pine) Conifer/Deciduous Conifer: Breaking needle buds
  - Pine: Emerging needles

Intensive sampling stage ends when full leaves emerged/full canopy formed, and standard sampling season begins. During standard sampling season, sampling is reduced to once/two weeks to survey for open flowers.

Commencing three weeks before anticipated first date of senescence, based on local and/or MODIS data, sampling frequency increases to weekly. When one individual reaches the 'trigger leaf off intensive sampling stage', observation frequency will increase to 3x (Phase I) or 2x (Phase II) sampling until all leaves are dropped/senescence is complete.

- Trigger leaf-off intensive sampling stage are as follows:
  - Graminoids/Forbs >5% dried or dead leaves
  - Deciduous Trees/Shrubs = 1 colored leaf
  - Evergreens = no leaf off intensive sampling stage

Time periods to commence intensive sampling phases on a site-specific basis may be modified as predictive accuracy increases (e.g. if it is possible to model start of season based on local temperature

and moisture conditions with reasonably accuracy, and/or reliable local bio-indicators of start of season (e.g. phenocam greening, tower CO2 measurements) in order to increase sampling efficiencies. Thus we anticipate that the labor required for phenology sampling will be the greatest in the initial years of NEON and decline over time.

6.4 Logistics and Adaptability

6.4.1 Site-Specific Modifications

Modifications will need to be made for sites with plants that flower before leaf-out; likely modifications include sampling 1x/2x weeks beginning a few weeks before anticipated leaf out. As described above, modifications will also need to be made for sites without a clear seasonal greening pattern; planned modifications include year-round sampling with longer intercensus intervals. Modifications will also need to be made for cropped (agricultural) sites; in these sites NEON will simply monitor the planted species as well as some opportunistic weeds, targeted species will potentially change annually to track crop rotations. All site specific details including site-specific modifications, species selection and sampling windows will be captured and tracked as part of the phenology sampling protocol (AD[05]).

At a limited number of sites, where the tower airshed does not extend to the north of the tower, it is possible that the phenocam will overlook an area that differs in plant community composition than that found along the transect. In this case, if none of the species selected for phenology monitoring along the transect are present in the phenocam field of view, individuals that are dominant in the phenocam field of view will be selected for monitoring and will be added to the list of species monitored along the transect.

6.4.2 Incorporating New Technologies

Automated phenological monitoring using programmable, battery powered digital cameras has the potential to extend the spatial scale of automated sampling of plant phenology beyond the single phenocam situated on the instrument tower. However, the ability to derive accurate phenological information for a variety of taxa from these is still an active area of research (Crimmins & Crimmins 2008; Benton 2009). As these technologies evolve and costs decrease over the lifetime of the Observatory, it may become feasible to partially or wholly substitute automated measurements for technician observations. We anticipate that the initial years of calibration with dominant species will be extremely important for evaluating the potential to achieve automated monitoring of the species-specific phenophases.

As of this point in time, NEON does not plan to incorporate phenocams in the phenology plots.

6.4.3 Changes to Financial and/or Logistical Constraints

In the event the proposed sampling exceeds budgetary constraints, the technical working group recommends the following descope options (1): Sample relocatables on an every-other-year schedule, rather than annual sampling of phenology at all 3 sites; (2) At relocatables, sample only dominant species and/or species that are also sampled at the core site, skipping the more extensive community sampling. It is essential to retain the sampling frequency especially during the transition periods between phenophases and in order to detect changes over time a continuous record is best therefore, there is currently no descope recommendation for phenology sampling at the core site.

NEON is slated to sample for 30 years, and these are only a selection of the possible changes that may need to occur during the lifetime of the Observatory. Consultation with the NEON science staff and the technical working group should be made in order to ensure that changes to methodology, sample timing, frequency and allocation are consistent with NEON's mission to provide high-quality, long-term data across the continent.

7 REFERENCES

Ault, T. R., A. K. Macalady, G. T. Pederson, J. L. Betancourt, and M. D. Schwartz. 2011. Northern Hemisphere modes of variability and the timing of spring in western North America. Journal of climate 24:4003–4014.

Bonan, G. B. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. science 320:1444–1449.

Chuine, I. 2000. A unified model for budburst of trees. Journal of Theoretical Biology 207:337–347.

Chuine, I. 2010. Why does phenology drive species distribution? Philosophical Transactions of the Royal Society B: Biological Sciences 365:3149–3160.

Cleland, E. E., J. M. Allen, T. M. Crimmins, J. A. Dunne, S. Pau, S. E. Travers, E. S. Zavaleta, and E. M. Wolkovich. 2012. Phenological tracking enables positive species responses to climate change. Ecology 93:1765–1771.

Cleland, E. E., I. Chuine, A. Menzel, H. A. Mooney, and M. D. Schwartz. 2007. Shifting plant phenology in response to global change. Trends in Ecology & Evolution 22:357–365.

Davis, F., R. Ostfeld, B. Parmenter, A. Hansen, L. Poff, J. Schimel, B. Lauenroth, J. Baron, and M. Ben-David. 2008. NEON Fundamental Sentinal Units Description of Data Products and Algorithms. Page 44. NEON Tiger Team Report.

Denny, E. G., K. L. Gerst, A. J. Miller-Rushing, G. L. Tierney, T. M. Crimmins, C. A. F. Enquist, P. Guertin, A. H. Rosemartin, M. D. Schwartz, K. A. Thomas, and J. F. Weltzin.The USA National Phenology Network protocols: Standardized phenology monitoring methodology for plants and animals.

Diez, J. M., I. Ibáñez, A. J. Miller-Rushing, S. J. Mazer, T. M. Crimmins, M. A. Crimmins, C. D. Bertelsen, and D. W. Inouye. 2012. Forecasting phenology: from species variability to community patterns. Ecology Letters 15:545–553.

Grime, J. P. 1998. Benefits of plant diversity to ecosystems: immediate, filter and founder effects. Journal of Ecology 86:902–910.

Hufkens, K., M. A. Friedl, T. F. Keenan, O. Sonnentag, A. Bailey, J. O'Keefe, and A. D. Richardson. 2012. Ecological impacts of a widespread frost event following early spring leaf-out. Global Change Biology 18:2365–2377.

Ibáñez, I., R. B. Primack, A. J. Miller-Rushing, E. Ellwood, H. Higuchi, S. D. Lee, H. Kobori, and J. A. Silander. 2010. Forecasting phenology under global warming. Philosophical Transactions of the Royal Society B: Biological Sciences 365:3247–3260.

Inouye, D. W. 2008. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. Ecology 89:353–362.

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev. 2012. Uncertainties in terrestrial carbon budgets related to spring phenology. J. Geophys. Res. 117:G01030.

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev. 2013. Predicting changes in temperate forest budburst using continental-scale observations and models. Geophysical Research Letters:n/a–n/a.

Jolly, W. M., R. Nemani, and S. W. Running. 2005. A generalized, bioclimatic index to predict foliar phenology in response to climate. Global Change Biology 11:619–632.

Kampe, T. U., B. R. Johnson, M. Kuester, and M. Keller. 2010. NEON: the first continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. Journal of Applied Remote Sensing 4:043510–043510.

Keller, M., D. S. Schimel, W. W. Hargrove, and F. M. Hoffman. 2008. A continental strategy for the National Ecological Observatory Network. Frontiers in Ecology and the Environment 6:282–284.

Liang, L. A., M. D. Schwartz, and S. L. Fei. 2011. Validating satellite phenology through intensive ground observation and landscape scaling in a mixed seasonal forest. Remote Sensing of Environment 115:143–157.

McKinney, A. M., P. J. CaraDonna, D. W. Inouye, B. Barr, C. D. Bertelsen, and N. M. Waser. 2012. Asynchronous changes in phenology of migrating Broad-tailed Hummingbirds and their early-season nectar resources. Ecology 93:1987–1993.

Miller-Rushing, A. J., D. W. Inouye, and R. B. Primack. 2008. How well do first flowering dates measure plant responses to climate change? The effects of population size and sampling frequency. Journal of Ecology 96:1289–1296.

Morisette, J. T., A. D. Richardson, A. K. Knapp, J. I. Fisher, E. A. Graham, J. Abatzoglou, B. E. Wilson, D. D. Breshears, G. M. Henebry, and J. M. Hanes. 2008. Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century. Frontiers in Ecology and the Environment 7:253–260.

Moussus, J.-P., R. Julliard, and F. Jiguet. 2010. Featuring 10 phenological estimators using simulated data. Methods in Ecology and Evolution 1:140–150.

National Research Council (US) Committee on Grand Challenges in Environmental Sciences. 2001. Grand challenges in environmental sciences. National Academy Press, Washington, D. C.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42.

Richardson, A. D., T. Andy Black, P. Ciais, N. Delbart, M. A. Friedl, N. Gobron, D. Y. Hollinger, W. L. Kutsch, B. Longdoz, S. Luyssaert, M. Migliavacca, L. Montagnani, J. William Munger, E. Moors, S. Piao, C. Rebmann, M. Reichstein, N. Saigusa, E. Tomelleri, R. Vargas, and A. Varlagin. 2010. Influence of spring and autumn phenological transitions on forest ecosystem productivity. Philosophical Transactions of the Royal Society B: Biological Sciences 365:3227–3246.

Richardson, A., and J. O' Keefe. 2009. Phenological Differences Between Understoryand Overstory: A Case Study Usingthe Long-Term Harvard Forest Records. Pages 88–117 *in* A. Noormets, editor. Phenology of ecosystem processes. Springer Science + Business Media.

Schimel, D., W. Hargrove, F. Hoffman, and J. MacMahon. 2007. NEON: A hierarchically designed national ecological network. Frontiers in Ecology and the Environment 5:59–59.

Schwartz, M. D. 1998. Green-wave phenology. Nature 394:839–840.

Schwartz, M. D., and J. M. Hanes. 2010. Intercomparing multiple measures of the onset of spring in eastern North America. International Journal of Climatology 30:1614–1626.

Singer, M. C., and C. Parmesan. 2010. Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? Philosophical Transactions of the Royal Society B: Biological Sciences 365:3161–3176.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. 2007. IPCC Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

USA-NPN National Coordinating Office. 2012. Identifying and prioritizing data products and tools for use in science, management, and decision making. Research Coordination Network workshop report, University of Wisconsin-Milwaukee.

Vitasse, Y., C. François, N. Delpierre, E. Dufrêne, A. Kremer, I. Chuine, and S. Delzon. 2011. Assessing the effects of climate change on the phenology of European temperate trees. Agricultural and Forest Meteorology 151:969–980.

Wolkovich, E. M., B. I. Cook, J. M. Allen, T. M. Crimmins, J. L. Betancourt, S. E. Travers, S. Pau, J. Regetz, T. J. Davies, and N. J. B. Kraft. 2012. Warming experiments underpredict plant phenological responses to climate change. Nature 485:494–497.

APPENDIX A PHENOPHASE DEFINITIONS

This appendix (provided by Denny *et al.* in revision) describes phenophase definitions by plant type. Shaded phenophases in are not sampled by NEON but are included here to demonstrate where NEON and NPN protocols align and where they differ.

Table 1. Summary table of phenophases monitored for Angiosperms and Gymnosperms

	Phenophase title	Forb	Evergreen Forb	Grass/Sedge/Rush	Deciduous Tree/Shrub	Drought-deciduous Tree/Shrub	Broadleaf Evergreen Tree/Shrub	Cactus	Evergreen Conifer (excluding pines)	Pine	Deciduous Conifer
Vegetative phenophases	Initial growth	X		X							
	Breaking leaf buds				X		X				
	Young leaves		X			X	X				
	Leaves	X		X	X	X					
	Increasing leaf size				X						
	Colored leaves*				X	X					
	Falling leaves				X						
	Breaking needle buds								X		X
	Emerging needles**									X	
	Young needles								X	X	
	Needles										X
	Colored needles										X
	Falling needles										X
Reproductive phenophases	Flowers or flower buds***	X	X	X	X	X	X	X			
	Open flowers	X	X	X	X	X	X	X			
	Pollen release****	X	X	X	X	X	X	X	X	X	X
	Pollen cones								X	X	X
	Open pollen cones								X	X	X

Fruit phenophases	Fruits	X	X	X	X	X	X	X			
	Ripe fruits	X	X	X	X	X	X	X			
	Recent fruit or seed drop	X	X	X	X	X	X	X			
	Unripe seed cones								X	X	X
	Ripe seed cones								X	X	X
	Recent cone or seed drop								X	X	X

* excluded for species with no noticeable color change leading up to leaf senescence

** "Emerging needles" is included for pines instead of "Breaking needle buds" in order to capture the period when needles unfold from their fascicle sheaths after the bud has broken and the candle has elongated

*** entitled "Flower heads" for grasses and sedges

**** in angiosperms, only included for allergen species in *Nature's Notebook*

A.1 Angiosperm Phenophase Definitions

Leaf Phenophases

Initial growth

(***Forb***) New growth of the plant is visible after a period of no growth (winter or drought), either from above-ground buds with green tips, or new green or white shoots breaking through the soil surface. Growth is considered "initial" on each bud or shoot until the first leaf has fully unfolded. For seedlings, "initial" growth includes the presence of the one or two small, round or elongated leaves (cotyledons) before the first true leaf has unfolded.

(***Grass/Sedge***) New growth of the plant is visible after a period of no growth (winter or drought), either as new green shoots sprouting from nodes on existing stems, or new green shoots breaking through the soil surface. For each shoot, growth is considered "initial" until the first leaf has unfolded.

(***Rush***) New growth of the plant is visible after a period of no growth (winter or drought) as new green shoots breaking through the soil surface. For each shoot, growth is considered "initial" until the exposed, green portion of the shoot has reached approximately 2 inches (5 cm) in length.

Breaking leaf buds

(***Tree/Shrub***) One or more breaking leaf buds are visible on the plant. A leaf bud is considered "breaking" once a green leaf tip is visible at the end of the bud, but before the first leaf from the bud has unfolded to expose the leaf stalk (petiole) or leaf base.

How many buds are breaking?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Young leaves

(***Forb***) One or more young leaves are visible on the plant. A leaf is considered "young" before it has reached full size or turned the darker green color or tougher texture of mature leaves on the plant. Do not include fully dried or dead leaves.

(***Tree/Shrub***) One or more young, unfolded leaves are visible on the plant. A leaf is considered "young" and "unfolded" once its entire length has emerged from the breaking bud so that the leaf stalk (petiole) or leaf base is visible at its point of attachment to the stem, but before the leaf has reached full size or turned the darker green color or tougher texture of mature leaves on the plant. Do not include fully dried or dead leaves.

How many young leaves are present?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Leaves

(***Forb***) One or more live, fully unfolded leaves are visible on the plant. For seedlings, consider only true leaves and do not count the one or two small, round or elongated leaves (cotyledons) that are found on the stem almost immediately after the seedling germinates. Do not include fully dried or dead leaves.

(***Grass***) One or more live, green, unfolded leaves are visible on the plant. A leaf is considered "unfolded" once it unrolls slightly from around the stem and begins to fall away at an angle from the stem. Do not include fully dried or dead leaves.

What percentage of the plant is green?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

(***Sedge***) One or more live, green, unfolded leaves are visible on the plant. A leaf is considered "unfolded" once it has grown long enough that the two halves of the leaf blade have begun to spread apart like an open book. Do not include fully dried or dead leaves.

What percentage of the plant is green?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

(***Rush***) One or more live, green, unfolded leaves are visible on the plant. A leaf is considered "unfolded" once the exposed, green portion of the leaf (or shoot) has reached approximately 2 inches (5 cm) in length. Do not include fully dried or dead leaves.

What percentage of the plant is green?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

(***Tree/Shrub***) One or more live, unfolded leaves are visible on the plant. A leaf is considered "unfolded" once its entire length has emerged from the breaking bud so that the leaf stalk (petiole) or leaf base is visible at its point of attachment to the stem. Do not include fully dried or dead leaves.

What percentage of the canopy is full with leaves? Ignore dead branches in your estimate.

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Increasing leaf size

(***Tree/Shrub***) A majority of leaves on the plant have not yet reached their full size and are still growing larger. Do not include new leaves that continue to emerge at the ends of elongating stems throughout the growing season.

What percentage of full size are most leaves?

Less than 25%; 25-49%; 50-74%; 75-94%; 95% or more

Colored leaves

(***Tree/Shrub***) One or more leaves (including any that have recently fallen from the plant) have turned to their late-season colors. Do not include fully dried or dead leaves that remain on the plant.

What percentage of the canopy is full with colored leaves?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Falling leaves

(***Tree/Shrub***) One or more leaves are falling or have recently fallen from the plant.

Flower Phenophases

Flowers or flower buds

(***Forb/Rush/Tree/Shrub/Cactus***) One or more fresh open or unopened flowers or flower buds are visible on the plant. Include flower buds that are still developing, but do not include wilted or dried flowers.

How many flowers and flower buds are present? For species in which individual flowers are clustered in flower heads, spikes or catkins (inflorescences), simply estimate the number of flower heads, spikes or catkins and not the number of individual flowers.

(*Forb/Rush/Cactus*) Less than 3; 3 to 10; 11 to 100; 101 to 1,000; More than 1,000

(*Tree/Shrub*) Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Flower heads

(***Grass/Sedge***) One or more fresh flower heads (inflorescences) are visible on the plant. Flower heads, which include many small flowers arranged in spikelets, emerge from inside the stem and gradually grow taller. Include flower heads with unopened or open flowers, but do not include heads whose flowers have all wilted or dried.

How many fresh flower heads are present?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; More than 1,000

Open flowers

(***Forb/Rush/Tree/Shrub/Cactus***) One or more open, fresh flowers are visible on the plant. Flowers are considered "open" when the reproductive parts (male stamens or female pistils) are visible between or within unfolded or open flower parts (petals, floral tubes or sepals). Do not include wilted or dried flowers.

What percentage of all fresh flowers (buds plus unopened plus open) on the plant are open? For species in which individual flowers are clustered in flower heads, spikes or catkins (inflorescences), estimate the percentage of all individual flowers that are open.

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

(***Grass/Sedge***) One or more open, fresh flowers are visible on the plant. A flower is considered "open" when reproductive parts (male anthers or female stigmata) can be seen protruding from the spikelet. Do not include flowers with wilted or dried reproductive parts.

What percentage of all fresh flowers (unopened plus open) on the plant are open?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Pollen release

(***Forb/Grass/Sedge/Rush/Tree/Shrub/Cactus***) One or more flowers on the plant release visible pollen grains when gently shaken or blown into your palm or onto a dark surface.

How much pollen is released?

Little: *Only a few grains are released.*; **Some:** *Many grains are released.*; **Lots:** *A layer of pollen covers your palm, or a cloud of pollen can be seen in the air when the wind blows.*

Fruit Phenophases

Fruits

(***Forb/Grass/Sedge/Rush/Tree/Shrub/Cactus***) One or more fruits are visible on the plant. *Species-specific description included here.*

How many fruits are present?

(*Forb/Grass/Sedge/Rush/Cactus*) Less than 3; 3 to 10; 11 to 100; 101 to 1,000; More than 1,000

(*Tree/Shrub*) Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Ripe fruits

(***Forb/Grass/Sedge/Rush/Tree/Shrub/Cactus***) One or more ripe fruits are visible on the plant. Species-specific description included here.

What percentage of all fruits (unripe plus ripe) on the plant are ripe?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Recent fruit or seed drop

(***Forb/Grass/Sedge/Rush/Tree/Shrub/Cactus***) One or more mature fruits or seeds have dropped or been removed from the plant since your last visit. Do not include obviously immature fruits that have dropped before ripening, such as in a heavy rain or wind, or empty fruits that had long ago dropped all of their seeds but remained on the plant.

How many mature fruits have dropped seeds or have completely dropped or been removed from the plant since your last visit?

(*Forb/Grass/Sedge/Rush/Cactus*) Less than 3; 3 to 10; 11 to 100; 101 to 1,000; More than 1,000

(*Tree/Shrub*) Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

A.2 Conifer Phenophase Definitions

Needle Phenophases

Breaking needle buds

(***Evergreen conifer, excluding pines***) One or more breaking needle buds are visible on the plant. A needle bud is considered "breaking" once a green needle tip is visible at the end of the bud, but before the first needle from the bud has unfolded and spread away at an angle from the developing stem.

How many buds are breaking?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

(***Deciduous conifer***) One or more breaking needle buds are visible on the plant. A needle bud is considered "breaking" once a green needle tip is visible at the end of the bud, but before the first needle from the bud has unfolded and spread away at an angle from the developing stem, or from other needles in a bundle.

How many buds are breaking?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Emerging needles

(***Pine***) One or more emerging needles or needle bundles (fascicles) are visible on the plant. A needle or needle bundle is considered "emerging" once the green tip is visible along the newly developing stem (candle), but before the needles have begun to unfold and spread away at an angle from others in the bundle.

How many needles or needle bundles are emerging?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Young needles

(***Evergreen Conifer, excluding Pine***) One or more young, unfolded needles are visible on the plant. A needle is considered "young" and "unfolded" once it has spread away from the developing stem enough that its point of attachment to the stem is visible, but before it has reached full size or turned the darker green color or tougher texture of mature needles on the plant.

How many young needles are present?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

(***Pine***) One or more young, unfolded needles are visible on the plant. A needle is considered "young" and "unfolded" once it begins to spread away at an angle from other needles in the bundle (and is no longer pressed flat against them), but before it has reached full size or turned the darker green color or tougher texture of mature needles on the plant.

How many young needles are present?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Needles

(***Deciduous Conifer***) One or more live, unfolded needles are visible on the plant. A needle is considered "unfolded" once it begins to spread away at an angle from the developing stem enough that its point of attachment to the stem is visible, or from other needles in a bundle so that it is no longer pressed flat against them. Do not include fully dried or dead needles.

What percentage of the canopy is full with needles? Ignore dead branches in your estimate.

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Colored needles

(***Deciduous Conifer***) One or more needles (including any that have recently fallen from the plant) have turned to their late-season colors. Do not include fully dried or dead needles that remain on the plant.

What percentage of the canopy is full with colored needles?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Falling needles

(***Deciduous Conifer***) One or more needles are falling or have recently fallen from the plant.

Pollen Cone Phenophases

Pollen cones

(***All conifers***) One or more fresh, male pollen cones (strobili) are visible on the plant. Cones have overlapping scales that are initially tightly closed, then spread apart to open the cone and release pollen. Include cones that are unopened or open, but do not include wilted or dried cones that have already released all of their pollen.

How many fresh pollen cones are present?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Open pollen cones

(***All conifers***) One or more open, fresh, male pollen cones (strobili) are visible on the plant. Cones are considered "open" when the scales have spread apart to release pollen. Do not include wilted or dried cones that have already released all of their pollen.

What percentage of all fresh pollen cones (unopened plus open) on the plant are open?

Less than 5%; 5-24%; 25-49%; 50-74%; 75-94%; 95% or more

Pollen release

(***All conifers***) One or more male cones (strobili) on the plant release visible pollen grains when gently shaken or blown into your palm or onto a dark surface.

How much pollen is released?

Little: *Only a few grains are released.*; **Some:** *Many grains are released.*; **Lots:** *A layer of pollen covers your palm, or a cloud of pollen can be seen in the air when the wind blows.*

Seed Cone Phenophases

Unripe seed cones

(***All conifers***) One or more unripe, female seed cones are visible on the plant. *Species-specific description included here.*

How many seed cones are unripe?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Ripe seed cones

(***All conifers***) One or more ripe, female seed cones are visible on the plant. *Species-specific description included here.*

How many seed cones are ripe?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000

Recent cone or seed drop

(***All conifers***) One or more seed cones or seeds have dropped or been removed from the plant since your last visit. Do not include empty seed cones that had long ago dropped all of their seeds but remained on the plant.

How many seed cones have dropped seeds or have completely dropped or been removed from the plant since your last visit?

Less than 3; 3 to 10; 11 to 100; 101 to 1,000; 1,001 to 10,000; More than 10,000