Shifting Seasons on National Forests: Regional Pilot (R9) Opportunities Assessment

USA npn National Phenology Network

Arizona

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Forest Service U S Department of Agriculture

Shifting Seasons on National Forests: Regional Pilot (R9) Opportunities Assessment

September 2023

USA National Phenology Network Technical Series 2023-001.

Suggested citation: Goland, Rachel, Gibadlo, Hailee, Murray, Georgia, and Rosemartin, Alyssa. 2023. Shifting Seasons on National Forests: Regional Pilot (R9) Opportunities Assessment. USA-National Phenology Network Technical Series 2023-001. www.usanpn.org.

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Executive Summary

In 2022, the US Forest Service Office of Sustainability and Climate (OSC) partnered with the USA National Phenology Network (USA-NPN) to better understand unit-level opportunities for the application of phenological information in forest management and planning in Region 9. This report summarizes four areas of opportunity identified after several months of research, meetings with unit-level Forest Service staff, and a survey. For each area of opportunity, we provide background, discuss the role of phenology, information gaps, existing resources and partnerships, future directions, and next steps. The four areas are:

Vulnerability Assessments

Phenological factors are already present in many Vulnerability Assessments. We summarize this existing work and propose a systematic way to consider phenological factors in terms of their role in exposure, sensitivity, and adaptive capacity.

Next Step Option 1: Identify a forthcoming Vulnerability Assessment that would be a good vehicle for incorporating further phenology information.

Next Step Option 2: Write a publication to further clarify and define the role of phenology in Vulnerability Assessments.

Next Step Option 3: Create a Damage Index data layer showing spatial trends in late frost events over a set time period.

Next Step Option 4: Collaborate with staff at the Superior National Forest to create phenological monitoring protocols for their pilot assisted migration plan.

Carbon Stewardship

Climate change will likely alter forest phenology by changing growing seasons, which in turn will alter dynamics of carbon storage and sequestration.

Next Step Option 5: Develop preliminary recommendations on which tree species are expected to be climate-resilient and optimally sequester carbon.

Next Step Option 6: Convene experts to evaluate plausibility of incorporating within-year and species-level information in carbon assessments.

Next Step Option 7: Develop a phenology monitoring project to measure the length of the leafing season within forest stands with different degrees of canopy closure.

Recreation and Education

Climate change may affect visitation rates to forests, causing upticks in visitation in certain seasons, and decrease in others. More visitation in certain seasons may cause the public to interact with organisms at different points in their life cycle, with both potential negative and positive consequences.

Next Step Option 8: Launch a wildflower campaign and forecast to engage, educate, and guide visitors.

Next Step Option 9: Create regional or national materials that leverage seasonal changes to tell the climate change story.

Habitat and Species Management

Keystone species in threatened habitats may be of particular interest to track as could their pests or diseases that may be exacerbated by climate change.

Next Step Option 10: Work with Finger Lake National Forest, New York Phenology Project, and NYS Hemlock Initiative to improve the hemlock woolly adelgid Pheno Forecast.

Next Step Option 11: Work with Hoosier National Forest to develop a new Pheno Forecast for two sap-feeding beetles known to spread oak wilt.

Next Step Option 12: Collaborate with Superior National Forest on early detection of emerald ash borer.

Next Step Option 13: Collaborate with Appalachian Mountain Club's Mountain Watch to expand Nectar Connectors campaign to mountain landscapes to understand pollinator mismatch.

Next Step Option 14: Collect additional data on balsam fir and develop a new Pheno Forecast for eastern spruce budworm.

We conclude by describing challenges, resource limitations, scaling our efforts, and potential solutions. We look forward to taking the next steps to create or leverage actionable phenology datasets, partnerships, and products for improved forest management and climate change resilience on national forest lands.

Introduction

Phenology, the timing of plant and animal life cycle events, including leaf out in trees and insect emergence, is key to understanding climate impacts on natural systems. Phenological information can be used in determining species' vulnerability to climate, managing invasive species, planning for visitation, and telling the story of climate change.

In 2022, the US Forest Service Office of Sustainability and Climate (OSC) partnered with the USA National Phenology Network (USA-NPN) to better understand unit-level opportunities for the application of phenological information in forest management and planning. The USA-NPN is a federally funded organization, based at the University of Arizona, focused on enhancing science, decision-making, and engagement with phenological information. The USA-NPN provides a platform for collecting, storing, and sharing phenological information, called *Nature's Notebook*, a network of partners who coordinate volunteer monitoring, a rich suite of training resources, tools for data visualization and analysis, as well as a suite of climate-based data products that shed light on phenological patterns (Crimmins et al., 2022). The USDA Forest Service (USFS) and the USA-NPN have collaborated for many years, including work with the Office of Sustainability and Climate, the Northern Institute of Applied Climate Science (NIACS), Forest Health, State and Private Forestry, the Northern Research Station, and with the Citizen Science Coordinators. Relevant to this project, the USFS 2019 Data Products and Tools Working Group report, developed by Resource Inventory and Monitoring Coordinators (RIMC) and OSC with USA-NPN input, points to the utility of USA-NPN products to support climate change adaptation. Through this effort, we seek to develop a stronger understanding of the potential for phenological information to be widely used at the unit and regional levels.

Region 9 (Northeast) was selected as the focus for this pilot effort, based on the dramatic seasonal changes happening (particularly at higher elevations and latitudes), and the presence of many USA-NPN partners to engage in potential partnerships. In R9, USFS manages 17 national forests and one national tallgrass prairie to maintain their health, diversity, and productivity. One key partner in the region is The Appalachian Mountain Club (AMC). AMC is a conservation and recreation non-profit with more than 89,000 members spanning from Maine to the Washington, DC area. Since 1876, the AMC has relied on volunteers for many aspects of their work including

Photo: Cate Bligh

maintaining trails, leading hikes, and providing educational programming. The organization also supports science-based conservation and research with a Research Department that provides credible, high-quality scientific information and analysis in support of AMC's mission with a primary focus on natural ecosystems.

AMC has been conducting phenology monitoring in the White Mountain National Forest since 2004, with contributions from citizen scientists. Now using the USA-NPN protocols and database, AMC's phenology data are aligned with this national network and comparable to other sites across the country. AMC also has a long history of collaborations with USFS. Because of this history, their citizen science engagement, and the organization's continued efforts to monitor phenology, they were subcontracted by USA-NPN to work on this project. AMC staff have contributed significantly to this report and have synthesized and shared lessons learned from their two decades of phenology monitoring in White Mountain National Forest.

In early 2023, USA-NPN staff and contractors reviewed unit-level, regional, and OSC and NIACS reports and websites, published literature on relevant topics, and met with unit-level and regional staff in botany, climate, wildlife, recreation, and invasive species management (see Table in Appendix 1). In addition, we garnered information via a survey sent out to all R9 Planners, Environment Coordinators, and Climate Change Coordinators to better understand opportunities and barriers (Appendix 2).

This report summarizes four areas of opportunity identified through this research and relationship building. We provide background, discuss the role of phenology, information gaps, existing resources and partnerships, future directions, and next steps for each area. Finally, we identify barriers and challenges in realizing these opportunities.

We envision this report serving USFS regional and unit staff, as well as regional and national staff in determining where to place emphasis in future efforts to incorporate phenology into forest management and planning under climate change.

Four Areas of Opportunity

Vulnerability Assessments are key tools that enable managers to understand and respond to climate change impacts on forests, and thus a natural place to evaluate climate impacts on forests via phenology. Phenological factors are already present in many Vulnerability Assessments. We summarize this existing work and propose a systematic way to consider phenological factors in terms of their role in exposure, sensitivity, and adaptive capacity.

Carbon Stewardship was selected because of the high interest expressed by USFS staff members, its close relationship with forest management activities, and the direct implications carbon storage has on buffering the effects of climate change. Climate change will likely alter forest phenology by changing growing seasons, which in turn will alter the dynamics of forest carbon storage and sequestration. Understanding and ground truthing how tree phenology is changing at the species level in the face of climate change can help fine tune carbon cycle models and aid in informing long-term decisions about how to manage forests for optimal sustainable carbon sequestration and storage.

Recreation and Education are essential components of the National Forest system. Recreation is the sphere in which individual forests interact most with the public. Climate change may affect visitation rates to forests, causing upticks in visitation in certain seasons, and decrease in others. More visitation in certain seasons may cause the public to be interacting with organisms at different points in their life cycle, with both potential negative and positive consequences. Identifying the phenology of key species in forests and providing educational opportunities can increase visitor stewardship. One way to realize both goals is through citizen science, which both the AMC and USA-NPN carry out through platforms such as iNaturalist and *Nature's Notebook*.

Habitat and Species Management is central to forest and grassland management and decision-making. Phenological information supports forest and grassland health, ecological impact assessments, and forest health, diversity, and productivity. Keystone species in threatened habitats may be of particular interest to track as could their pests or diseases that may be exacerbated by climate change. Here we highlight opportunities to support management for alpine and spruce-fir habitats and invasive species.

Vulnerability Assessments

Background

Vulnerability assessments (VAs) are used to determine the extent to which a system is "susceptible to and unable to cope with the adverse effects of climate change" (Brandt et al., 2016). With dramatic changes in temperature and precipitation regimes already observed over the last century, knowing the biological, chemical, and physical changes that will affect forests is paramount. To conduct a VA, experts analyze past climate trends, project future climate scenarios, run models to determine, for example, suitable habitats for tree species, and bring together natural resource experts to assess the system's exposure and sensitivity (together referred to as impacts; Swanston et al., 2018). The completed VA is intended to serve as a guidance document to inform management strategies and priorities.

Vulnerability integrates three components: exposure, sensitivity, and adaptability (Figure 1; Glick et al., 2011). Exposure reflects the amount of environmental stress on a resource, sensitivity reflects the response to the stress, and adaptability reflects how well the resource can adjust to the stress. Combined, these three factors determine vulnerability, or the susceptibility, of an ecosystem to negative climate change effects (Glick et al., 2011; Brandt et al., 2016). The most vulnerable species and ecosystems, therefore, will be most at risk from climate change effects, whether from increased exposure, high sensitivity, low adaptability, or a combination of factors.

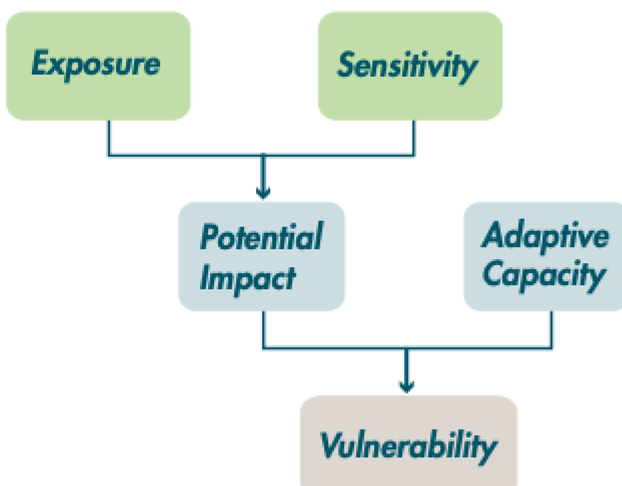


Figure 1. A conceptual model for vulnerability. Vulnerability consists of adaptive capacity and potential impact. Potential impact, in turn, consists of exposure and sensitivity (taken from Glick et al., 2011).

In Region 9, in terms of **exposure**, winters are warming, precipitation events are becoming more intense (heavy), and more precipitation is falling as rain. These trends are projected to intensify over time and represent substantial environmental stress on northeastern ecosystems. (Swanston et al., 2018). Certain forest communities will be more **sensitive** or susceptible to these changes, including boreal forests dominated by spruce-fir trees. **Potential impact** for boreal forests (for example) is the combined effects of warming temperatures and the trees' inability to tolerate these temperatures. We see greater **adaptive capacity** in more southerly forest communities with greater species diversity, and more species that are already adapted to warmer conditions and reduced snowpack (Swanston et al., 2018). Land managers in R9 can use this information to aid the transition of forests by helping more resilient species establish (Janowiak et al., 2018).

Vulnerability assessments rely on expert opinion, peer-reviewed literature, policy documents, strategy papers, and government reports, which often have key social and policy context (Swanston et al., 2018). Traditional Ecological Knowledge (TEK) is also an important knowledge source for VAs, allowing a deeper historical record, based on knowledge accumulated over multiple generations. This is particularly relevant given recent guidance from the Biden administration on incorporating Indigenous Knowledges (The White House, Office of the Press Secretary, 2022). In the VA from the Great Lakes Indian Fish and Wildlife Commission (GLIFWC), interviews with tribal elders, harvesters, and knowledge holders informed which species were included in the assessment and which species were most vulnerable to climate change (Panci et al., 2018).

Role of Phenology

Climate and nutrient cycling data are the main basis for the VA framework, though some biological response data are also incorporated. From a review of current VAs, phenology is mentioned as an indicator of changing ecosystems, with examples of observed changes from contemporary literature (Appendix 3). Areas where these analyses mention phenology include lengthening of growing seasons due to warmer temperatures, (i.e., earlier leaf spring emergence and later fall die-back), animal behavior and traits, and phenologically-dependent human activity such as tourism and timber harvesting (Brandt et al., 2016; Butler-Leopold et al., 2018; and others, see Appendix 3).

We see significant opportunities for further developing phenological information in VAs. In our survey of unit-level staff (Appendix 2), all respondents identified the potential of phenological information to inform VAs. Many phenological events are sensitive to changes in climate variables, especially in areas dominated by strong seasonality such as Region 9. In some cases, changes in the timing of phenological events due to climate change may increase species'

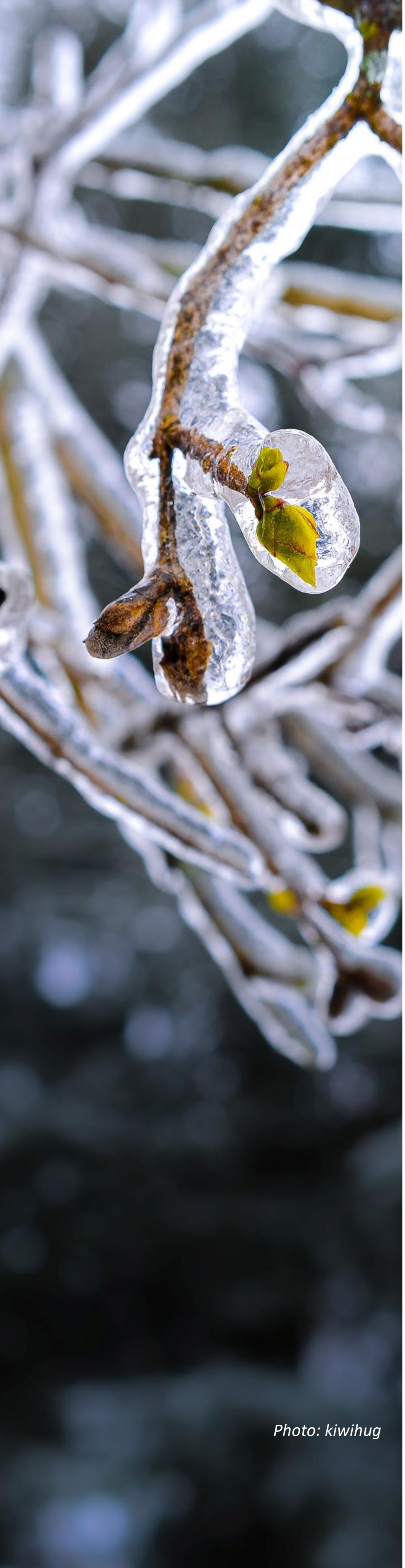


Photo: kiwihug

vulnerability, while in other cases changes in phenology may hint at the degree of adaptive capacity a species possesses. Shifting phenological windows between plants and animals, plants and plants, or organisms and their environment can interrupt reproduction, increase competition for resources, change carbon dynamics, and alter symbiotic relationships (Heberling et al., 2019, Piao et al., 2019).

We have identified the following ways in which phenological information can support each dimension of a Vulnerability Assessment.

Exposure

Trends and projections in leaf out and bloom dates based on the USA-NPN's Spring Indices can provide a measure of climate change exposure. Exposure is often calculated based on average seasonal temperatures, which, while important, may not represent the climate in the way it is experienced by a species or ecosystem. The USA-NPN's Spring Indices (usanpn.org/data/spring_indices) summarize climate data in a way that has been shown to be biologically relevant, indicating the biological start of spring. A trend in leaf out date for a particular area of interest can indicate how much change in seasonal timing the area has or will experience. While the USA-NPN does not yet produce a Fall Index, this could be a useful addition, and could serve a similar purpose for understanding exposure to change in the cues that affect fall phenology.

Changes in both the magnitude and seasonal pattern of rain and snowfall increase exposure. For instance, "flash droughts" in early spring can kill the fungal parasite of spongy moth larvae and contribute to outbreaks.

Sensitivity

"False Springs", defined by a warm/early spring followed by a hard frost event, are a concern given the advancement of spring with climate change (Casson et al., 2019). Certain species are more sensitive to freezes than others, based on physiological tolerances, their ability to re-initiate development after damage, and their phenological cues. Not all species in temperate forests leaf out at once; understory plants and young trees tend to green up first, followed by the canopy. Even within a single forested area, false springs may not be uniformly occurring between individuals of the same or different species (Chamberlain et al., 2019; Richardson & O'Keefe, 2009). Additionally, species that flower first and then leaf out (e.g., red maple) may be more at risk than species that leaf out first and then flower (e.g., hickory) since reproductive tissue is generally more cold-sensitive and more costly to produce (CaraDonna & Bain, 2016). Further, many species can re-foliate more readily than they can re-flower. Flower loss impacts the plant's ability to reproduce, as well as the availability of pollen, fruit, and seeds as food sources for other species.

Phenological mismatch is another dimension of sensitivity to consider. Shifting phenological windows between plants and animals, plants and plants, or organisms and their environment can interrupt reproduction, increase competition for resources, change carbon dynamics, and alter symbiotic relationships. The (version 1) GLIFWC Vulnerability Assessment for Snowshoe Hare identified mismatch between the hare's fur color and the surrounding environment (specifically, snow cover timing) as a major component of the species' vulnerability. Zimova et al. (2016) found that the increased predation risk caused by this mismatch is projected to lead to major population declines by the end of the century. Along similar lines, a plant species that has a specialist pollinator is likely to be more sensitive to mismatch than a generalist plant (Weaver & Mallinger, 2022).

Adaptive capacity

The ability to shift phenology based on seasonal changes in the physical environment and changes in interacting species' phenology is phenological adaptive capacity. This capacity can be present at the individual genotype level (phenotypic plasticity), the population level (genetic diversity), and the community level (phenological diversity). Robin Clark (Anishinaabekwe from Bawating, a member of the Sault Ste. Marie Tribe of Chippewa Indians) often recommends that we observe plant phenology because it provides an opportunity to learn from plants how to adapt, how to shift in time with changing conditions.

Phenological adaptive capacity can be thought of as the ability of a species to 'keep up' with climate-induced changes to the seasons. Continuing the examples from above, a theoretical snowshoe hare subpopulation that adjusted molt dates to match changing snow cover dates demonstrates adaptive capacity. In the case of a species with a specialist pollinator, adaptive

capacity would be higher for species that are able to shift bloom times to match earlier insect emergences, compared with those species not able to shift their phenology.

Phenological adaptive capacity can also be evaluated at the level of functional type. For instance, Heberling et al. (2019) found that tree canopy phenology in Concord, Massachusetts tracks seasonal climatic changes more readily than understory forbs, leading to a compression of the period during which sunlight is available for forbs. This gives canopy species an adaptive advantage over forbs. Conversely, in their study in the Northeastern US, Alecrim et al. (2023) found that warming induced faster shifts in leaf-out for forbs than for trees, effectively producing an expansion of the period when light falls on the understory. AMC data confirm Alecrim et al. (2023); understory forbs' flowering times in the northern Appalachians are seeing more advancement than tree leaf-out per one degree Celsius of spring warming (Tourville et al., submitted).

Considerable work has also shown that invasive species are better able to track changing springs than native species, conferring a competitive advantage and increased adaptive capacity to seasonal changes (Maynard-Bean et al., 2020; Wolkovitch & Cleland, 2010).

We can also characterize adaptive capacity at the ecosystem level: What comprises a phenologically resilient system? One potential answer is that a variety of plants with different flowering times and consumers with high resource needs at varying times reflects a temporal richness which is conducive to a resilient ecosystem (Armstrong et al., 2016). This is known as "phenological diversity" or "resource waves" (Armstrong et al., 2016). For example, North American black bears are able to take advantage of a long berry season in which fruiting phenology varies greatly among species and across space (Armstrong et al., 2016). The temporally and spatially extensive berry resource wave in the Northeast is an important food source for other animals as well, including insects, birds, and rodents.

Salmon in the Pacific Northwest are another example of an important resource wave that provides inputs of marine nutrients into a terrestrial system that would not otherwise have access to that resource (Deacy et al., 2017). A compression of these types of foundational resource waves could have cascading effects on biodiversity and ecosystem health. Understanding how their phenology may be altered in the face of climate change will provide important insight into an ecosystem's phenological adaptive capacity.

Plant adaptive capacity is also influenced by winter chilling, which can significantly influence plant phenology. When winter chilling is insufficient, plants may rely less on temperature cues for phenological changes, thus lowering their adaptive capacity to climate change (Deacy et al., 2017; Way & Montgomery, 2015). In our conversation with Superior National Forest (SNF) staff we learned that an Annual Winter Seasonal Severity Index (AWSSI) is generated for the SNF. This index is used across the United States and is a point value based on various measurements including snow fall, snow depth, and temperature (Boustead et al., 2015). An understanding of how winter is changing as climate change progresses, combined with a robust understanding of how chilling affects local species' phenology could lend important insight into the phenological adaptive capacity of certain plants. Integration of the AWSSI and the USA-NPN Spring Indices also holds promise for understanding the combination of weather impacts that ecosystems are experiencing in a given year.

Information Gaps

The USFS has a robust VA framework, with many informative examples in terms of future impacts to forests. Three different models were used in the Northern New York and New England VA to project suitable tree habitat (Climate Change Tree Atlas), predict tree growth through climate variables, and model changes in tree species such as density and abundance (LANDIS PRO) (Janowiak et al., 2018).

At the same time there is considerable existing research, data, and expert knowledge pertaining to phenology as it relates to the components of a VA (as elaborated above), that could be translated and incorporated into the existing robust USFS VA framework. There is an opportunity to synthesize existing data in new ways, or to develop new observational data via USA-NPN data collection campaigns (usanpn.org/nn/campaigns) to fill gaps. Potential areas of expansion include plant-insect interactions for both pollinators and pest species, woodland understory and overstory interactions (forest plant competition, light resources, carbon cycling), migration of threatened bird species and the resources they rely on, and hibernation and emergence of protected bat species.

Photo: Annie Spratt

A further opportunity may lie in the development of knowledge on the intraspecies variation of phenological phenotypic plasticity. In the Northern NY and New England VA, phenotypic plasticity, the ability to adapt to environmental change via phenotypic variation, is identified as an important component of adaptive capacity for species (Janowiak et al., 2018). Phenological plasticity, defined as the phenotypic plasticity of life cycle events, may be an indicator of adaptability and therefore vulnerability of a species (De Lisle et al., 2022). The current NSF-funded USA-NPN campaign, Quercus Quest (usanpn.org/nn/QuercusQuest) supports researchers investigating how the exchange of genetic material allows oaks to adapt to new environments.

Finally, assisted migration is an area of increasing interest in the forest management community. Broadly, it is well known that tree populations are locally adapted to their climate and tend to grow and initiate phenophases optimally in areas that mimic the local climate they are sourced from (Aitken & Bemmels, 2016). With rising temperatures and extended growing seasons at higher latitudes and altitudes in the Northeast, it follows that seeds may be better suited to grow in these locations if sourced from lower latitudes and altitudes. This is a form of assisted migration and could increase forest resilience and decrease vulnerability to climate change.

In a 2020 study in Minnesota, researchers found that seeds sourced from more southerly locations performed better than local seeds in a variety of ways, including in their abilities to phenologically track the growing season (Etterson et al., 2020). With climate change, many experts advise that managers begin sourcing seeds from more southerly locations since these seeds will be adapted to the more northerly climates of the near future. Etterson et al. (2020) indicates that the need to begin assisted migration in northern forest is already present in northeastern forests. Assisted migration has the potential to increase forest resilience and can help ensure that the benefits of these forests (cultural, carbon, habitat, etc.) remain intact in the face of climate change.

Assisted migration efforts are budding on national forest lands. During our initial call with the Superior National Forest (SNF) we learned that staff at SNF are working to create a pilot assisted migration plan. In a subsequent meeting to learn more about this plan, we discussed the need for the creation of replicable and spatially consistent monitoring protocol to evaluate assisted migration efforts. Phenology would likely be a part of this monitoring protocol since an individual's ability to track growing seasons is indicative of its' productivity and ability to survive long winters and false springs. In addition, comparisons of the phenology of locally and non-locally sourced seedlings, including timing of bud break and bud set, and the timing and amount of flower and fruit production, could provide valuable insights into the success of assisted migration efforts and the need to further adjust seed sources. In a subsequent call, silviculturists at SNF indicated that phenology could also be used to inform areas to target seed collection from trees used in assisted migration, based on where *Nature's Notebook* observers reported high numbers of ripe seeds.

Existing Resources and Partnerships

Vulnerability assessments harness the power of partner organizations and their ability to help connect regions, analyze, and gather large amounts of data, and bring science to the forefront of land management. Phenology and phenology-relevant information is already captured in many VAs (Appendix 3).

At the same time, there is a growing body of scientific literature as well as state and federal agency reports that address the phenological factors that are relevant to vulnerability. There is also substantial deep and long-term knowledge held by Indigenous communities, some of which may be appropriate to share and integrate with non-Indigenous expert and academic knowledge to build a more complete understanding of how phenology serves as a liability or asset to plants and animals under climate change.

Further, certain kinds of phenology data collection are straightforward and can be undertaken by citizen scientists. There is an abundance of plant phenology data in databases maintained by citizen science programs, including the USA-NPN's *Nature's Notebook* program as well as iNaturalist, a crowdsourcing app. These data have been utilized in peer reviewed literature and shown to be robust and improve models (Fuccillo Battle et al., 2022; McDonough MacKenzie et al., 2020; Elmendorf et al., 2019). The practice of harnessing the power of partners to create multi-tiered assessments means there is room to further the scope and depth of VAs by the inclusion of phenology data from partners.

Photo: Eric Prouzet

Potential Directions

Through developing our understanding of the Vulnerability Assessment process by reading reports and published literature, as well as understanding the species and systems that are top-of-mind for Forest-based managers, we have identified many ways that phenological information can be leveraged to reach USFS objectives. For instance, at Green Mountain National Forest, we heard about interest in rare plants, forest transition, and regeneration. At White Mountain National Forest, we heard interest in plant/pollinator relationships and forest regeneration. At Hoosier National Forest, we heard interest in oak decline and monitoring for climate change impacts more broadly. Finally, at our meeting with the Superior National Forest (SNF), staff echoed interest in invasive species monitoring and management, broad scale climate monitoring, and plant/pollinator dynamics.

SNF staff also cited concerns about changes in the timing of blueberry fruiting which is important as a wildlife food source, for native harvesting, and a local festival, and changes in maple tapping timing. In addition, staff mentioned that the harvesting of birch bark by Indigenous people for traditional use historically occurs in concert with wild rose blooming and questioned if a future mismatch might alter this traditional timing. Finally, SNF staff mentioned interest and current work in assisted migration for forest regeneration and we held a subsequent meeting to further discuss this topic.

Potential Next Steps:

#1 - In collaboration with OSC/NIACS, we could identify a forthcoming Vulnerability Assessment process that would be a good vehicle for incorporating further phenology information, along any of the lines elaborated above.

#2 - Given that there is not currently a summary document that outlines the ways in which phenology fits in VAs, we could convene additional experts to create a publication to further clarify and define the role of phenology in Vulnerability Assessments. Parts of this section of this report, along with additional recommendations, could be converted into a paper or white paper that would support people in multiple state and federal agencies to use phenological information in VAs.

#3 - By combining existing data on spring timing and frost events, we could create a Damage Index layer. This data layer would show trends in false spring damage over past years (number to be determined) and could also include projections for the future, allowing land managers to better understand which locations are at highest risk for frost damage. This could inform where to focus management efforts such as assisted migration by indicating which areas may be at the highest risk of late-frost mortality.

#4 – In collaboration with staff at the Superior National Forest we could aid in creating phenological monitoring protocols for their pilot assisted migration plan. This could take the form of monitoring the phenology of planted trees. Trail cameras could be used, following existing protocols used by other NPN partners, to reduce the number of site visits to the planting area; photos could be assessed at the end of the season and the data entered into the NPN's database.

Carbon Stewardship

Background

As global climate change advances, carbon stewardship has become an area of increased interest and research in the forest management community, including at the USFS. Carbon sequestration is the process in which atmospheric carbon is taken up by plants via photosynthesis. Carbon is then stored as biomass or in the soil. Forests sequester and store a significant portion of the terrestrial carbon on earth. This storage of carbon serves to buffer the climatic effects of anthropogenic greenhouse gas release into the atmosphere.

The USFS, through the National Forest System, manages 193 million acres of forest and grassland (Janowiak et al., 2017). As part of this work, the USFS tracks and estimates forest carbon through data obtained in the Forest Inventory and Analysis (FIA) database (USDA Forest Service, 2021). Using this database, the USFS and its partners collect and compile plot-level data including tree species, size, health, and mortality. From this information the USFS can estimate carbon in various forest carbon pools at the national, state, and national forest unit level. Carbon Net Annual Stock Change is measured by comparing FIA snapshots taken every 5 years, and interpolating to estimate annual stocks, to shed light on how forest carbon stocks are changing over time (Smith et al., 2010). This approach provides a general estimate of year-to-year carbon flux but does not account for within-year patterns and variations (such as extended growing season), which may impact sequestration and storage.

Forest carbon is typically broken down into five pools: aboveground biomass, belowground biomass, deadwood, litter, and soil (Giebink et al., 2022). The relative importance of these pools varies from forest to forest (Giebink et al., 2022), although soil tends to contain about three times the carbon in vegetation (Giebink et al., 2022; Lawrence et al., 2023). Measuring these carbon pools and understanding their dynamics well enough to predict future conditions, particularly belowground, is a significant challenge in forest carbon management and stewardship research. Researchers are actively working to untangle the complex dynamics of the carbon cycle in forest systems.

Broadly, the USFS FIA estimates of forest carbon aid in demonstrating the United States' commitment to sustainability in the face of climate change. For example, synthesized FIA data is regularly shared internationally with the United Nations Framework Convention on Climate Change (UNFCCC) as part of large-scale greenhouse gas reporting (Giebink et al., 2022). Closer to home, carbon assessments are important tools that allow forest managers to understand how much carbon is being stored in forests, and how that storage changes over space and time. A


Photo: John Reed

comprehensive understanding of carbon cycling and accurate carbon assessments can help inform important forest management decisions such as when to harvest timber, how much to harvest, and what species to prioritize for harvest, regeneration, or planting.

Role of Phenology

From our research and conversations with researchers and USFS staff, we have determined that, at this time, phenological data would be most useful in aiding estimates and understanding the dynamics of the aboveground biomass pool. According to the *U.S. Forest Carbon Data: In Brief*, although most forest carbon is stored in the soil, 59% of carbon flux (flow between the atmosphere and the forest) occurs within the aboveground biomass pool (Hoover & Riddle, 2022). Within this pool, the bulk of aboveground biomass in forests consists of trees rather than understory plants (Gilliam, 2007). Most existing data sources and potential partners (see below) are already focusing their efforts on trees. Additionally, timber harvesting is one of the most significant drivers of changing carbon in national forests and relates primarily to the management of trees (Birdsey et al., 2019).

For these reasons, the rest of this section devoted to carbon stewardship is focused on utilizing phenological information to aid in estimates of aboveground tree biomass. This is not meant to ignore the importance of other forest carbon pools or other sources of aboveground biomass. However, we believe that a focus on aboveground tree biomass will be the most utilitarian starting point for potential future efforts to incorporate phenology into forest carbon assessments and stewardship.

Tracking and managing the aboveground biomass carbon pool is closely tied to understanding forest phenology. In temperate forests, like those of Region 9, carbon sequestration in tree biomass occurs during the growing season when trees are photosynthesizing and growing. A longer growing season has the potential to increase carbon sequestration during that season

(Keenan et al., 2014), though the impacts of drought and nutrients must also be considered. It is very likely that climate change, and the resultant changes in growing seasons, will have a significant effect on carbon dynamics in forests across the globe.

It is important to note that even without climate change, carbon storage in forests is highly dynamic over space and time. Any environmental disturbance, such as a timber harvest, wind event, or insect infestation that affects forest biomass and/or health can have significant implications on carbon sequestration and storage (Birdsey et al., 2019; Frank et al., 2015). For example, a summer with high levels of defoliation by forest pests may result in decreased carbon sequestration that season due to tree mortality and lowered photosynthetic capacity. Drought is another compounding stressor that could potentially result in limited carbon sequestration, even if temperature conditions are favorable for photosynthetic activity (Frank et al., 2015).

Notably, vulnerability to insect defoliation or other stressors will likely be exacerbated by climate change. The changes in growing season, combined with the predicted compounding stressors on forests from climate change (drought, disease, severe weather, etc.), will undoubtedly change the dynamics of forest carbon sequestration and storage in the Northeast and globally. While an extended growing season may compensate for other stressors such as drought, there are still many unknowns (Grossiord et al., 2022) and it is important to note that a longer growing season due to favorable temperatures does not automatically guarantee more carbon sequestration if other stressors are limiting tree productivity.

Relatedly, processes or management activities that increase forest resilience will likely increase the ability of that forest to store carbon. Sustainable forest management is therefore an essential pillar to ensure that forests remain stable carbon sinks now and in the future. To do this, a more robust understanding of how climate change could affect forest phenology is necessary.

Information Gaps

As previously mentioned, climate change is extending growing seasons in the Northeast for many organisms, with earlier springs and later falls (Keenan et al., 2014). This extended growing season has the potential to increase forest carbon sequestration and storage. However, as seasonal shifts occur due to climate change, there are still many uncertainties associated with carbon cycle dynamics. Phenological data has the potential to provide powerful and useful information to inform carbon modeling, assessments, and stewardship in northeastern forests.

Satellite, Modeling, and Ground-truthed Data Mismatches

A major uncertainty in estimating aboveground forest carbon is the inconsistencies between models, satellite imagery, and on-the-ground data (Giebink et al., 2022). Since the understory typically greens before the forest canopy, satellite data may prematurely and erroneously record tree leaf-out in the spring. This can result in the appearance of a much longer growing season for trees than is actually occurring on the ground.

There are also discrepancies between satellite and model-generated data. For example, in a 2022 study, researchers forced a global land surface model (LSM) to agree with satellite estimates of leaf area index (LAI) (Fox et al., 2022). This LSM forms the terrestrial component of the Community Earth Systems Model and models several global scale ecological processes including the carbon cycle. The forced reconciliation of satellite LAI estimates with the model resulted in an average, but not spatially homogeneous decrease in carbon uptake and water loss compared to the flux estimates the model alone had generated (Fox et al., 2022). In other words, without the satellite data, the land surface model is likely erroneous in its predictions of leaf on and leaf off timing which in turn results in discrepancies in our understanding of carbon fluxes. While the satellite LAI estimates helped refine the model, other LAI estimates exist and were not tested in this study (Fox et al., 2022). The misalignment between the models used to estimate the carbon cycle, satellite data, and on-the-ground observations of leaf-on/leaf-off events is a notable discrepancy in carbon assessments and modeling.

Plant Functional Types in Carbon Models

Another factor to consider is that when modeling tree phenology using land surface models, trees are typically not represented at the species level. Instead, grid cells are designated based on Plant Functional Type (PFT). PFTs lump species based on factors such as leaf retention (deciduous or evergreen) and leaf type (broadleaf or needleleaf; Fox et al., 2022). There is significant diversity in life history strategy and physical traits within each PFT designation and tree response to climate change stressors can vary significantly by species. For example, a 2014 review analyzed the effects of photoperiod (daylength) and temperature cues on phenology (Way & Montgomery, 2015). While temperature is expected to change with climate change, the photoperiod will remain constant. Therefore, trees that rely on thermal cues will likely shift their phenology more readily than photoperiod cued trees.

This review found that generally, maximum growth of high latitude conifer species such as pines, tamaracks, and spruces were more heavily affected by day-length than temperature changes and are therefore less likely to alter their phenology with rising temperatures (Way & Montgomery,

2015). However, despite attempts to make generalizations based on niche, leaf type, taxonomy, or physiology, tree reliance on photoperiod versus temperature cues for leaf out phenology appears to vary at the species level (Way & Montgomery, 2015). For example, eastern white pine and Himalayan pine appear to be photoperiod sensitive, relying on length-of-day cues. Conversely, black pine and Scotch pine are, according to the literature, photoperiod insensitive. This example illustrates that, within a single genus, *Pinus*, individual species appear to have different cues that trigger their phenological responses.

The same review also found that other species have "equivocal" responses, meaning that literature conclusions on photoperiod versus temperature cue dependencies were mixed (Way & Montgomery, 2015). This mixed response could be explained by variations in winter chilling. Evidence indicates that winter chilling can affect a species' reliance on temperature versus photoperiod: in systems with insufficient winter chilling, photoperiod may be a more important cue. Therefore, plants that experience milder winters may not be as responsive to early warming and their growing season will then be constrained. Generally, there are still many unknowns regarding inter-species differences in phenological responses to rising temperatures. However, this is strong evidence that this variation does exist and the genetic underpinnings of this variation is an area of active research (Way & Montgomery, 2015).

The lack of species level information in modeling forest carbon represents a significant gap in the knowledge and ability of these models to accurately estimate carbon sequestration and storage. Trees likely have diverse, species-specific responses to climate change. However, the land surface model lumps many species together in a single PFT designation. For example, in temperate systems birches and poplars tend to leaf out earlier than oak and ashes (Richardson & O'Keefe, 2009). However, species from all four of these genera could be grouped under the same PFT in a carbon model since they are all temperate broadleaf deciduous species.

Furthermore, in addition to each species having different reliance on cues that modulate growing season length, species vary in their wood density. For example, according to the Wood Density Database (db.worldagroforestry.org/wd), quaking aspen has an average density of 0.3723 grams per cubic centimeter. White oaks, on the other hand, are nearly double and have a density of 0.6618 grams per cubic centimeter. Again, these two species could be grouped under the same PFT despite having substantial differences in densities and therefore the amount of carbon stored in their biomass. It is important to understand tree phenology at the species level because not only do trees vary by species in their growing season timing, they also do not uniformly sequester carbon when they are growing.

More ground-truthed, species-level data relating to tree phenology, especially leaf-on/leaf off dates, could help fine tune relevant models and resolve this discrepancy, resulting in more accurate carbon estimates. Additionally, because trees vary in density and carbon storage capacities, understanding how individual species will phenologically respond to climate change can help optimize forest management strategies and deepen our understanding of forest carbon sequestration and storage.

Forest structure

Staff at Hoosier National Forest (HNF) indicated that phenology has potential to inform the impact of forest structure on carbon sequestration. One area of need is to better understand the phenology of trees in forest stands with different degrees of canopy closure to determine whether phenology differs in, for example, closed versus open forest stands. This would require measurements of not only phenology but also the degree of canopy closure, age classes of trees, and other measures. These other measures of forest structure exist for some areas in HNF; these could be supplemented with additional phenology data collected at these locations. A second approach would involve planting seedlings sourced from the same trees in forest stands with different degrees of canopy closure, then tracking their phenology over time.

False Springs

A better understanding of false springs could also aid in improving our understanding of forest carbon. With climate change, earlier spring warming temperatures can lead to earlier leaf out in trees. This, coupled with late-season hard frosts can cause damage to the new plant growth. This phenomenon is known as “false spring” (Allstadt, 2015). Late-season frosts can result in the loss of leaves and reproductive material, depending on the species. While many trees can recover from this type of damage, this can be costly for the tree, reducing its fitness and resiliency to

subsequent stressors. Additionally, damage from a false spring event shortens the growing season since the tree must recover, therefore reducing the amount of time the tree can be sequestering carbon. A 2012 study focused on the false spring damages in the Northeast estimated that late frosts in high elevation forests reduced annual gross productivity by 7-14% (Hufkens et al., 2012).

False spring dynamics will likely change with climate change. Generally, false springs are not predicted to increase uniformly across the Northeast (Allstadt, 2015, Martinuzzi et al., 2016). However, false springs can occur at relatively small spatial scales and it is possible that they may increase frequency in some eastern forest areas of the United States (Allstadt, 2015; Martinuzzi et al., 2016; Casson et al., 2019). High altitude areas appear to be especially vulnerable to false springs damages (Hufkens et al., 2012). Additionally, since different species each appear to rely on different suites of phenological cues, false spring risks at the species level will also likely shift with climate change (Chamberlain et al., 2019).

From our conversations, it appears that false springs and their effects on carbon storage in aboveground tree biomass are not included in current carbon models. A better understanding of the species-level, spatial, and temporal trends in false springs and their effects on forest carbon is needed to allow for a more comprehensive understanding of how forest carbon dynamics may change over time and which species may be at most risk.

Species-Level Adaptability

Finally, to manage forests with carbon in mind, it is important to not only understand forests as they are now, but also to be able to predict future outcomes and manage forests accordingly. As climate change progresses, it is very likely that forest composition will change significantly in the Northeast (Janowiak et al., 2018). Phenological data could play an important role in knowing which trees are adjusting best to changing climate. For example, phenology data could be used to better parameterize extensions to landscape models like Landis–II, which forecasts changes in the forested landscape.

As another example, in our conversation with Superior National Forest staff, we learned they are in the process of developing an assisted migration plan. As previously mentioned in the Vulnerability Assessments section, phenological data can play an essential role in assisted migration by informing land managers which species or populations will be the best suited candidates for optimal survival and health in a specific forest. Overall, an improved understanding of how different species of trees are responding to climate change and how well they will sequester carbon in the face of climate change will aid in making management decisions such as which trees to harvest and which trees to favor for regeneration or planting. This knowledge helps ensure that our future forests continue to be robust carbon sinks.

Existing Resources and Partnerships

There are already a handful of established tools and organizations that are collecting or generating data that are directly related to carbon storage, forest phenology, and/or growing season length. Of note is the AmeriFlux Network, a network of flux tower sites that measure carbon dioxide, water, and energy fluxes across North, Central, and South America. These data can be used to determine growing season length and therefore have direct ties to phenology (Richardson & O'Keefe, 2009).

Another relevant organization is the PhenoCam project. This project is housed by Northern Arizona University and is a collection of over 700 sites, each collecting landscape-scale digital images every half hour. Images are then analyzed for phenological information and made available for researchers. Notably, the PhenoCam project is already engaged in building relationships with the AmeriFlux Network according to their website.

ForWarn is another existing data resource that uses satellite data to track disturbances across the continental United States. The system tracks disturbances such as storms, insects, and fires by tracking changes to the Normalized Difference Vegetation Index (NDVI). NDVI is a measure of vegetation greenness which can also be used to estimate growing season timing. ForWarn collects NDVI data throughout the year and develops land surface phenology which broadly captures landscape scale green up and green down timing. Data provided by ForWarn allows users to examine how greenness (and often phenology) is changing in real time each year and allows for year-to-year comparisons of growing seasons.

Additionally, the AMC is using canopy-level digital photo series from inexpensive plant cameras to document canopy green-up and growing season length. Red Blue Green (RBG) color coordinates can be extracted from a region of interest (ROI). Three examples of the ROI (red box) in different images are shown below in Figure 2.

Figure 2. AMC plant camera images with region of interest (ROI) aligned for cross comparison. The greenness color coordinates (Gcc) are calculated from RGB extracted data from the ROI and generate a time series from the digital image series as shown for the year 2019 (see Figure 3) and fit with a logistic regression function. The start of spring was calculated as the inflection point of the curve where Gcc values increase dramatically in the spring, corresponding to canopy leaf-out and green-up.

The low-cost plant camera estimates of the start of spring or canopy closure can be used to improve estimates derived from satellite imagery data. Leaf out data from the USA-NPN can further validate these estimates. Figure 3a shows the AMC's low-cost camera 2019 PhenoCam results as compared to Figure 3b USA-NPN observational data. The estimates of the start of spring differ by 3 days. Several efforts have been made to facilitate access and integration to multiple streams of phenology data to enable researchers and managers to leverage the value each provides, including the Advanced Phenology Information System (Morisette et al., 2021).

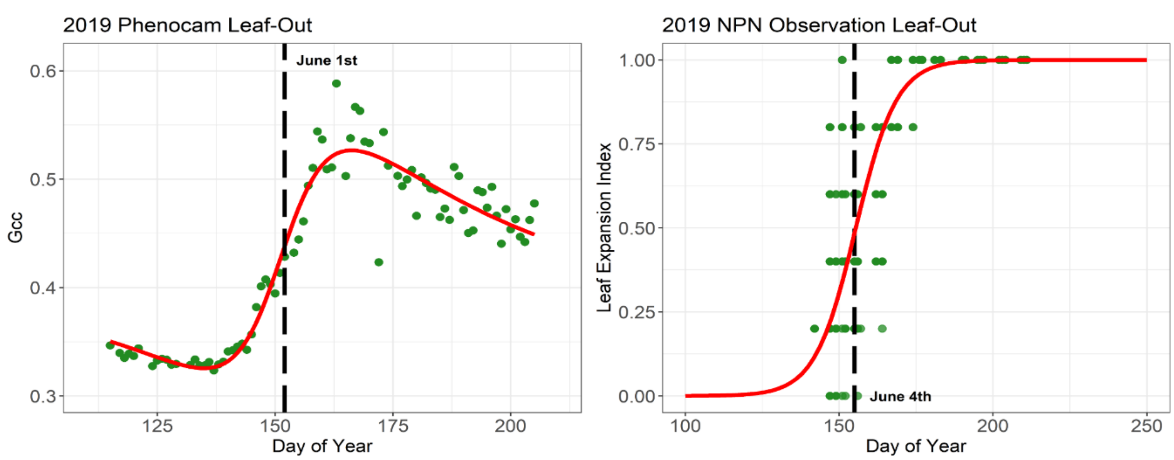


Figure 3. 2019 (a) Greenness color coordinates (Gcc) data at Pinkham Notch, NH with a modeled line fit and date of start of spring (SOS) modeled as June 1st and (b) NPN observation data as leaf expansion index with SOS modeled as June 4th.

The USA-NPN also delivers a pilot suite of Land Surface Phenology products (usanpn.org/data/land_surface_phenology). Users can access maps that show green-up and brown-down dates, and other greenness measures for the years 2001 to 2017. Data for this tool are sourced from the USGS Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Dynamics data and processed by collaborators at North Carolina State University.

Finally, the Community Land Model (CLM) is a complex model of Earth's terrestrial ecosystems and includes carbon cycling. The CLM forms the terrestrial component of the Community Earth System Model (CESM) and is the product of the collaborative efforts of many researchers and working groups. This model does represent phenological dynamics, as they directly relate to terrestrial carbon and energy fluxes. However, as noted above, the model is not consistently in agreement with satellite or ground-truthed data and does not incorporate species level data or late frost damages into its calculation. Additionally, to our knowledge, this model deals with global scale energy, water, and carbon fluxes and is not utilized by forestry professionals of USFS staff.

There are also existing tools used for modeling carbon and aiding forest management decisions that would greatly benefit from phenological data. For example, the USFS Climate Change Tree Atlas is an online tool that predicts future suitable habitat for over one hundred tree species in the United States. There are also other existing forest impact models such as LINKAGES and LANDIS PRO that attempt to predict changes in forest composition over time. These models do not provide precise spatial or temporal information about future forests but are instead designed for a broad examination of possible future trends and changes. However, none of these models factor in current or projected changes in phenology (Janowiak et al., 2018). As growing season length has already been shifting with climate change, species level phenological data could be a useful input that would improve the accuracy and granularity of these models' predictions. This in turn can help refine forest carbon stewardship by allowing land managers to have a more comprehensive understanding of how to manage their forest units for present threats and future resilience.

Due to the high level of interest and research in forest carbon cycling and estimation, it is likely that other potential partners exist and will emerge if we continue our research and conversations with forest management professionals, conservation organizations, and researchers.

Potential Directions

USFS representatives at the regional and unit-level all point to carbon stewardship as a subject of high interest. This opportunity may be better realized at the regional or national level, rather than at the individual forest unit scale. FIA plot data, which provides the USFS with national carbon estimates, requires a significant investment in personnel time for monitoring and data analysis

(USDA Forest Service, 2015). Notably, it appears that most other existing tools for estimating growing season length and carbon storage/cycling rely heavily on remotely sensed data and/or modeling. Fine-scale, species-level phenological data generated using USA-NPN's *Nature's Notebook* tool, could be a highly valuable addition to these data streams.

USA-NPN, perhaps in partnership with one of the organizations mentioned above, and/or carbon modelers within USFS and other academic partners could aid in providing an improved and integrated length of growing season dataset. One approach could be to combine FIA data on species composition, with USA-NPN data on phenology at the species level, to make larger scale estimates of season start and end, which could be compared to estimates from remotely sensed data (Melaas et al., 2016). The data generated would provide the beginning of a long-term data set recording species level changes in growing season length at the national forest unit scale. This information could aid in tracking changes in aboveground carbon storage and enhancing predictions for the future of forest carbon. Maps of green up and brown down for USFS units could also serve as public engagement platforms, allowing members of the public to track seasonal changes in their local forests or forests they plan on visiting. We also see an opportunity to further engage with the public on the topic of carbon stewardship; both Hoosier NF and Green Mountain NF staff mentioned the importance of public understanding of storage and sequestration trade-offs in timber projects.

Another potential direction would be to measure phenology within forest stands with different canopy structure, ranging from closed to open. This would inform whether the growing season length is related to the degree of canopy closure.

Finally, provisioning the USFS with improved data on growing seasons and how individual species are demonstrating shifts in phenology in response to climate change could help improve models such as the Climate Change Tree Atlas and Landis-II. This in turn would aid in informing forest management decisions for optimized forest carbon stewardship now and in the future.

Potential Next Steps

#5 - Develop preliminary, location-specific recommendations regarding which species of trees will be best suited for carbon sequestration and have optimal resilience to climate change stressors. This information can help inform evaluation of projects (timber harvest, energy development, etc.) at the unit level. It is likely that while some information is available in reports and the literature to make these recommendations, further information collected via USA-NPN campaigns could be generated in support of this effort.

#6 - Convene a team of experts to assess the plausibility of enhancing national (or international) carbon models with richer phenological information (species-specific, including false spring), with the ultimate aim of improving regional assessments/estimates of USFS contribution to sequestration and storage.

#7 - Develop a project to measure differences in phenology in forest stands with different degrees of canopy closure to determine whether closed or open canopies are correlated with longer growing season length. This could take the form of adding phenology monitoring to canopy assessments already conducted at Hoosier National Forest, conducting monitoring of phenology and measures of canopy closure at locations outside of the forest, or planting genetically identical seedlings within stands with differing forest structure to identify any differences in phenology.

Recreation and Education

Background

Region 9 forests experience over 12 million visits annually (Recreation Reimagined R9 Strategic Plan). National forests offer myriad recreational opportunities, including but not limited to hiking, skiing, snowshoeing, hunting, fishing, and water sports. Nationally, the outdoor recreation economy produced $689 billion and 4.3 million jobs in 2021 and hiking was one of 4 activities with the highest growth rates since Jan 2020 (outdoorindustry.org/resource/state-of-the-outdoor-market).

In our conversations with Forest staff, we noted that some forests are more focused on increasing visitation and engagement. For example, Finger Lakes National Forest (FLNF) staff noted a general uptick in visitation due to the global pandemic. FLNF indicated that they are seeking opportunities to capitalize on the increased interest by engaging visitors in education and citizen science.

Forests offer landscapes that are natural classrooms for learning and strengthening connections to the land and each other. Dynamic educational opportunities are key as visitation to the country's public lands has increased in recent decades and will continue to increase (Marshall et al., 2018). Further, lack of public engagement through conservation education threatens fragile ecosystems that exist within national forest lands (e.g., visitors unknowingly trample fragile alpine zones).

Role of Phenology

There are seasonal patterns in visitation that depend on recreational use and visitor priorities. With climate change, forest visitation patterns are shifting in time and space. Green Mountain National Forest staff reported that the summer hiking, mountain biking, and camping seasons are growing longer, which can stress staff resources as well as already over-used natural areas. Superior National Forest echoed this sentiment, noting increased shoulder season use of the over one-million-acre Boundary Water Canoe Area Wilderness contained within the Forest boundary. With overuse, the Forest and partners will not only need to address trail and recreation infrastructure degradation, but they also need to consider vegetation restoration and diverting users to other destinations. Changes to visitation in spring and fall, particularly, have implications for humans interacting with ecosystems during critical life cycle events, like animal reproduction.

Visitation timing may be targeted for phenological events in plants and animals. The phenology of charismatic species and landscapes, such as leaf color change in the fall, and wildflower displays in the spring can drive visitation, and predictions of these events can support visitors in timing travel and Forests in planning for visitors. In contrast, certain sensitive phenological events, like bird nesting and bear and bat hibernation emergence, may require diversion of visitors for species protection. Managers may plan trail and road closures to prevent human-wildlife conflict and ensure that human disturbances are minimal during critical life cycle events such as mating, nesting, or hibernation. Phenological knowledge, particularly short- and long-term predictions, can help to align timing to maximize positive and minimize negative interactions between people, plants, and wildlife. Three of seven survey respondents saw potential in the application of phenological information in recreation, for instance, in planning temporary trail closures (Appendix 2).

Phenology has always been a key piece of visitor engagement on public lands, even if not known by that term. Visitor centers typically have logbooks where seasonal sightings are recorded, and programs are often timed to connect visitors with key seasonal transitions (such as hearing the spring peepers). Phenology in interpretation is expanding, particularly in the context of climate change (e.g., at the National Park Service; Rosemartin et al., 2021). Charismatic recreation areas such as the alpine zones of the White Mountain National Forest and the Boundary Waters Canoe Area Wilderness in the Superior National Forest already attract thousands of visitors annually. For areas like these on national forests, there is high potential to leverage already present and invested recreationalists and partner groups to collect citizen science data and engage in educational opportunities on national forest lands.

Coupled with the recent expansion of citizen or volunteer science programs on public lands, there is a powerful opportunity to engage visitors in a hands-on/participatory way in seasonal changes across national forests. Citizen science has many advantages, including educational and recreational benefits to participants, increases in environmental awareness and appreciation for biodiversity, and greater spatial and temporal coverage in data collected (Bonney et al., 2009). McKinley (2017) specifically frames citizen science in the federal resource management agency context and finds that well-designed citizen science can help agencies meet their needs for sound science as well as public input and engagement. The USA-NPN has several templates available for signage related to describing phenology monitoring efforts and offering instructions for visitors on how to collect data that have been used by many of its partners for public engagement.

Information Gaps

We see several promising areas for the application of phenological information in recreation. Climate change is causing milder and shorter winters, with changes to spring and fall as well, resulting in accompanying changes in recreational uses. To better inform tourists in planning their visits in spring and fall, as well as to assist USFS staff in preparing for increased visitation, there is an opportunity for more robust predictions of spring wildflower blooms and fall leaf color change.

Managers and documents from GMNF/FLNF, WMNF, and HNF also point to a need for information on bat hibernation periods, to inform trail closures, burn times, and/or timber harvest activities. Spring temperatures are correlated with cave-dwelling bat (*Myotis* spp.) activity, particularly in spring at the conclusion of hibernation (Muthersbaugh et al., 2019). There may also be potential in predicting hibernation release for bears, to mitigate human-wildlife conflict (New York State Department of Environmental Conservation issues warnings about when to watch out for bears; dec.ny.gov/press/127450.html).

There is an opportunity to use the dramatic impact of seasonal change on recreation, especially winter recreation, to engage visitors in understanding climate change and supporting mitigation and adaptation. AMC has found success in joining an international citizen science project called Community Snow Observations (outdoors.org/resources/amc-outdoors/conservation-and-climate/community-snow-observations-come-to-the-white-mountains) that engages winter recreationists in hands-on monitoring by documenting simple snow depth while out recreating.

There is a significant opportunity for first engagement or exposure with a large public audience at national forest visitor centers and through programs on national forest land. For example, within Region 9, the WMNF is one of the most visited protected landscapes with over 3.4 million visitors annually and is within 100 miles of major Northeast cities (Ferguson et al., 2022). A 2016 survey of 855 on-site WMNF visitors found 73% were non-New Hampshire residents who traveled an average distance of ~378 miles from home (Ferguson et al., 2022). AMC estimates that 500,000 visitors pass through front and backcountry lodges they operate on the WMNF annually and they have been educating visitors about plant phenology and the opportunity for citizen science. In

2022, Naturalist programs at backcountry huts that covered either Mountain Watch and/or iNaturalist reached 326 kids and 2,090 adults. Similar programs, educational brochures, and bathroom stall posters at visitor centers could be replicated or modified to spread the word about citizen science opportunities and the importance of monitoring plant seasonal changes in the context of climate change.

In our conversation with the Finger Lakes National Forest, interest in engaging visitors through education was expressed. As a small forest within a tight knit community, FLNF sees education as a way to strengthen community ties. The integration of phenology education will help community members and forest visitors understand how the forest is changing with climate change.

Existing Resources and Partnerships

Citizen Science Phenology Programs for Engagement and Data Collection

Campaigns through the USA-NPN's *Nature's Notebook* platform encourage citizens to record plot-based data for certain plants or animals (e.g., Green Wave, Nectar Connectors; usanpn.org/nn/campaigns). Further infrastructure around USA-NPN's Local Phenology Programs is available to organize and get the most out of citizen science efforts. In R9, there are many active programs, including EarthWise Aware in the Boston area and the Phenology Trail at College of Menominee Nation in Wisconsin. USA-NPN data have been used in over 130 peer-reviewed articles about the status of changing phenology for plants and animals in the United States (www.usanpn.org/publications). Additional programs are mentioned below under Existing Resources and Partnerships for Species and Habitat Management.

Specific to Wildflower Forecasts

The AMC began mountain wildflower monitoring, via a program called Mountain Watch, in 2004 at set locations in the White Mountain National Forest, NH. The approach was both to train seasonal staff to observe plots with targeted plant species and to recruit volunteer recreationists to help document alpine plant flowering, an event that attracts hikers to the mountains annually. Once the USA National Phenology Network came into being, the AMC began to align its protocol and migrated to this program, adding vegetative phenophases and fruiting. By 2013, AMC was utilizing the USA-NPN's system and thereafter all data has been entered into *Nature's Notebook*. Monitoring at NPN plots is largely supported by seasonal trained naturalists that provide educational 1-hour programs at the 8 backcountry huts. AMC also has formal educational programs that have modules that include both phenology and climate change education. The dataset AMC has accumulated may be used to develop a wildflower forecast in alpine and forested sites. Below is the sequence of 3 alpine plant open flowers timing for 2019, Figure 4. Woodland forbs data began in 2008 and today includes species found across Region 9 including Canada mayflower and yellow trout lily, as well as those well distributed in the northern areas of Region 9: bluebead lily, bunchberry, and Labrador tea. In 2023 AMC will be adding starflower and threeleaf goldthread which are also well distributed across the region.

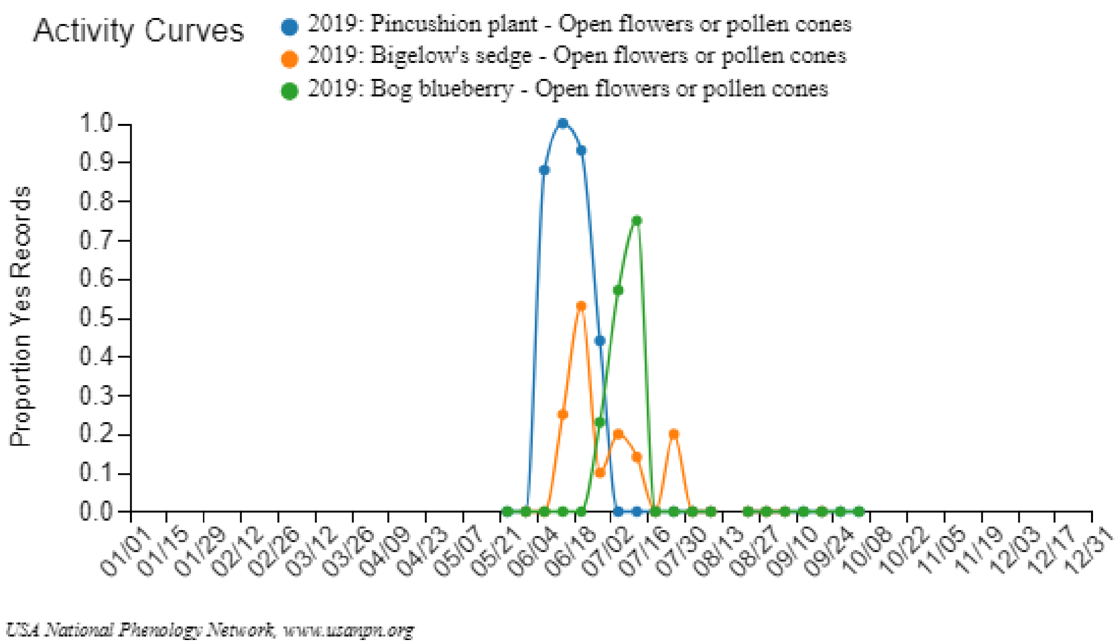


Figure 4. 2019 NPN activity curves of open flower timing for 3 alpine plants in the Northeast.

Specific to Leaf Color Change Forecasts

Since 2015, the USA-NPN has run a national campaign focused on leaf out and leaf color change in maples, oaks, and poplars, called the Green Wave Campaign. Hundreds of Local Phenology Programs and observers contribute to the dataset. Today there are over 6.5 million records for these three genera in the *Nature's Notebook* database. Figure 5 shows peaks in leaf color change 2019-2022, for red maples across the US, as a demonstration of the resolution and type of data available because of this campaign. There is potential to develop a "Fall Index" to complement the USA-NPN's Spring Index, which could serve in both short-term forecasts and long-term projections

of leaf color change in Region 9 and across the country. There are at least three fall foliage maps currently offered in the US (by New England Yankee Magazine, The Foliage Network and SmokyMountains.com). These maps are images only (precluding analysis) and are real-time as observations are submitted, without a forecast component to support planning.

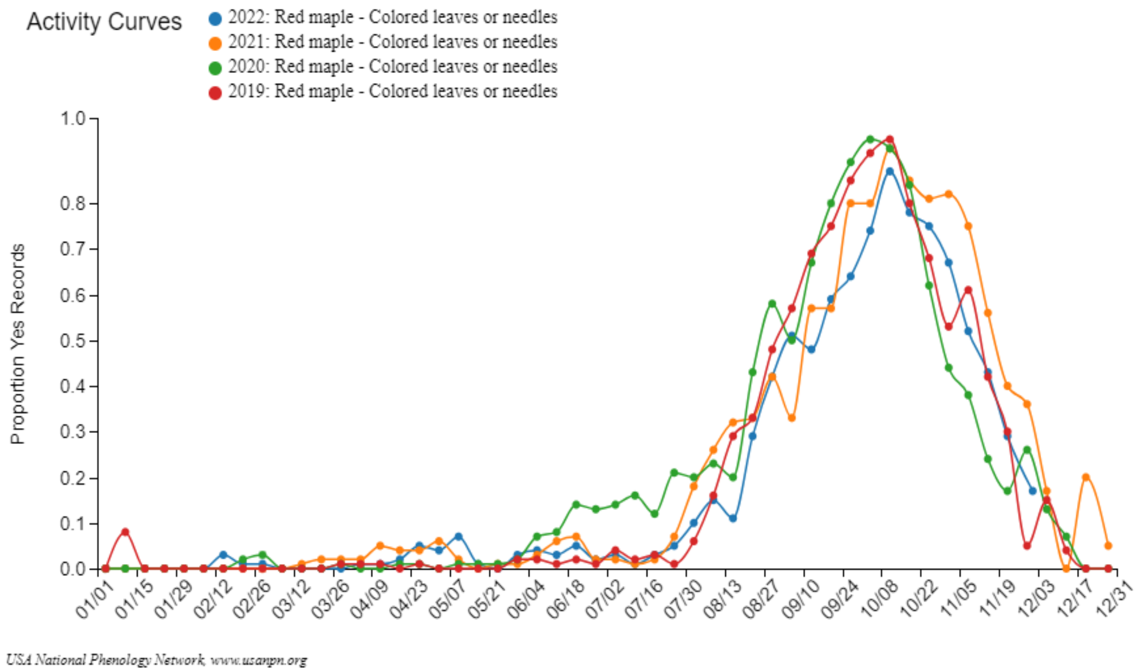


Figure 5. Leaf color change curves for red maple (2019-2022), source USA-NPN Visualization Tool.

Potential Directions

Our research and conversations with USFS staff suggest that there is potential for data collection in partnership with AMC, USA-NPN, and iNaturalist that could both engage visitors and contribute to future models predicting charismatic phenological events at national forests.

We see a project centered on blooming in mountain wildflowers or fall deciduous tree leaf color change as the two most tractable projects near-term. A wildflower-focused effort is the more "shovel-ready" of the two, given the nearly 20-year dataset held by AMC and strong on-the-ground partnerships. Longer term, and given more demand, we could consider a bat hibernation start/end, bear hibernation start/end, and sensitive bird nesting product, that would serve to inform visitor use management.

Potential Next Steps

#8 - We could develop a project that builds on the existing AMC Mountain Watch project, extending the citizen science monitoring through both *Nature's Notebook* and iNaturalist to Green Mountain National Forest. We could identify a researcher to support development of a wildflower forecast that USA-NPN could operationalize; this forecast would be relevant to both WMNF and GMNF.

#9 - There are several potential ways to advance the educational opportunities we identified here. We could develop regional or national materials that leverage seasonal changes to tell the climate change story. Alternatively, educational resources could be targeted to a particular project such as the wildflower or fall foliage projects suggested above (or other efforts mentioned in other sections, such as hemlock wooly adelgid). We would envision collaborating with the USFS Education Office in development of programming, signage, StoryMap, and phenology educational resources. We would also connect with Forest units and Local Phenology Programs in the region who have well-developed education programs.

Habitat/Species Management

Background

In terms of ecoregions, R9 is diverse; major ecoregions include Northern Forest and Eastern Temperate Forest, while smaller ecoregions include Northeastern Highlands in the eastern portion to Northern Minnesota Wetlands in the western areas (EPA, 2023). With such diversity, conservation and management strategies vary by forest unit. Generally, units manage for conservation, through intervention designed to ensure the maintenance of habitats and to meet the requirements of ecosystems or specific species. These types of activities are often tied to natural resource assessment which provide timely information to decision and policy makers on the current condition of a natural resource and evaluate factors that are affecting that resource (Joyce & Janowiak, 2011). Habitat and species conservation are also often considered in Forest Plan monitoring where Adaptive Management is applied. Adaptive Management relies on monitoring and research to gain knowledge and understanding and feeds that back into a management plan with desired goals and outcomes.

Role of Phenology

Monitoring is essential for periodic natural resource assessments and long-term efforts such as in Forest Plans and Monitoring Plans. In terms of climate change, forest units may need decades of information to assist them with assessment and future planning, including identifying additional monitoring needed to document the effects of climate change in their area. As mentioned previously, long-term climate data are available and used in Vulnerability Assessments but biological response data is often lacking. Long-term and standardized phenology monitoring of one or more species can provide resource managers with both species-specific information and general insight into ecosystem responses to shifting seasons (Cleland et al., 2012).

Specific biological indicators from shifting climate conditions include identifying climate change responsive and non-responsive species, identifying mismatches in resources, change in the length of the growing season, and change in timing of ecologically significant phenological events such as flowering times or fruiting times.

Species/Habitats Most at Risk from Climate Change

Spruce-Fir habitat has been identified as having moderate to high vulnerability to climate change (Janowiak et al., 2018; USDA Forest Service 2022). High elevation spruce-fir provides key habitat for Bicknell's Thrush, Blackpoll Warbler, Purple Finch, Peregrine Falcon, Golden Eagle, American Pipit, Spruce Grouse, Three-toed Woodpecker, Canada Jay, American Marten, Rock Vole, and Northern Bog Lemming (Publicover et al., 2016). Increasing knowledge about the phenology of balsam fir and spruce species could be helpful in management responses necessary to protect this forest type and inhabitants from both natural (e.g., spruce budworm) and climate change stressors. Regeneration of balsam fir was raised as a concern at WMNF.

Mountain bird populations that utilize spruce-fir habitats are declining. Since 2010, the following mountain birds across the Northeast have seen declines: Yellow-bellied Flycatcher, Winter Wren, Bicknell's Thrush, Swainson's Thrush, Hermit Thrush, Blackpoll Warbler, and White-throated Sparrow, with an average decline greater than 39% of their populations (Hill, 2022). Bicknell's Thrush is particularly vulnerable as it is limited to montane spruce-fir habitat mostly above 2800 feet in disturbed forests or high elevation ridges with dense stunted balsam fir (Bicknell's Thrush report, fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5200533.pdf).

Northeast alpine habitats are limited in spatial scale but are essential to the character of the northern Appalachian Mountains. A recent analysis of historical temperature and snow records reveal even the highest mountain in the Northeast, Mount Washington, is now warming and the condition of winter is changing but elevational differences also exist (Murray et al., 2021). Elevational differences in winter temperature trends offer some hope of lagging severe climate change (Murray et al., 2021) with possible climate change refugia in montane areas (Morelli et al., 2017) that can sustain cold habitats as cold and snow cover are lost at other low elevation locales (Contosta et al., 2019).

Invasive Species

All the unit-level staff we spoke with raised concerns about invasive species. Six of seven survey respondents selected the management of invasive species as a promising application of phenological information. Invasive species can have significant impacts on their host and on the native species they compete with. Invasive plants have been shown to adapt better to climate change than their native counterparts. One study found that since the 1800s invasive plant species shifted flowering an average of 11 days earlier than native species did and were more aligned with warming temperatures (Willis et al., 2010). In 2021 alone, eastern forests saw 3.5 million acres of defoliation and 2.6 million acres of tree mortality from pests and diseases (USDA Forest Service, 2022). The spongy moth has been in outbreak for the past two years in parts of

New England and in 2021 damaged 2.6 m acres, while emerald ash borer damaged 2.2 million acres (USDA Forest Service, 2022). Maine has reported that hemlock decline and mortality is increasing with warming temperatures and drought conditions (USDA Forest Service, 2022). Warmer winters and wetter springs also lend to fungal growth and combined with summer drought, can create favorable conditions for White Pine Needle Damage (WPMD). This condition is caused by multiple fungal pathogens. Changing climatic conditions may also result in vectors of oak wilt, another fungal disease, traveling further north into Canada (Pedlar et al., 2020). Phenological information about target pests and invasives, as well as their host plants, can assist resource managers in planning eradication and/or control.

Indirect impacts of climate change are also expected to factor into future forest health. While there is mixed evidence on how added warming and changing precipitation patterns will impact the spruce budworm (SBW) there is concerning evidence that climate change could worsen its impact. Spruce budworm is a native insect that cyclically impacts northern softwood species with severe consequences approximately every 30-60 years. The last outbreak in New Hampshire was in 1983 (www.unh.edu/unhtoday/2020/04/eastern-spruce-budworm-outbreak-looming-unh-researchers-provide-guidance). The impact of climate change on outbreaks is unknown, with some evidence that it may be less of a concern as it migrates north, and spruce-fir populations decline (Janowiak et al., 2018). In contrast, a recent paper showed that under a warming climate the phenological synchrony increased between spruce budworm emergence and balsam fir and black spruce bud break per degree increase in temperature (Pureswaran et al., 2019). As a result, climate change has the potential to increase the vulnerability of balsam fir and black spruce to the spruce budworm.

Phenological mismatches

Mismatches within natural ecosystems have been documented, because not all species respond synchronically to warmer springs (Herberling et al., 2019; Alecrim et al., 2023). Evolutionary, population-level, biodiversity, and ecosystem function impacts are consequences of these mismatches (Visser & Gienapp, 2019). Plant-pollinator mismatch was raised as a concern at GMNF and FLNF. The severity of these impacts, combined with known variations in phenology across elevational gradients, indicates a need for species level understory and forest canopy phenology measurements across mountain landscapes.

Phenological mismatches for migratory species can also be pronounced as they may experience different climate advancements in spring in their overwinter habitat, arriving too early or too late in summer breeding destinations, and missing important food sources. Mismatched timing between plants and pollinators could impact pollinator populations, which have been declining due to a number of anthropogenic causes including climate change. The reciprocal impact to flowering plants without pollinators may be as large as one third of seeing no seeds and 50% half suffering 80% or more reduction in fertility emphasizing their critical role in successful plant reproduction (Rodger et al., 2021) and consequently ecosystem stability, biodiversity, and food security. Management that seeks to preserve both plant biodiversity and pollinators could help to mitigate climate change mismatches albeit specialists, reliant on one species, may be still at risk.

Information Gaps

There is significant overlap in identified knowledge gaps in previous sections for habitat and species management, indicating efforts could have multiple benefits across the four topics we present here. Particular to the identified sensitive habitats climate change is expected to negatively impact balsam fir forests as discussed above and extreme weather can cause nesting failures in inhabitants like Bicknell's Thrush. Tracking spruce-fir forest phenology in concert with other local efforts (e.g. Mountain Bird Watch; mountainbirds.vtecostudies.org/state-of-mountain-birds-report), could provide insight into overall ecosystem health and synchronicity. Further, tracking understory mountain forb flowering, which is already a component of AMC's Mountain Watch, could further our understanding of plant resource waves for pollinators and subsequent frugivores and the potential for varying shifts in phenology across elevations with climate change.

How alpine ecosystems will fare under a continued changing climate is uncertain (Kimball et al., 2021), but their limited habitat does not provide many options if exposure thresholds are reached. AMC researchers are finding some evidence of increasing woodiness and shrub cover in a time series of alpine plant community data in Northeast alpine areas (Tourville & Murray, unpublished data) as well as treeline expansion upslope (Tourville et al., 2023). Key questions remain regarding plasticity in key species in this habitat to keep up with spring warming.

Supporting biodiversity and specifically phenological diversity across a landscape, could be an important management approach in terms of resource waves for mobile consumers (Armstrong et al., 2016) especially as climatic stressors and conditions change species distributions. Mountain landscapes provide natural resource waves because of the temperature gradients with elevation and aspect. Wildflower phenological monitoring can provide information on flower resources for pollinators in relation to resource gathering and foraging and mountains provide a natural gradient.

Existing Resources and Partnerships

Mountain/Spruce-Fir habitat

USA-NPN has 58 sites in the Northeast with phenology data on balsam fir including 2 sites with 10 years of data. Figure 6 shows initial growth in balsam fir (Figure 6a), comparing a warm May (2015; Figure 6b) vs. a relatively normal year (2016; Figure 6c). These years had observations at the same sites. This baseline data may inform the response of balsam fir to warming which is important in understanding SBW potential damage.

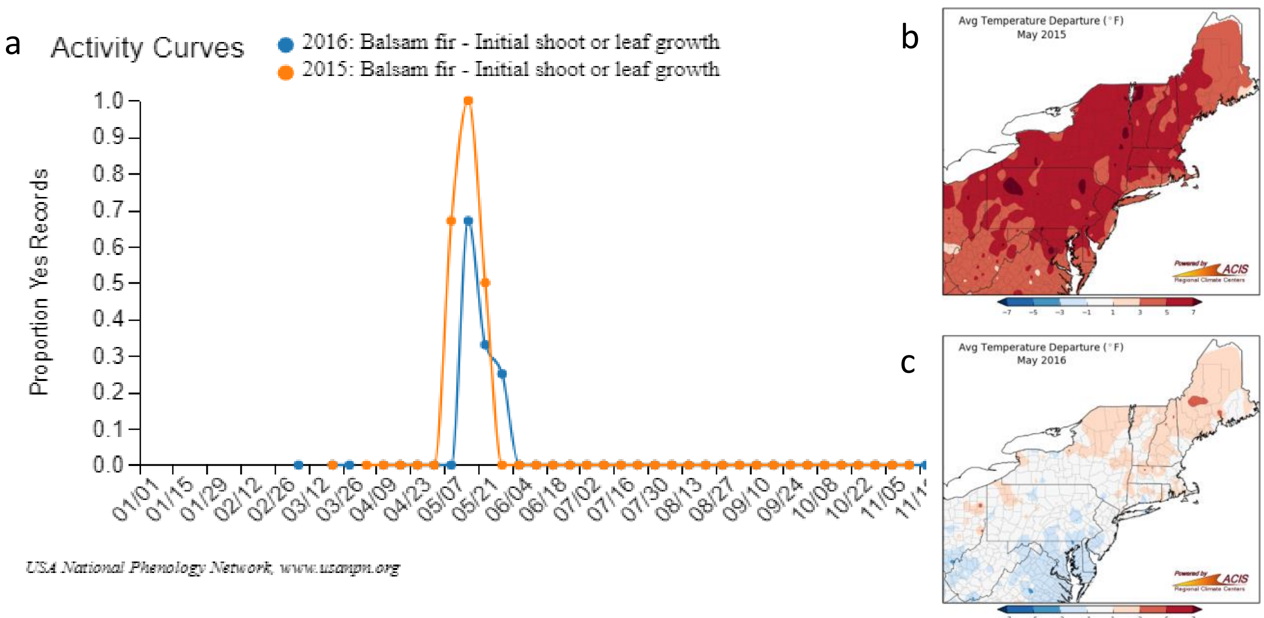


Figure 6. (a) Balsam fir initial shoot activity curves in 2015 and 2016 displaying data from the Northeast U.S., average temperature departure from normal in the Northeast U.S. in (b) 2015 and (c) 2016.

Mountain Birdwatch is another volunteer program that takes place in the eastern New York and Northern New England mountains and is directed by the Vermont Center for Ecostudies. This program is well established and provides presence absence data on a set of 11 mountain bird species. The program recruits hikers who bird a little (birders who like to hike!) to survey bird populations in spruce-fir forests.

AMC has been monitoring plant phenology since 2004 in the White Mountain National Forest, NH and uses the USA-NPN protocols and database. AMC has found a combination of citizen science approaches has led to the most success: permanent plot with USA-NPN provide consistent and detailed phenology data, while the crowdsourcing tool iNaturalist provides significantly more data points but has more limited phenological phases and more focus on the showier plants (Appendix 4).

By aligning the iNaturalist observations with NPN phenophases, AMC has been able to enhance spatially distributed data. AMC's Mountain Watch project has provided baseline information on flowering times of 7 common woodland species and 8 above treeline species. An initial analysis also found that alpine species are not as responsive to spring warming as other species in terms of the number of days shifted in flowering times for every 1 degree of warming (Tourville & Murray, unpublished data). Data also demonstrate how the different species' flowering times are staggered across spring.

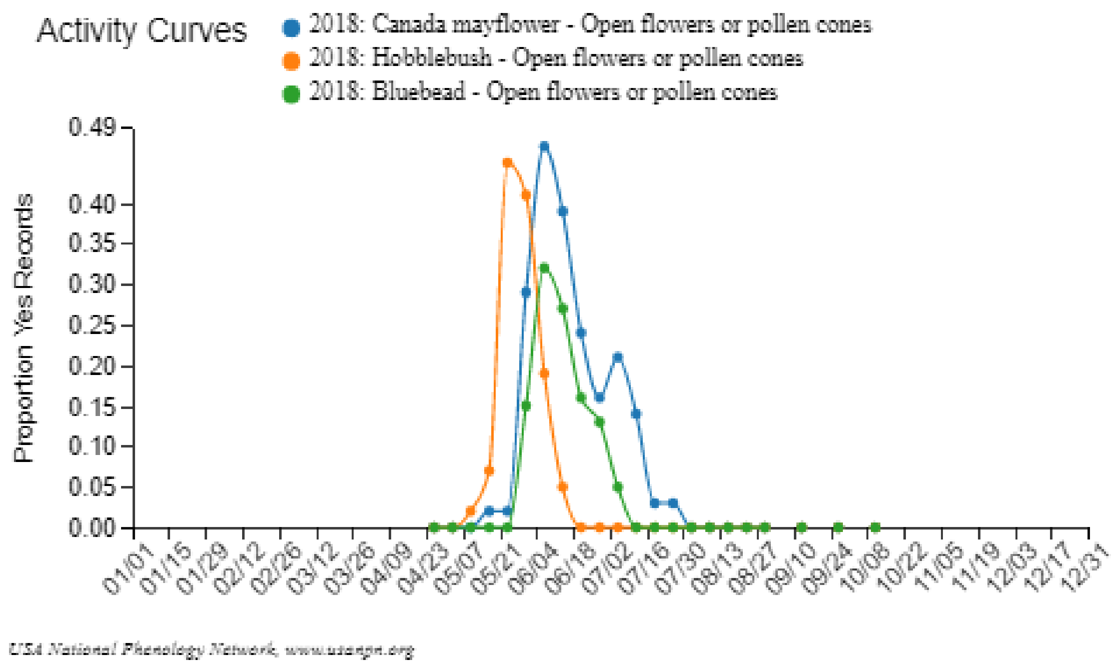


Figure 7. 2018 activity curves for 3 woodland plants, bobblebush, bluebead lily, and Canada mayflower.

Looking at an individual year, 2018, USA-NPN plot data for three berry forming species (hobblebush, bluebead lily, and Canada mayflower) are shown with different or longer flowering times from each other, see Figure 7. While these species may attract different types of pollinators, there is likely some overlap and therefore staggered nectar resources. Within a species, a phenological resource wave is observed where Canada mayflower flowers from day of year 158-197 (June 7th to July 16th), 2019 across a mountain elevational gradient, see Figure 8. This provides approximately 5 weeks of nectar resources from a single species. This graph shows a well distributed set of iNaturalist observations across elevation which helps to fill in some spatial gaps around our NPN plots including above 3,800 feet.

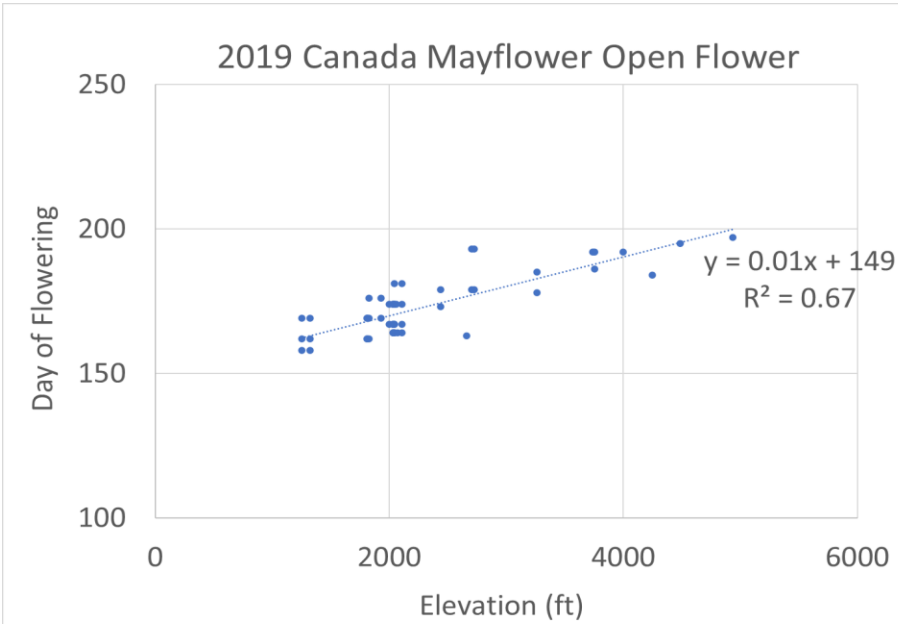


Figure 8. 2019 Canada mayflower open flower observations vs. elevation in feet.

Montane habitat

As mentioned previously, AMC has 18 years of alpine flowering data collected in Northeast alpine areas, largely in the White Mountain National Forest. This unique alpine dataset can be used to understand species' response to climate change. Additional analysis of a temperature dataset with local scale data, accounting for complex topography, and factoring in other variables such as snowmelt, is the next step in understanding how these species are experiencing climate change.

The program's success is due, in part, to the long-term infrastructure of the huts and lodges staffed by the AMC, allowing NPN plots to be monitored with sufficient frequency. The program also includes iNaturalist projects that mirror NPN phenophases focused on reproduction. Merging these multiple data streams, the project has amassed over 500,000 observations of its target alpine and woodland species in the Northeast alone.

AMC's analysis of flowering time for 7 woodland and 6 alpine (3 true alpine and 3 boreal) species over 15-18 years provides important mountain plant phenology data that can serve as a baseline for wildflower models and future predictions. Figure 9 shows flowering day of year histograms, or flowering curves, with median flowering times noted. A spring warming sensitivity analysis of the White Mountain region data shows that the woodland species are flowering 6.2 -12.9 days earlier per 1 degree C of warming while only the 3 boreal species (not the 3 true alpine) are seeing 2.7 - 4.3 days earlier per 1 degree C of warming, see Tables 1 and 2 (Tourville et al, submitted; Tourville & Murray, unpublished data). The general lack of spring sensitivity detected in true alpine plants is being investigated further using more local temperature data that may better capture the slower warming rates on NH's highest peak (Murray et al., 2021) and the microtopographic variability typical of the White Mountain alpine areas. However, other factors, such as snowmelt timing, may also be helpful predictors.

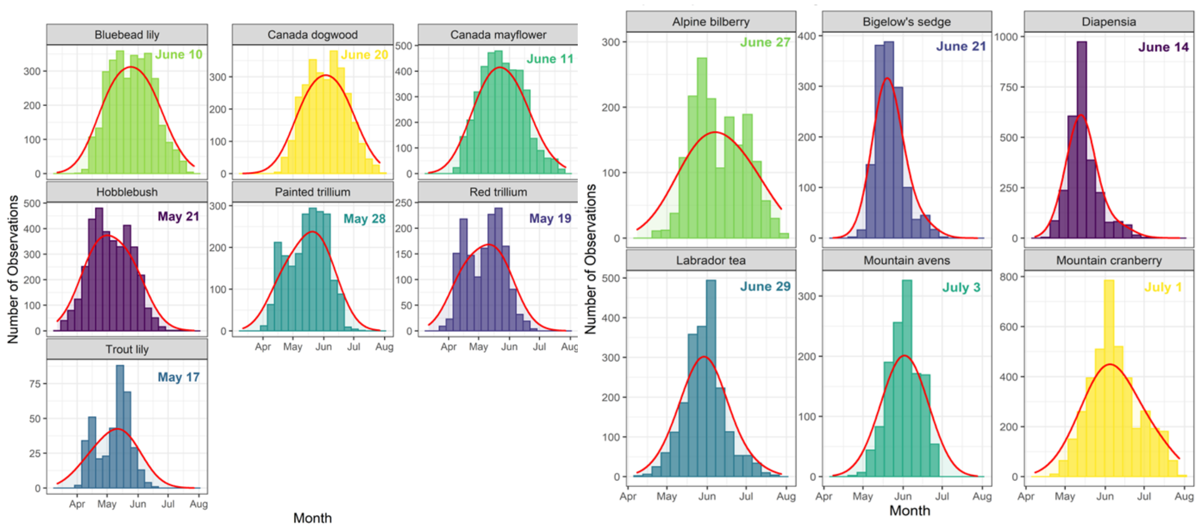


Figure 9. Temporal flowering range of woodland and alpine species in the White Mountains in New Hampshire from 2004-2022 using observations collected via hut *Nature's Notebook* plots and iNaturalist (Mountain Watch programs). Median flowering date represents the middle of the observed flowering period.

Table 1. Mean spring temperature sensitivity as median day of flowering per degree Celsius for our target **woodland plants.** Negative numbers show earlier (advancing) flowering times, ** denote confidence intervals (CI) did not over-lap with zero, indicating strong evidence in earlier flowering.

Species	Number of observations	Mean spring temperature sensitivity
Blue-bead lily	3,816	-6.2**
Canada dogwood	3,261	-7.9**
Trout lily	1,791	-12.9**
Canada mayflower	4,975	-10.1**
Red trillium	4,018	-11.5**
Painted trillium	3,152	-8.7**
Hobblebush	4,108	-7.1**

Table 2. Mean spring temperature sensitivity as median day of flowering per degree Celsius for our target **alpine and boreal plants.** Negative numbers show earlier (advancing) flowering times, ** denote confidence intervals (CI) did not over-lap with zero, indicating strong evidence in earlier flowering.

Species	Number of observations	Mean Spring Temperature Sensitivity
Bigelow's sedge	1,785	-1.4
Diapensia	3,032	-0.3
Mountain avens	1,328	-2.7**
Labrador tea	3,094	-3.5**
Alpine bilberry	3,912	0.9
Mountain cranberry	4,318	-4.3**

Invasive species

The USA-NPN already has several data products to help resource managers prepare for when to look for pests and how to time management actions, including observational data campaigns (described above) and Pheno Forecasts (usanpn.org/news/forecasts).

Pheno Forecasts: Pheno Forecast maps predict key life cycle stages in invasive species, to improve management efficacy. For insect pest species, Pheno Forecasts are based on published growing degree day (GDD) thresholds for key points in species life cycles. These key points typically represent life cycle stages when survey or management actions are most efficient. These maps are updated daily and are available as current day and six-day forecasts. Email notifications aare available 6 and 14 days prior to the predicted event. The USA-NPN offers 19 Pheno Forecasts, including spongy moth caterpillar emergence, emerald ash borer adult emergence and egg hatch, and the hemlock woolly adelgid eggs and nymphs. Eradication and control strategies depend on comprehensive knowledge of species reproduction cycles and temperature thresholds. These forecasts are routinely used by landscapers, foresters, and growers to time treatment more efficiently.

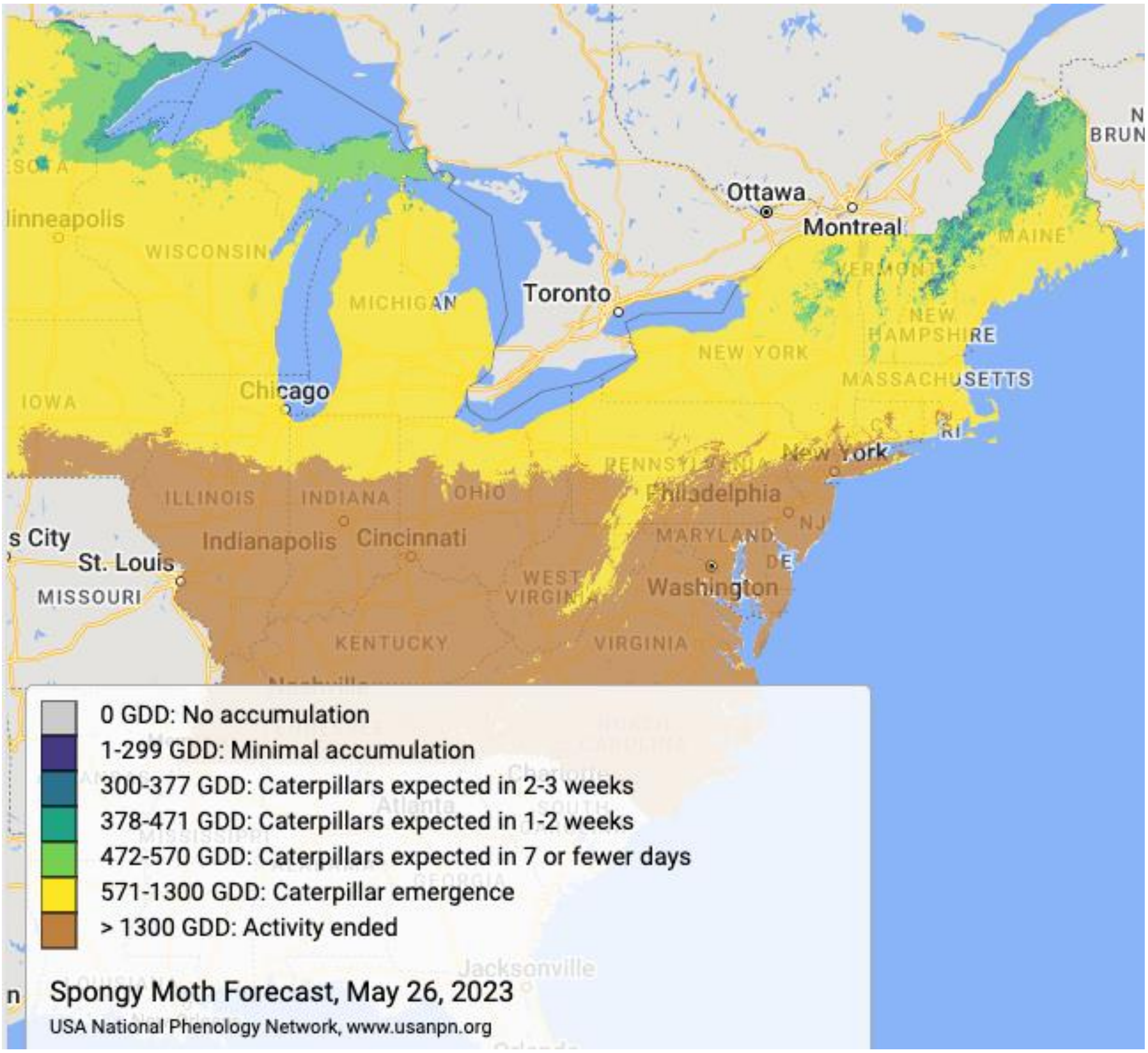


Figure 10: Example Pheno Forecast, for spongy moth caterpillar emergence, as of May 26, 2023.

The direct monitoring of invasive plant species of concern is also ongoing at USA-NPN. A USA-NPN campaign that focused on Japanese knotweed is now concluded and data are being analyzed with the intent to develop a flowering forecast for the species. This forecast would aid managers in optimizing the timing of eradication efforts, so they are the most effective and safe (well before seed sets and enables spread). A comprehensive list of existing USA-NPN efforts on invasive species that occur in the Northeast and Midwest is given below in Table 3.

Table 3. Forest Pests and their interactions with climate and how phenology reporting aides land managers.

Insect/ Disease	Climate/weather interaction	Current or future Phenology monitoring and reporting
Spongy Moth	Mixed. Lower survival in warmer temps/less snow has been reported. Drought in spring can result in higher populations due to reduction in fungal predators.	USA-NPN has existing Pheno Forecast for caterpillar emergence Part of USA-NPN Pest Patrol Campaign
Emerald Ash Borer	None known	USA-NPN has existing Pheno Forecasts for adult emergence and egg hatch Part of USA-NPN Pest Patrol Campaign
Asian Longhorn Beetle	Can live in a wide climate range, may allow advantage in changing climate More generations per year in warmer locations/years, helps with spread	USA-NPN has existing Pheno Forecast for adult emergence Part of USA-NPN Pest Patrol Campaign
Hemlock Woolly Adelgid	Warming winters have resulted in lower HWA mortality. This in combination with drought has led to hemlock decline in Maine.	USA-NPN Pheno Forecast for eggs and active nymphs exists, could be enhanced with recent research from NYS Hemlock Initiative Part of USA-NPN Pest Patrol Campaign
Oak Wilt	Warmer conditions will allow some sap feeding beetle vectors to travel further north spreading the fungus that causes the oak wilt	The USA-NPN could add a Pheno Forecast and observational data campaign to identify adult flight in the sap-feeding beetles in the Nitidulidae family that spread the disease, to inform management (avoid cuts during adult flight).
Eastern Spruce Budworm	Warmer springs may align balsam fir bud break to host emergence, resulting in more SBW damage	Potential future for USA-NPN Pheno Forecast for a given SBW stage Existing USA-NPN data on Balsam fir with 58 sites.

Pollinators and other phenological mismatches

There are many ongoing projects focused on pollinators among partners and within and beyond the USFS. Here we share overviews of ongoing projects that could be expanded or integrated into Region 9 forests' monitoring or partnerships. USA-NPN's Nectar Connectors (usanpn.org/nn/campaigns) is a campaign directed at tracking the phenology of a wide variety of nectar producing plants across the USA that support important pollinating species with a focus on the Monarch butterfly.

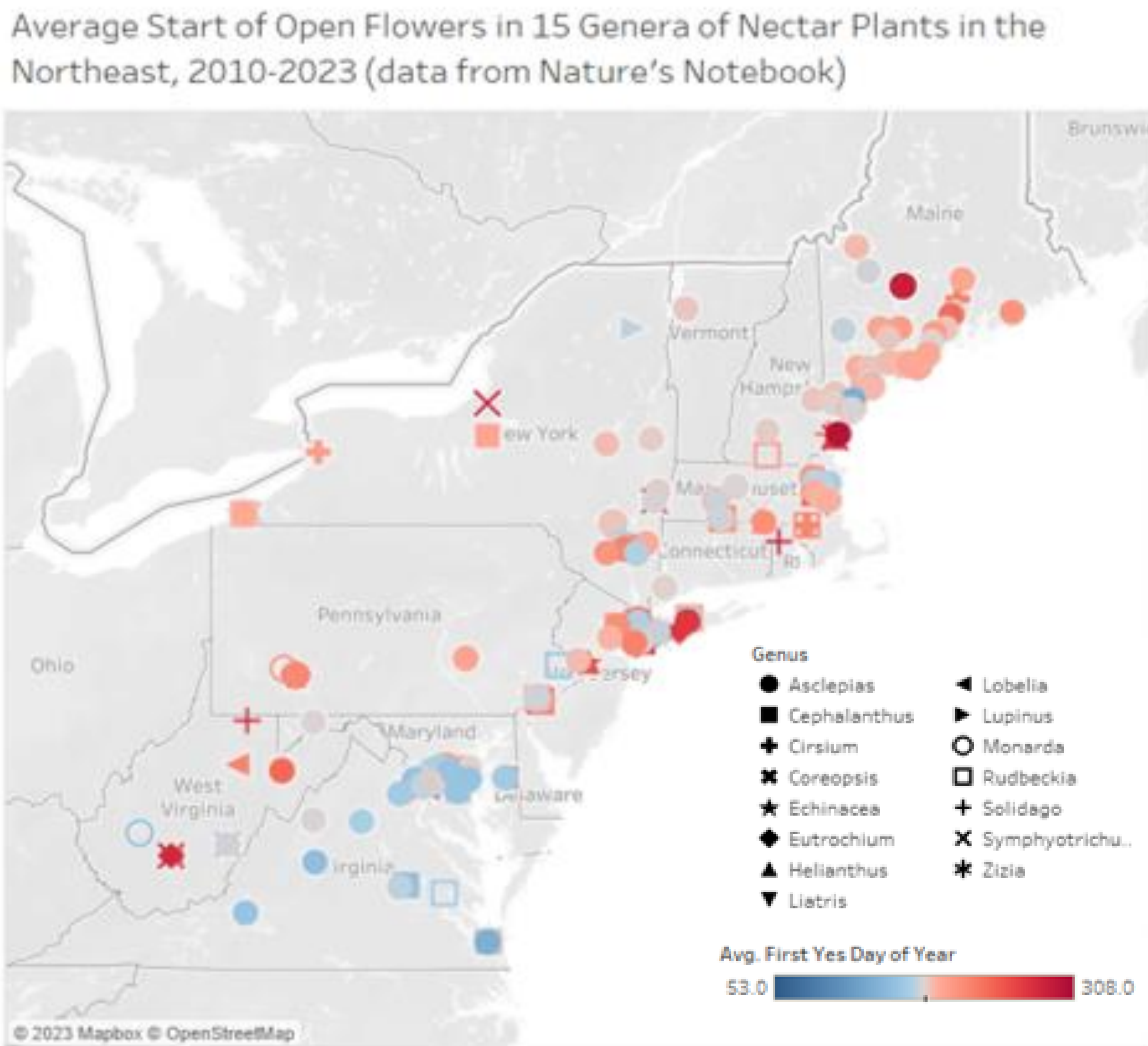


Figure 11. Average start of open flowers for Nectar Connector Plants in the Northeast.

Citizen science projects that directly monitor pollinators include E-butterfly (e-butterfly.org/ebapp/en), a successful program that could provide some pollinator data and Monarch Watch (monarchwatch.org).

A USFS project from western Montana may be relevant as a model. The project Assessing Pollinator Friendliness of Plants and Designing Mixes to Restore Habitat for Bees (fs.usda.gov/research/treesearch/63732) addresses pollinator decline by identifying pollinator friendly seed mixes to use in revegetation projects in recently disturbed federal lands. The work includes phenology calendars to provide coverage throughout the season, which could be refined and expanded nationally.

AMC's Mountain Watch is an existing robust dataset that could be used to leverage models of mountain wildflower phenology, including in Northeast alpine habitats, in relation to canopy closure and/or pollinator activity.

iNaturalist is an existing resource to get presence/absence data on flowering plants and pollinators. The yellow-banded bumblebee is a species of concern due to severe declines in recent decades and is well-documented in iNaturalist. The species has been seen at higher elevations in WMNF and GMNF in August and may benefit from later flowering species in snowbank communities above treeline.

Aquatics/species of concern

While the partners engaged thus far are less strong on freshwater systems, there is potential for phenological information to support our understanding of climate impacts in freshwater systems. The forest units in Region 9 have significant surface water resources, containing 962,000 acres of lakes and 15,000 miles of streams. Existing programs that may be appropriate to expand in the region include, UNH's volunteer-based rainbow smelt monitoring (seagrant.unh.edu/volunteer/coastal-research-volunteers/current-projects/rainbow-smelt-monitoring); engaging the fishing community with Science on the Fly (scienceonthefly.org). Similarly, there was interest at Hoosier NF around the phenology of herpetofauna. The USA-NPN houses some relevant data. Additionally,ARMI (armi.usgs.gov) and FrogWatch (or Vernal Pool groups; harriscenter.org/programs-and-education/citizen-science/vernal-pool-project), might be strong partners in this arena.

Potential Directions

There are multiple opportunities to support conservation of species and habitats throughout Region 9 that can incorporate phenology monitoring and analysis. Interest in invasive species, pollination, and forest health were common concerns for on-the-ground USFS managers. We see opportunities for new forecasts and phenology data collection by USA-NPN and partners that could integrate climate change related issues to adaptive management and forest plan monitoring.

Potential Next Steps:

#10 - Develop a project at Finger Lake National Forest where New York Phenology Project coordinates citizen science to engage visitors in monitoring Hemlock and HWA. The USA-NPN would improve HWA forecast using recent research (Limbu et al. 2022) that leverages citizen science data and efforts of NYS Hemlock Initiative. Specifically, this would include updating Hemlock Woolly Adelgid forecasts based on the latest models developed by collaborators with the New York State Hemlock Initiative at Cornell University that have identified an improved start date for accumulating heating degree days. This improved forecast would shorten the window that volunteers and staff would scout for eggs and support the timing of biocontrol release by the New York State Hemlock Initiative.

#11 - Develop a project in collaboration with Hoosier National Forest where the USA-NPN develops a new Pheno Forecast for adult flight in two sap-feeding beetles known to spread the fungal pathogen that causes oak wilt. The forecast would serve managers in knowing the times to avoid cutting oak to avoid spreading the disease.

#12 - Collaborate with partners and staff at the Superior National Forest where staff noted concerns about the Emerald Ash Borer, which has been observed nearby but has not yet been found in the forest. Ground observations of Emerald Ash Borer in and around Superior, with partners, via the Pest Patrol Campaign would aid in early detection and subsequent management of the pest within the national forest. This in turn could aid in reducing the spread of the pest and increasing the survival of native ash trees in the forest.

Potential Next Steps, continued:

#13 - Expand USA-NPN's Nectar Connector campaign in concert with AMC's Mountain Watch towards better understanding plant pollinator mismatch in mountain landscapes as well as changing phenology diversity and shifts in canopy leaf out vs. understory flowering. Current coverage of the USA-NPN's existing pollinator plant species could be expanded if Region 9 forest units were interested, which could help broaden northern forest regions' understanding pollinator resources availability and how these nectar providing plants are responding (or may not be) to climate change. Large leaf goldenrod and three-toothed cinquefoil could be good species, found in these mountains, with links back to tracking phenological diversity.

#14 - Build on the existing USA-NPN balsam fir phenology dataset with a goal of tracking their response to climatic changes, such as drought and warming temperatures. With red spruce recovery from acid deposition and calcium depletion, it may be informative to determine if phenology in that species is changing as well. Further, if phenological shifts are happening in either of these species it would inform whether they are more at risk from spruce budworm. NPN sees potential for a new Pheno Forecast for eastern spruce budworm if it was advantageous to the USFS.

Barriers to Implementation

USA-NPN, along with the potential partners and USFS employees we met with, are enthusiastic and excited about this effort. However, it is important to recognize the barriers and challenges that accompany this work so we can plan around these constraints. In our survey (Appendix 2), several key barriers were highlighted, including resource limitations, the highly variable nature of phenology, and the long time period required to assemble a robust dataset, as well as a lack of awareness of the available resources.

Resource Limitations

USFS staff in Region 9 manage multiple shifting priorities and will likely have limited staff and staff time available to devote to any collaboration. USA-NPN is also a relatively small organization working on a diverse array of projects with many different partners. It is likely that potential partners are similarly constrained in staffing availability and time.

While limited staff availability is certainly a challenge, USA-NPN does have a highly developed network of partners and is well-placed to continue developing additional working relationships. Over the past year, we have connected with some of NPN's existing partners in the region (including the New York Phenology Project/Community Greenways Collaborative, the New York State Hemlock Initiative, Minnesota Phenology Network, and the Great Lakes Indian Fish and Wildlife Commission), and plan to continue this work through 2023 and beyond. By engaging with partners now and in the future, we hope to disperse the workload, gain diverse perspectives, and tap into volunteer efforts to overcome the challenges of resource limitations.

Citizen Science Challenges: Project Design, Volunteer Training/Retention, and Data Collection Platforms

One way to simultaneously combat limited staff availability and funding at the USFS and USA-NPN is to expand citizen science initiatives and volunteer-collected data in national forests. Throughout our conversations with unit-level USFS employees we have made sure to discuss staff availability and interest in engaging with partners and volunteers. Working with volunteer citizen scientists has numerous benefits including improved visitor engagement, an enhanced sense of place for participants, and science education opportunities in national forests. Citizen science is also a legitimate and robust form of scientific data collection and, if properly executed, can result in actionable and useful information (McKinley et al. 2017).

In our survey of USFS unit-level staff in R9, we found that four of seven respondents were interested in the potential of citizen science, while the remaining three needed more information to decide. We also heard interest in citizen science in our conversations with USFS staff. The Forest Service's Citizen Science Competitive Funding Program (CitSci Fund), which couples efforts of the USFS and a partner organization in the collection of citizen science data, provides an important potential way to move this work forward. It may be worth seeking feedback on the program's timeline and requirements, to increase the applicant pool.

While there are many possibilities for engaging citizen scientists in targeted phenology monitoring that can aid in USFS forest management, we also recognize that citizen science campaigns have their own associated challenges and limitations. First, it may take significant effort and planning to broker appropriate partnerships for citizen science projects. Launching a citizen science effort also requires a large investment in volunteer recruitment, training, and retention. For phenology specifically, certain phenophases may be challenging for people to recognize and it is important that training is provided so that citizen scientists are able to collect accurate and useful data. Coordinating this training can be a challenge, especially when projects are sited in relatively remote rural areas. However, there are also ways to combat these difficulties: citizen science leaders, once trained, can serve as resources to recruit and train others. The USA-NPN online resources for training observers and leaders (available at learning.usanpn.org) can help ameliorate this challenge.

Additionally, not all data collection efforts are well suited to large-scale citizen science initiatives. To use the limited staff time of the USFS and partner organizations wisely, it is important that the project is accessible to many demographics without special equipment needs being a barrier. For example, in our discussion with the New York State Hemlock Initiative (NYSHI) we learned that the detection of the hemlock woolly adelgid's (HWA) aestivation break (the separation of sclerites) often requires the use of a dissecting microscope, and even experts can disagree about the presence or absence of this development. Most citizens do not have easy access to such a piece of equipment and therefore detection of this HWA phenophase is ill-suited for a citizen science effort. Conversely, trained citizen scientists can readily identify HWA eggs.

In addition, the projects selected must be suitable to sustainably recruit and/or retain volunteers with an appropriate level of training and investment in the project. Because of the large investment in training required for monitoring more complex ecological cycles, the NYSHI told us that they currently rely on "super-volunteers," a small constituency of highly invested and trained volunteers for their citizen science data collection. AMC also has relied on super-volunteers and existing sustained groups (e.g. Alpine Stewards) for data collection. Additionally, AMC has found the need for a citizen-science focused seasonal position to keep up the drumbeat needed for annual recruitment and retention. The quality of long-term monitoring of phenology highly benefits from repeat observers that get to know the phenophase nuances, especially for some plant types such as trees.

Citizen science data collection tools also come with their own challenges. For example, *Nature’s Notebook*, USA-NPN’s data collection platform, relies on site-based data. Due to the ephemeral nature of phenology, frequent visits to each site are necessary to have useful data. Therefore, sites should not be established without some sort of larger framework to ensure that long-term data collection and frequent visits will result from this work. For example, the AMC has established USA-NPN sites located near each backcountry hut in the White Mountains of New Hampshire. Each hut is seasonally staffed by a naturalist who has a variety of duties which include visiting these plots and recording the data regularly. The funding and workflow framework, which mandates the hiring of a designated seasonal staff person to do this work has resulted in the collection of reliable and frequent phenological data at the AMC *Nature's Notebook* sites. When establishing a citizen science project, it is also important to carefully consider the chosen platform for collecting citizen science data (See Appendix 4 for more information on using iNaturalist and *Nature's Noteboo*k for different purposes, and in concert).

Scaling

In addition to limited resources, in researching different Region 9 forests and speaking with unit-level staff in different locations, we learned that each forest differs in staffing levels, priorities, and scale. All are actively working to facilitate the multi-use mandate of the USFS National Forests, but this can look quite different at each location. We recognize that the potential for the application of phenological information in R9 may differ in other USFS regions.

If we were to move forward on one of the opportunities identified here that is more local/unit-scale (for instance, an HWA project at FLNF), the content of the effort would not necessarily scale to other forests. However, certain lessons learned, like combining citizen science, education, and Pheno Forecasts, might be relevant to other future efforts. If we opt to move forward on incorporating phenology into Vulnerability Assessments, that may scale more intuitively, as VAs are already happening at many scales across the nation.

Conclusion

Phenological data is a useful and powerful tool for tracking climate change and informing forest management practices. We have determined that there are four major areas of opportunity – Vulnerability Assessments, Carbon Stewardship, Recreation and Education, and Species/Habitat Management – where phenology data can be best leveraged to inform and improve forest management actions.

Many concepts addressed in this report span multiple opportunity categories and may be especially promising starting points. Any work to better manage forest pests or invasives, as described in the Habitat/Species Management section, will also serve to lower forest vulnerability and improve forest carbon storage. False springs and adaptive capacity are other examples of concepts that could benefit from more phenological data and apply to multiple areas of opportunity.

We found that many Region 9 Forest Land and Resource Management Plans are due for an update. We are hopeful that the conversations we are having now, and the increased focus on sustainability and climate change within the USFS, will create interest in adding in phenologically centered monitoring items during the next round of Management Plan updates. It is also possible that some of the phenological forest monitoring needs in updated plans could be met by new partnerships brokered by USA-NPN through this project.

There are a wealth of existing data resources and potential partnerships that can be utilized to collect, manage, and analyze phenological data. Many are summarized or mentioned in this report (or in Appendix 5), but it is likely that there are many more in existence. USA-NPN, which already has many partners in R9, can serve as a broker of potential partnerships. First steps in brokering these relationships would be to identify potential partner groups, assess their applicability to the areas of opportunity and the resources they have available, and pitch this project (broadly or as a specific next step outlined in this report) to their staff. This partner identification process is a tractable next step we hope to take following the reception of this report by USFS staff.

It is possible that, through these potential partnerships, we could expand or design citizen projects to meet USFS monitoring needs. Not only can citizen science projects provide useful datasets for forest management, but citizen science initiatives can also serve as powerful vehicles to increase public engagement, personal connection, and education on national forest lands.

As we continue this work, there may be barriers to project implementation that become apparent. We are already actively thinking about known barriers and we are prepared to come up with creative solutions and strategies to overcome these challenges and others that may emerge. Upon receiving feedback from USFS following this report, we look forward to taking the next steps to create or leverage actionable phenology datasets, partnerships, and products for improved forest management and climate change resilience on national forest lands.

Photo: Jessica Fadel

Acknowledgements

We are grateful to the many USFS biologists, botanists, ecologists, specialists, and other staff who gave their time to share ideas and input for this Assessment. Erin Posthumus, Theresa Crimmins, Sarah Nelson, and Jordon Tourville reviewed and improved this Assessment. Dave Moore provided valuable input on the content of this Assessment.

This Opportunities Assessment was funded by Master Challenge Cost Share Agreement #22-CS-11132400-353 between the USDA Forest Service Office of Sustainability and Climate and the USA National Phenology Network at the University of Arizona.

Appendix 1 - Summary of Meetings with Unit-level Staff

Region 9 Forest or USFS Office	Date(s)	Medium	Person(s) and title	Review of OA draft & Comments
Forest Unit Level Staff				
Green Mountain National Forest	February 24th, 2023 March 16th, 2023	Virtual Virtual	Shawn Langston- Wildlife Biologist Mary-Beth Deller- Botanist & Non-native Invasive Plant Program Coordinator	Sent for review July 27th, 2023, no changes.
Finger Lakes National Forest	March 30th, 2023	Virtual	Matthew Lark- Natural Resource Specialist Greg Flood- Wildlife Biologist	Sent for review July 21, 2023, no changes.
White Mountain National Forest	April 3rd, 2023	In-Person, White Mountain National Forest Headquarters Campton, NH	Ecoteam- various biologists	Sent for review July 21, 2023, no changes.
Hoosier National Forest	May 19, 2023	Virtual	RD Sample - Forest Ecologist	Review Comments: - Influence of climate change on bats - Influence of forest structure on carbon sequestration
Superior National	May 30,	Virtual	Katie Frerker -	Review Comments:

Forest	2023		Forest Ecologist, Climate Change Coordinator Jack Greenlee - Ecologist	- Potential mismatch of blueberry fruiting for ecological and cultural significance - Phenology of birch bark harvest
Superior National Forest; Washington Office National Forest Service	June 29th, 2023	Virtual	Katie Frerker - Forest Ecologist, Climate Change Coordinator	See above.
National Level Staff				
Washington Office National Forest Service	February 15th, 2023	Virtual	Lani Chang - Adaptive Management Specialist	Sent for review August 3, 2023, no changes.
Washington Office National Forest Service	June 29th, 2023	Virtual	Sarah Anderson- Ecologist	Sent for review on June 30, 2023, no changes.
Office of Sustainability and Climate	July 19th, 2023	Virtual	Sara Amiot - Forest Monitoring and Climate Change Coordinator and Carbon Team Member Erin Berryman - Analyst and Carbon Team Member	Sent for review on July 19, 2023 to Sara, Erin and Todd Ontl, no changes.

Appendix 2 - Survey Results

[Survey open April - May 2023, received 7 responses from Hoosier, Greens/Finger Lakes, Superior, Chequamegon-Nicolet]

Survey Header

Shifting Seasons on National Forests - R9 Survey

A new partnership between USFS Office of Sustainability and Climate and the USA National Phenology Network launched in fall 2022. As part of this effort we are focusing on R9, seeking to understand the role of phenology in forest planning, monitoring and management.

This survey is designed to help us better understand Forest context and priorities, to inform this effort.

Thank you!

Questions and responses

1. What are some of the main concerns at your Forest, with regard to climate change?

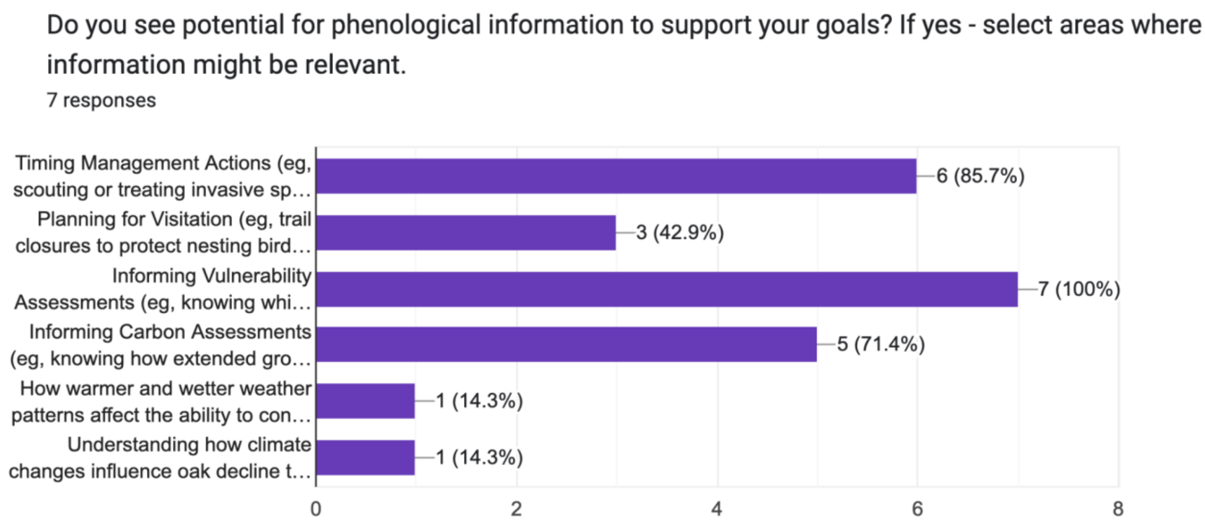
Our Forest Plan is from 2004. Everything we do is tied to that plan. Other national forests such as the Superior have looked at their entire forest through the lens of climate change, whereas mine just within the past year?! formed a small panel of higher ups. We work with NIACS for each big vegetation management project, but I don't think it's enough.

line officer engagement, making climate change a priority, public engagement for changed condition on the landscape

At my own functional level (Botany-Ecology) concerns include changes in insect (pollinator and seed dispersal) and floral/seed phenology (mismatched emergence), lowland conifer community vulnerability, and general rare plant community vulnerability.

Carbon sequestration and storage, timing of monitoring surveys, and forest health.

Our forest is at the southern edge of the boreal forest ecosystem and we're concerned the climate is warming faster than species can keep up. We anticipate the climate becoming too warm for many of our species and for phenological mismatches to occur.



2. What barriers do you see to using phenological information in any of the above applications?

My district alone covers over 400000 acres with limited staff. The actual information itself, I don't see any obvious barriers.

None really pop to mind.

specialists don't have time to consider - rush through NEPA process, lack of relationship between Northern Research Station and decision makers

It's highly variable (unexpected weather extremes)

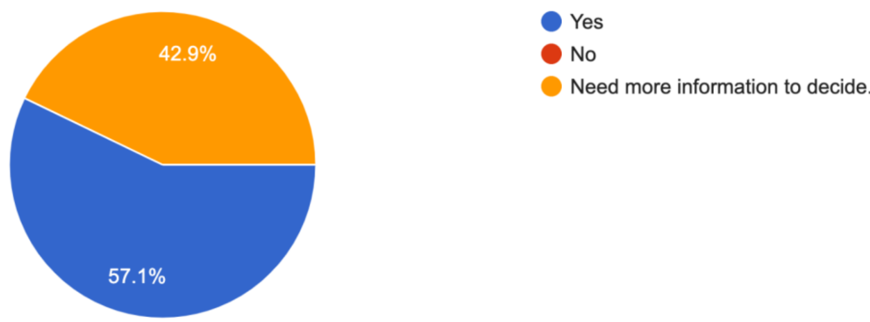
Time. Building a phenological database is time dependent (years) and is something the FS should have started 1-2 decades or more ago. It will take that amount of dedicated time before data gathered becomes statistically informative and valid. But it's never too late to start!

A lack of understanding what type and how much data is available.

Staff capacity to gather and analyze data

Are you interested in further exploring the potential of citizen science to engage visitors and gather needed information?

7 responses



Appendix 3 - Summary of Existing Phenological Information in Vulnerability Assessments

New England and northern New York (Janowiak et al. 2018)	Changes in seasonal patterns/ lengths ● Winter ice cover has decreased by 2 weeks ● Spring flow timing advanced by 1-2 weeks ● Winter weather- war/ Freeze cycles could decrease resilience of early flowering/leafing plants ● Decreasing snowpack could alter timing Changes in bird migration, animal breeding, flowering & Fruiting: ● Green up 10 days earlier at Hubbard Brook ● Earlier flowering by 1 week for most species ● Invasive/ nonnative species respond better to altered climate than native species ● Migrating birds arriving and mating earlier (From "seasonal" search- does not use phenology) Expansion of forest pests northward due to warmer temperatures and longer growing seasons (HWA & SPB mentioned) ● Maple syrup season relying on free/thaw is getting earlier although evidence is not conclusive on whether the season is getting shorter or sap yields are reduced ● Longer and earlier morel season ● Shifts in tourism- shorter winter recreation windows for winter activities ● Shifts in hunting seasons- waterfowl may migrate later in the season because of rising temperatures ● Decreased opportunity for winter fishing but increased for summer fishing
Mid-Atlantic (Butler-Leopold et al. 2018)	Annual phenology altered by climate and physical processes: ● Earlier spring from fewer cold days, ● Delay in leaf senesce due to warmer fall days as well Shifts in flowering, growing season length, changes in wildlife

	emergence and migration: ● Snowshoe hare coats continue to change seasonally even before there is snow on the ground, making them vulnerable to predation ● 10 species of native bees emerging 10 days earlier on average over past 130 years ● Purple martins (songbird) experiencing declines due to changes in food availability arriving earlier but the birds migrating at the same pace
Central Appalachians (Butler-Leopold et al. 2018)	Mentions timing of agricultural events: ● In Central Appalachian regions, however, growing season changes observed have mostly been due to delay of fall onset date, and spring has not shown as strong advancement in the region as compared to the Southeast and New England ● This growing season variation length has been linked to a “warming hole” and also with constantly cold/mild winter temperatures Phenology along with other factors can influence the nutrient cycling within a forest (I.e. changes in growing season length) Shifts in flowering, growing season length, changes in wildlife emergence and migration: ● Bees and purple martins example as in Mid-Atlantic VA ● Also in southwestern Ohio, out of 270 flowering plants, 60% flowering 10-32 days earlier over a 27 year period (1976-2003) ● Changes in phenology may be beneficial to some forests by being harmful to their pests → hatching of spongy moth larvae before budburst of host trees ● Non-native/ invasive plant species may benefit under climate change by responding with flowering times Tourism: ● Increase in visitation rates to escape the heat from cityscapes, or decrease in summer visitation rates if it temperatures reach unsafe heat levels
Urban: Chicago Wilderness Region (Brandt et al. 2017)	Shifts in climate may have effects on timing of: ● Flowering ● Fruiting

	● Leafing-out ● Pollinators
Michigan (Handler et al. 2014)	Physical and climate processes like snowpack and frost can alter phenology ● Sugar maples depend on growing degree days for leaf out, 20 year study across Michigan found that the season was 11.5 days longer on average. Maples in Northern Michigan affected by late season drought and cannot benefit from longer growing season. Native species may not be able to take as much advantage from longer growing seasons (p. 81)
Northern Wisconsin/Western Upper Michigan (Janowiak et al. 2014)	Physical processes driven by climate and weather in turn affect annual phenology Changing phenology observed with a changing climate relating to growing season length, flowering times, and bird migration patterns ● Sugar maple example from Handler et al. 2014 ● About half of migrating bird species to the Upper Peninsula arrived 19 days earlier in 1994 than in 1965 ○ Disproportionately affecting birds that overwinter in southern US versus in South or Central America ○ Range shifts with seasonal residents becoming yearlong and other birds pushing northward ● Phenology of plants not following soil frosts-at a higher risk ○ Increase infiltration (absorption) and therefore nutrient leaching
Northern Wisconsin (Swanston et al. 2011)	Phenological changes observed: ● Earlier spring flowering/leaf-out ● Warming temperature affects other environmental variables (hydrology, soils, nutrients) which then effects phenology, species composition, and range shifts ● Growing seasonal length from changes in plant phenology-especially plants that use temperature as a cue

Appendix 4 - iNaturalist and *Nature's Notebook*

iNaturalist is a citizen science platform that AMC uses to garner phenological data together with *Nature's Notebook*. While *Nature's Notebook* is a plot-based data collection platform, the iNaturalist app allows for significant spatial and temporal diversity and can capture citizen science observations of organisms anywhere at any time. It provides an option for less trained volunteers. Users of iNaturalist take photos of the organism of interest and upload them to the platform. A combination of artificial intelligence and the confirmation or suggestions of other users allows them to then identify the organism. Users can add these observations to various projects on the platform where they can be further curated or analyzed by the project administrators.

Ideally iNaturalist and *Nature's Noteboo*k would be using the same definitions for phenology. AMC does this by adding "fields" to projects to ensure phenophase attribution to iNaturalist pictures align with USA-NPN protocols. Their experience is that to use iNaturalist to collect phenology information it's important to:

- Use iNaturalist's "traditional project" option to collate species of interest in a set region
- Select species that are easy to identify and already being observed by users in iNaturalist
- Select species where the whole plant can be photographed, generally forbs
- Select easy to identify phenophases such as flowering
- Use "fields" in the project to define phenophases aligning with NPN
- Engage general audiences but also staff of organizations that are in the field
- Ensure resources are allocated to continued recruitment of volunteers and curation of data each year

AMC is also using iNaturalist as supplementary data to that collected at USA-NPN plots in the same region, allowing for merging of the crowdsourced flowering data with the more defined NPN plot dataset. iNaturalist is particularly helpful in mountain landscapes such as the White Mountains which have significant spatial diversity and also is difficult to set up permanent plots that can be monitored with the frequency needed.

iNaturalist data are most suited to gathering species distribution information. Phenological information at the population level (as individual plants are not monitored) can be obtained from iNaturalist. However, there are some limitations, for example, even with high quality photos, it is difficult or even impossible to capture certain phenophases using iNaturalist. Sedges have tiny flowering and fruiting structures that won't be seen in most smartphone photos. Additionally, physical touch may be required to assess fruit ripeness which therefore would not be captured in a photo alone. Unlike *Nature's Notebook* there is no absence data (a record of no flowers, prior to a flowering record) thus we have no information on the uncertainty in start or end date of a phenophase. Keeping these limitations in mind, iNaturalist is a powerful tool for getting significant amounts of data at the population level on easy-to-see phenophases, like wildflower blooms.

Appendix 5 - Complementary Data Resources

Certain data resources and existing tools are of particular utility in combination with USA-NPN data and could be leveraged to create or improve management models and tools for national forests (meet their goals). These tools and data resources are detailed below and are intended to illustrate the breadth and depth of available complementary data resources. Please note that this list is by no means exhaustive, and we expect additional data resources to emerge as this work continues.

Data Resource Name	Description/Notes	*Examples (existing or potential application)*
USFS Forest Inventory and Analysis (FIA) Database	Database of plot-level information on US forests collected by USFS staff and partners. Data from FIA feeds into many models and tools including the Climate Change Tree Atlas and invasive species mapping.	By combining FIA data on species composition with USA-NPN data on phenology at the species level, it may be possible to make large scale estimates of growing season start and end, partitioned by species.
USFS Climate Change Tree Atlas	Modeling tool that uses FIA data and future climate projections to predict future suitable habitat and natural migration potential for 125 tree species in the US.	Managers at national forests can use this tool to predict which tree species will be best suited (phenologically and otherwise) for investments in assisted migration efforts at a specific forest unit. Subsequent monitoring of survival and phenology, possibly using NPN *Nature's Notebook*, can inform adaptive management practices in growing future forests.
USFS Climate by Forest	Created by the USFS, this tool provides climate data (past and current) as well as climate forecasts under different warming scenarios for ecoregions of the national	By combining predicted growing degree days with current knowledge on species-specific growing degree day thresholds for various

	forests.	phenological events, researchers could predict changes in future growing seasons in different national forests.
Forest Service Climate Risk Viewer	This tool, still in the beta version, combines 28 datasets to allow resource managers to better visualize which areas will be especially at risk from climate change.	USA-NPN could provide a “damage index” data layer that combines the spring index with areas of hard frosts. When overlaid in the Risk Viewer, this could inform managers which areas may have dealt with recent frost damage.
Seedlot Selection Tool	This tool allows users to match seed sources and planting locations. This tool currently only applies to portions of the western US.	If this tool was expanded to Region 9, managers could combine seed source information with species-specific phenological data. Detailed information about climatic phenological cues in different species could further narrow down which species and seed sources would best match a certain location based on climatic limitations and their ability to phenologically optimize predicted conditions of future growing seasons. Another option: phenological data from common garden or genecological studies could be integrated into the underlying models for this tool to inform climatic transfer limits and further refine outputs.
Climate Adapted Seed Tool	This tool is currently focused on a select number of states in the Western US although there are	See example of potential application above.

	plans for expansion. It is designed to predict where the best seed sources for future climate conditions are at a given location. The tool also provides estimates of CO2 sequestration, board feet produced, and declines in productivity compared to the local seed.	
Climate Smart Restoration Tool	Developed using the same methodology as the Seedlot Selection Tool, this tool allows land managers to find seed sources for restoration efforts. The tool is currently focused on sagebrush and bluebunch wheatgrass in the western US.	See example provided in the Seedlot Selection Tool above.
PhenoCam Network	Network of cameras used to track vegetation phenology. Data from these cameras can be downloaded online.	By combining PhenoCam data and local NPN or iNatualist data, an organization could develop a more spatially refined, species specific understanding of their local phenology. This could inform optimal times to spray for invasives, close trails with vulnerable species, and more.
Ameriflux Network	Network of flux towers that measure carbon dioxide, water, and energy fluxes in various ecosystems across the Americas. Data from these towers can be downloaded online.	This data resource could be merged with local phenology data to better understand growing season lengths at more granular taxonomic levels.
EO Browser	This is a free web application tool that can be used to access, view, and analyze full resolution remote sensed data including DEM, Landsat, and MODIS.	Broad-scale phenological data from NDVI layers on the EO Browser could be combined with *Nature's Notebook* observations in overlapping areas to validate and refine

		growing season estimates.
ForWarn II	This tool, created by The Eastern Forest Environmental Threat Assessment Center (USDA Forest Service) is a satellite data resource that tracks disturbance effects by capturing NDVI data. This data also allows users to track greenness in real time and compare land surface phenology from year to year.	Broad scale changes in yearly phenology observed through ForWarn II could be compared to individual species of interest on *Nature's Notebook* and/or iNaturalist to better understand how these species are tracking changes in spring and fall timing.
Water Supply Stress Index	Housed through the Eastern Forest Environmental Threat Assessment Center (USDA Forest Service), this tool predicts water availability and carbon sequestration under various scenarios spanning through 2100.	By understanding where different areas of the US will be experiencing decreased water availability researchers could predict where future phenology may be delayed due to drought despite warming temperatures that might otherwise indicate extended growing seasons.
Accumulated Winter Season Severity Index	This dataset provides numerical scores for winter severity based on temperature average and extremes, snowfall and snow depth, and duration of winter temperatures. The index allows for objective comparisons of winter severity across space and time in the United States (Boustead et al. 2015).	By combining winter severity data with phenology data from NPN or iNaturalist, researchers could begin to examine the impacts of winter chilling and late frosts.
Fall Foliage Trackers	Currently offered in the US by New England Yankee Magazine, The Foliage Network, and SmokyMountains.com,these maps are images only (precluding analysis) and are real-time as observations are submitted, without a forecast component beyond that year to support planning.	National forests could collaborate with USA-NPN to improve these trackers and turn them into forecasts. These forecasts could then predict timing of tourist visitation peaks for foliage viewing. Collaboration with local new organizations and forecast sites could be a platform for reaching visitors and helping to

		inform visitors on forest conditions. Informational materials containing data about how fall timing is changing could be leveraged to tell the story of climate change to the public.
Mountain Birdwatch	This community science project facilitated by the Vermont Center for Ecosystem Studies is an annual birdwatch that occurs at about 750 locations. Volunteers record and share annual observations of 11 focal species to better understand mountain bird distribution and abundance for conservation and management efforts.	By integrating occurrence and abundance data from Mountain Birdwatch with phenological observations, managers could figure out when to enact trail closures. This data could also inform optimal times and places for birdwatchers to safely observe these species without disrupting sensitive phenophases such as nesting. In addition, phenological data on bird habitats and food resources could be integrated with this dataset to identify potential resource mismatches.
e-Butterfly	Citizen science database where users can upload butterfly occurrence data.	Targeted data from e-butterfly could be combined with local NPN data to identify potential ecological mismatches between butterflies and nectar sources.
iNaturalist	Citizen scientist database for documenting and identifying organisms	iNaturalist has global reach and already contains many observations in Region 9. This tool is already being used by Appalachian Mountain Club scientists to track changes in flowering time in the White Mountain National Forest. The engagement of citizen scientists along with the feasibility of this tool makes it a

		great resource to inform phenological climate response in forests.
New York State Hemlock Initiative (NYSHI)	Project at Cornell University that coordinates various stakeholder efforts in controlling HWA and conserving hemlocks in New York State. Also conducts research and houses community science projects, some of which directly relate to HWA and biocontrol phenology.	The NYSHI has a citizen science initiative using *Nature's Notebook* to collect data on HWA phenology. This information is used to inform timing of biocontrol treatments.
eBird	Based out of the Cornell Lab of Ornithology, this is a database of user bird sightings, recordings, and photos. Allows global scale understandings of bird migrations and populations.	By curating observations of birds in a geographically specific area, a national forest could use this information to predict when to mow safely without disturbing ground nesting birds.
NABat	NABat is a "multiagency, multinational effort" designed to conduct standardized monitoring of bats across North America (Loeb et al. 2015). This informs the abundance and distribution of bats across the continent.	NPN could create Pheno Forecasts for important bat species and overlay them with NABat occurrence data. This information could assist forest managers in timing harvests, burns, and other forest management activities to minimize disturbances to local bat populations.

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