Chapter 27
Phenology in Higher Education

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Abstract Phenological data collection and analysis are well-suited to higher education settings, providing valuable opportunities for hands-on data collection, manipulation, and interpretation. Few subjects are more conducive or accessible for engaging diverse learners in meaningful and impactful science at such large scales and minimal cost. In this chapter, we provide a range of examples of how instructors have incorporated observing and analysis of seasonal phenomena into their curricula. Many of these examples can be readily replicated and folded into new courses.

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27.1 Introduction

Phenology is an ideal topic for integrating into higher education settings, bringing a range of benefits to students as well as to science and society. First, engaging students in collecting phenological reports offers real-world data collection experience, honing observation skills. The act of stepping outside for this activity can offer a welcome respite from the grind of lectures and bookwork. The observations collected, when contributed to established programs, support the growth of these data resources and, ultimately, research undertaken with these data. Additionally, the act of contributing to data and science in such a "real world" way can be inspiring and empowering for students. A high school student tracking plant phenology in Minnesota, USA expressed this sentiment beautifully when he shared, "I realize…there's so much going on that scientists can't do it all on their own, they can't observe every tree. I think it's cool that I, as a student, I can go out and add to that science, it makes me feel like I have at least a little bit of impact." (University of Minnesota 2017). Finally, phenological data and information can be used in a range of ways to support the development of students' inquiry and analysis skills.

In this chapter, we provide examples of phenology-themed college- and university-level educational resources, highlighting commonly used data collection platforms (Budburst, iNaturalist, *Nature's Notebook*, and PhenoCam) and curriculum for classroom exercises that utilize both observational and remotely sensed phenological datasets. Our focus is primarily on North America, though some options are international in their applicability.

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27.2 Phenological Data Collection and Inquiry Using Existing Platforms

In the United States, Budburst, iNaturalist, and *Nature's Notebook* are platforms commonly used for collecting phenological observations. Budburst (budburst.org) is focused on collecting data on plant phenology and plant-animal interactions to answer questions about climate change and human impacts on the environment. Budburst began in 2007 and has been hosted by the Chicago Botanic Garden since 2017. Budburst has two main goals—supporting research and education—and is accessible to participants of all ages and science backgrounds. Since its inception, Budburst has had educational aims at its core and is designed for everyone from young students to adult learners.

iNaturalist (inaturalist.org) is a social platform that encourages people to observe, identify, and share biodiversity information. iNaturalist is an ideal platform for introducing the concept of species identification, biodiversity, and phenology in a classroom setting. While primarily a social media and species identification platform, iNaturalist can also be used to document and track plant and animal phenology. Users can enter observations through two main apps: the iNaturalist platform, where students create an account, or the Seek app offered by iNaturalist, which does not require an account.

Nature's Notebook (naturesnotebook.org), a platform for contributing observations of organismal developmental status over the year, is maintained by the USA National Phenology Network (USA-NPN) (Rosemartin et al. 2014). Offering rigorous observation protocols for over 1800 plant and animal taxa, the platform is used by dozens of higher education venues for documenting phenology as a part of ecology and global change courses. Since the launch of *Nature's Notebook* in 2009, individuals and groups of volunteers have contributed over 35 million observations at more than 20,000 locations across the U.S. These data are frequently used in scientific analyses and to support real-time management decisions (Crimmins et al. 2022).

27.2.1 Weaving Budburst into the Classroom

Since its founding, Budburst has focused primarily on the *Phenology and Climate* project, which focuses on better understanding how plants are being impacted by climate change. More recently, Budburst has expanded to include research focused on plant-animal interactions with the *Pollinators and Climate* project. Budburst has also launched short-term research projects. As an example, the *Nativars* project, which ran from 2018 to 2023, focused on pollinator visitation rates to native versus cultivars of select species of plants.

Budburst hosts Next Generation Science Standard-aligned (www.nextgenscience.org) curriculum and learning activities for students in grades preK-12 as well as higher education. Budburst educational activities are used in classrooms across the U.S. and are freely available on the Budburst website in both English and Spanish. While Budburst is used in classrooms all over the country, the program also operates locally in Chicago, Illinois.

Incorporating Budburst into a curriculum provides students with the opportunity to conduct real, hands-on scientific research. The program is particularly well-suited for students at the college level. Budburst's established research projects and protocols provide guardrails while allowing students and educators the freedom to pursue their own interests and research questions inside an established framework. Additionally, educators and students have access to a database with nearly 330,000 data points spanning 17 years. Students can collect their own data and also use the international Budburst database to investigate patterns at different spatial and temporal scales. For example, within the *Phenology and Climate* project, which has the overarching aim of documenting phenological shifts in plants worldwide, students can compare the phenology of plant species, the same plant species in different geographic locations, or data across years.

The *Nativars* project was a more-focused version of the *Pollinators and Climate* project in which participants tracked pollinator visitation rates to blossoming flowers. In this project, schools, organizations, and individuals who participated set up a formal research garden with native plant species and cultivated varieties of each native (nativars). Each native and its respective nativars were planted in crop rows with replication and clear labels. Undergraduate students at Westchester Community College in Valhalla, New York who participated in this project observed individual plants in the research garden and documented pollinator visitation, noting the type and frequency of pollinator visitation to each bloom.

More recently, in the relaunched local educational program, Budburst began partnering with high schools and colleges in Chicago, IL. One such partner is National Louis University, a Chicago-based private university that increases access to higher education for students from historically excluded groups. National Louis University was interested in incorporating a community science program into their lab-based undergraduate environmental biology courses to provide students with hands-on scientific research opportunities. Students in these courses lack access to laboratory facilities, so the integration of Budburst provided an important opportunity for them to participate in an authentic research program using field-based techniques. Students participated in the *Phenology and Climate* project by identifying three to four plants for weekly phenology monitoring. These observations served as a basis for discussions and lessons around the scientific process, data analysis, and ecology.

27.2.2 Integrating Species Identification, Biodiversity, and Phenology Using iNaturalist

iNaturalist is a versatile platform, and there are several ways that it can be used to teach students about phenology in higher education settings (iNaturalist 2023).

Individual Observations: Students can create individual accounts and utilize iNaturalist to make observations in their area. To collect an observation, students capture a picture of the living organism they encounter. iNaturalist employs machine learning to identify the taxonomy of the organism, which is subsequently verified by other iNaturalist users. Once their observation is submitted and identified to the species level, students can access their account via a web browser to add phenology annotations. Within the web browser interface, students can also generate visualizations of phenological data that were contributed by other observers for the same species. As part of a project, students can explore iNaturalist data to identify species in their area that lack phenological annotations. They can then develop methods for regular visits to these areas to collect iNaturalist observations, add phenological annotations, and thereby expand the dataset. This activity enables students to enhance their species identification skills, document phenological changes throughout the semester, and identify and improve upon datasets with gaps in phenological data. The iNaturalist community forum (forum.inaturalist.org) offers multiple examples for using iNaturalist to explore phenological observations and patterns.

Projects: Instructors can create projects in iNaturalist, allowing students to combine their observations or join existing projects to expand a dataset (inaturalist.org/project). iNaturalist projects are versatile; students can develop a project as a class by identifying questions, formulating hypotheses, and then collecting and analyzing iNaturalist data. Instructors can design projects to last for a day, a semester, or longer, depending on the phenology questions the students are exploring. If students consistently add phenological annotations to their observations, they can compare phenological patterns collected in their classroom with those from different classes or years. Additionally, students can participate in larger, longer-running community projects to investigate patterns in phenological data and observe how their phenology observations align with current and historical trends. Students can use this platform to plan an iNaturalist bio blitz at their institution and invite students in related clubs or departments to participate.

Exploring Phenological Data: If barriers prevent students from collecting their own phenological data, they can use iNaturalist to explore phenological data submitted by other observers. The iNaturalist interface allows students to explore phenological patterns in different biomes, note migration patterns of animal species, and compare the timing of phenological phenomena with cultural celebrations. Students can explore iNaturalist maps, charts, and images to identify patterns in phenology and present these findings to their class.

iNaturalist is a dynamic and invaluable tool for both educators and students alike, facilitating a deeper understanding of biodiversity and phenology. As a global platform for citizen scientists to observe, identify, and share biodiversity information, iNaturalist's seamless integration of social networking and scientific inquiry fosters collaborative learning and community engagement, making it an ideal resource for introducing concepts such as species identification and phenology in educational settings. Whether through the collection of observations, collaborative projects, or the exploration of existing phenological data, students are empowered by iNaturalist to develop critical thinking skills, enhance their understanding of ecological principles, and contribute meaningfully to scientific research and discovery in an applicable and engaging way.

27.2.3 Collecting and Analyzing Data with *Nature's Notebook*

Nature's Notebook is widely adopted to engage students in collecting research-grade phenological observations. For example, the Ecology and Evolution course (BIOS 1620) at Western Michigan University incorporates a 6-week phenology and climate change research project during laboratory sessions, initiated in 2018 using the *Nature's Notebook* platform. To establish a monitoring effort, project leads selected one individual tree each of two oak and four maple species. In addition, leads established bird feeder observation stations at four locations on campus. Since the project launched, these sites have been observed by over 500 students over the course of 5 years as a part of class research projects. The research projects include making weekly observations of tree and bird populations on campus, taking photos, submitting phenological observations to *Nature's Notebook*, analyzing phenological data for patterns and trends, and presenting findings in an oral presentation.

In the BIOS 1620 course project, students work in groups to monitor the arrival of spring via observations of tree and bird phenology. The students use critical thinking skills to develop hypotheses that relate to climate or phenology. Examples of research questions that students developed include: Is there a change in breaking leaf buds over time? Do younger (smaller) trees bud out before older (larger) trees of the same species? Is bird activity related to day length? Do closely related native and non-native trees exhibit different timing of breaking leaf buds? To address these questions, students can combine and analyze class data from current and previous years, with temperature and precipitation data and phenological data available for download from the USA-NPN website.

Lab activities associated with the project include completing the online certified observer course offered by the USA-NPN, using the USA-NPN data visualization tool to look at patterns of phenology over time as it relates to environment, and using the US Forest Service's Climate Change Tree Atlas (Peters et al. 2020) and Climate Change Bird Atlas (Matthews et al. 2014) to predict the effect of climate change on tree and bird species in North America in a spatial context. The lab activities provide students with time and tools to interact with their own data and discover more broadly the connection between environment and ecology. In the exercises, observations of phenology are correlated with environmental factors to test whether the timing of life-cycle events is related to environmental predictors and whether the patterns in these variables change over time. Phenology and climate change research activities in the laboratory are part of the broader curriculum, which focuses on ecology, life history, evolution, and climate change.

Over the years, several important take-aways have emerged:

- Be flexible regarding which species the students observe; don't let this be a barrier to participating.
- Don't quit after a single year. The students feel they are a part of something now. It's not a one-off. Reinforce the importance of citizen science data in science. Show students publications using phenological observations for inspiration!
- Use the models and visualization tools as much as possible. Showing students how their observations help tell a more complete story is very meaningful.
- It is easy for students to think about and visualize the impacts of disturbance or urban settings on animals and plants. It is more difficult to get them to think in terms of climate impacts on life history. Exercises using the USA-NPN create the connections between a non-tangible thing, climate, and ecology, organismal biology, and evolution.

The outcomes of the BIOS 1620 course project are that students better understand the effects of climate on phenology and the connections between citizen science contributions to climate science, ecology, behavior, and evolution. The research experience provides a tangible example of how climate is influencing animal and plant life in their own backyards. In addition, students gain experience synthesizing information and communicating the conclusions drawn from their research to their peers.

27.3 Phenological Data Analysis in the Classroom

Phenological data can provide the basis for a wide range of data exploration, visualization, and analysis activities. Working with phenological data frequently offers very "real world" data experiences, requiring students to contend with incomplete and sometimes messy or conflicting observations. Contending with these challenges prepares them for future analyses with less-than-perfect datasets. In addition, the experience of analyzing and interpreting imperfect data can underscore the importance of both repeated observations and using care when collecting observations.

Phenological data are available from a variety of sources and through tools suitable for a range of skill levels. For example, the USA-NPN's observational data contributed through the *Nature's Notebook* platform can be explored through an online visualization tool (usanpn.org/data/visualizations). They can also be downloaded from an online query-building tool (usanpn.org/data/observational) or via an API, most readily by using the *rnpn* package in R (Rosemartin et al. 2022; R 2023). Daily minimum, maximum, and average temperatures and total precipitation sourced from Daymet (Thornton et al. 2021) are available as optional variables, which enables comparisons among environmental drivers and phenological response. Observations contributed to Budburst are available for download at budburst.org/data and iNaturalist observations can be accessed using an export tool on the project website (inaturalist.org/pages/how+can+i+use+it).

In the following sections, we describe a range of ways that instructors have incorporated phenological data analysis into their courses.

27.3.1 Scaffolding Explorations of Phenological Data

Project EDDIE (Environmental Data-Driven Inquiry & Exploration) Modules are educational resources available on the QUBES (Quantitative Undergraduate Biology Education and Synthesis) Hub (qubeshub.org), an online space for sharing STEM classroom activities and resources. The Climate Drivers of Phenology module (Mohl 2021) includes a series of three scaffolded activities appropriate for undergraduates exploring phenological data from the USA-NPN. Project EDDIE Modules are designed to scaffold the learning of quantitative skills. The first activity in the module asks students to predict how the day of bumble bee emergence has changed over time, and then to test their predictions with a simple graph using at least 9 years of USA-NPN data. Students learn to compare different subsets of the data using the slope, sample size, and R^2 values. They find that trends in the timing of emergence are more evident in some subsets of the data than in the whole dataset. The activities follow Project EDDIE's structure of scaffolding data exploration from making and interpreting simple scatterplots to making complex decisions about data analysis and interpretation to predict which species are likely to be impacted by climate change. The whole module requires about 4 h of class time. The download includes an instructor's manual and presentation slides, student handouts, and datasets for analysis; modification and adaptation are encouraged.

As a pre-assessment and in preparation for the phenology module, students are asked to consider three different questions. They use information found on the USA-NPN website to answer the first question: What is phenology and why do people care about it? Next, they use excerpts from the scientific literature (Pau et al. 2011) and from journalism (Albeck-Ripka and Plumber 2018) to consider: What environmental cues affect the phenology of organisms, and how might interacting species end up with phenological mismatches? Finally, they use their own reasoning to sketch some predictive graphs to answer the question: How would you expect the phenology of emergence to shift with a warming climate and with latitude? From these preliminary activities, students typically come to class with initial ideas that are expanded upon through collaboration, inquiry, and discussion.

Many educational resources about phenology focus on plants; this particular Module was designed specifically with a focus on invertebrates—in this case, bees. Nevertheless, class starts with a puzzle about annual changes in seed set in a spring ephemeral plant, *Corydalis ambigua*, which varies between 10% and 70% across years (Kudo and Cooper 2019). Students are asked to imagine what might cause this variation, and through guided discussion, they learn about the role of bumble bees as pollinators for this plant and the potential for a mismatch in the emergence of the bees and the flowering of the plants to explain such variation. They also learn how to graphically and statistically test for a relationship between a particular environmental cue and emergence phenology, which forms the basis of most of their quantitative work in the modules.

Prior to completing the EDDIE module, students should have an awareness of the diverse life cycles of invertebrates and the influence of temperature on the development of ectotherms. This background knowledge sets the stage for an exploration of the way a warming climate relates to the phenology of bumble bees and invertebrates more generally. The module focuses predominantly on temperature as the driving variable for phenology; however, students also learn that organisms rely on multiple and variable developmental cues such as day length and precipitation.

For the second activity in the EDDIE module, students use a more comprehensive USA-NPN dataset to identify which climate predictors, such as maximum and minimum winter and spring temperatures, best explain bumble bee emergence phenology. First, the class chooses one predictor, and groups explore and present the impacts of making different choices about how to subset the data. Next, the class decides on a particular dataset to study, and they compare latitude, longitude, elevation, and maximum temperature in each of the four seasons as predictors for bumble bee phenology.

Finally, the third activity in the EDDIE module asks students to compare the sensitivity of different species to one of the temperature variables. This might be done to predict whether interacting species will respond to climate change in similar or different ways, or to predict which species are most vulnerable to phenological shifts under climate change. For this activity, students learn to download, clean, and analyze a volunteer-collected phenological dataset.

After completing the EDDIE module, students typically have a lot of uncertainty about their ability to make claims with phenological data. In many cases, limited data are available for species of interest, and they have seen how looking at different subsets of the dataset can change the interpretations they might make. They are, however, much more familiar with the kinds of data and analyses that can be used to make statements about phenology, and they have thought through and tested several predictions. This puts them in a good position to critically read and discuss primary literature about phenology.

Instructors using this module typically follow the module by returning to the *Corydalis ambigua* story, reading, and discussing Kudo and Cooper's (2019) findings that the mismatch between flowering time and the emergence of bumble bees explains a lot of the variation in seed set. Students learn a specific case where bumble bee phenology really does matter, some skepticism about making general conclusions, even from big datasets, and some tools to help them continue to explore data to answer questions about phenology.

27.3.2 Using Phenology to Develop Research Skills

As an alternative to leveraging existing phenology-observing platforms like iNaturalist and *Nature's Notebook*, instructors may choose to establish custom data collection and management tools. Engaging students in tracking autumn phenology at Michigan State University is one such example. This effort was first introduced in 2008 as a low- to no-cost solution for embedding inquiry into an existing life science laboratory curriculum (Long and Wyse 2012). Students were challenged to design methods for documenting autumn phenological change in campus trees, use their methods to collect and analyze data over a whole semester, and then evaluate their methods in terms of data quality.

A strength of the original (2008) approach was its authenticity, since students were not provided protocols, but rather were asked to design original methods and troubleshoot the challenges that resulted from them. Despite significant benefits to students and graduate teaching assistants (Wyse et al. 2014), the approach was not without its challenges and fell short of the goal of building a student-generated long-term database of tree phenology that could be used to support research and instruction. Students' diverse methodological approaches resulted in data structures that varied across student teams, lab sections, and years, and therefore were difficult to align and aggregate.

In 2017, the project was re-envisioned for implementation in a large-enrollment introductory biology lecture course. An explicit aim of the design was to produce a robust and reliable dataset by standardizing data collection methods, training students how to collect data, and intentionally embedding redundant sampling. For the past 8 years, approximately 400 students each year (except 2020, on account of remote-only instruction) have collected phenological observations for the same 150 trees on campus and contributed these data to the Campus Trees Project database (bealbotanicalgarden.msu.edu/campus-arboretum/tree-map). During summer while leaves are still green, each tree in the study is photographed by a member of the project team to establish a baseline photo that provides a visual record of each tree's appearance prior to the onset of autumn senescence. In the first week of class, each student selects two trees from the database for which they will collect data weekly until all leaves have fallen or the semester ends. Each week, students enter data into an online form, including: a photograph of the whole tree, a numeric estimation of percent color change (% non-green color in tree canopy), and a numeric estimation of leaf fall (% leaves lost relative to baseline). Students are trained in class and through YouTube videos to use the data collection form, take high-quality photos (e.g., frame a tree within the camera's whole field of view, take photos during daytime, etc.), and troubleshoot issues they might encounter in the field (e.g., how to deal with tree canopies overlapping buildings or intersecting other trees).

The Campus Trees Project database includes records for at least 15 individuals from each of 10 species. This sampling ensured sufficient representation of tree diversity on campus and adequately captured variation likely to impact phenological

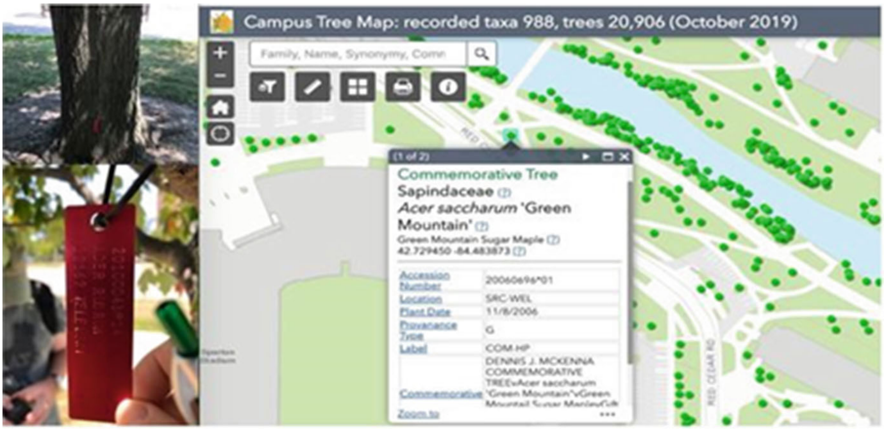

Fig. 27.1 Permanent labels affixed to trees (left) identify trees by genus, species, and accession number. Clicking on a tree (green dot) in the Interactive Tree Map (right) reveals metadata, including taxonomic information, GPS coordinates, accession number, planting date, provenance, and information about the tree's historical significance or role within a collection (e.g., reference specimens or commemorative trees denoting significant events in Michigan State University or world history)

patterns (e.g., tree age, south/north-facing aspects, distances from buildings) both within and across taxa. For example, students can compare phenology across species, between species within genus, and between genera within family.

Staff from Beal Gardens and Campus Arboretum at Michigan State University supported the project by tagging trees in the study with their genus, species, and accession number (Fig. 27.1). Tags promote the integrity of phenological data because few introductory biology students can identify trees to species, and intra-specific variation and the clumping of similar-looking species on campus can make identification difficult. In addition, arboretum staff created a filter for viewing trees in the Campus Trees Project using their Interactive Tree Map (Fig. 27.1), which helps students to locate trees on campus.

At present, approximately 2800 students have contributed data to the Campus Trees Project by making quantitative estimates of phenology and collecting weekly photographs. Engaging students in regular data collection communicates the importance of reliable and repeatable measures in scientific studies and promotes observational skills and connection with one's natural surroundings. In addition, students develop data literacy skills as they work together to generate, visualize, and interpret phenological data and explore patterns across species and years.

27.3.3 Full Semester Focus: Climate Change Ecology Course

Using phenology as a foundation to understand climate change impacts on biodiversity is one of the focuses of the upper- and graduate-level Climate Change

Ecology course taught at Bucknell University in Lewisburg, Pennsylvania. This full semester course is set up as a joint lecture and laboratory, which provides the needed in-class time to explore complex and exciting phenological research projects (e.g., Williams et al. 2021). Lectures include an array of topics, such as climate systems, historic climate change responses, species range shifts, conservation biology, climate policy, climate justice, and phenology, with emphasis placed on the last topic because it is a major component of the students' final project. Active learning exercises (e.g., think-pair-share, case studies, concept mapping, in-class discussions, sketch-noting, climate games, etc.) are used to engage students, help them understand and connect concepts, and provide opportunities for engagement with their peers and instructor.

The laboratory component of the Climate Change Ecology course helps students understand how scientists use and analyze data to investigate climate change impacts. Over the course of the semester, students learn the basics of coding with R, an open-source programming language (R Core Team 2022), including how to estimate basic statistics, model climate data, developing species distribution models, analyze phenological data, and graph and map spatial data. Most of the weekly assignments help students prepare for their two larger assessments. The first of the assignments uses R and GIS mapping to understand species sensitivities to climate change projections. The second, and final, project is a multifaceted approach to assessing phenological shifts over the past century.

The first assignment is centered around understanding and performing species distribution modeling. Students are tasked with selecting a species with sufficient distribution data and creating species distribution models to predict the current and future probability of occurrence of the species using R (R Core Team 2022). Online biodiversity repositories, such as a university's herbarium or herbaria consortium (e.g., Southeast Regional Network of Expertise and Collections (SERNEC): sernecportal.org/portal/) or the Global Biodiversity Information Facility (gbif.org/) are excellent sources for occurrence data. Climate data can be obtained from WorldClim (worldclim.org/). Model predictions are visualized using an ArcGIS Story Map (www.esri.com/en-us/arcgis/products/arcgis-storymaps/) and presented in class. While most students choose plant species such as Japanese flowering cherry, many animals, such as capybara, wildebeest, and alewife have exhibited interesting distributions.

Building on these skillsets, the final project explores the effects of climate on phenology. The project is comprised of four modules: (1) conducting phenological data assessments using a simple linear regression model, (2) preparing an annotated bibliography, (3) writing a research paper, and (4) recording a 10-min science communication video to be presented in class. Laboratory activities include data acquisition, data cleaning, linear regression modeling, graphing, and map making. The biodiversity repositories mentioned previously are used to obtain species occurrence and climate data, with additional attention being paid to gather the phenophase observations (e.g., flowering, fruiting) and collection dates. Students are taught how to empirically choose at least two climatic variables that significantly impact their focal species' phenology through a series of correlation tests. Once the climate variables of interest are selected, students use a simple linear regression model to assess climate change impacts on phenology. As their research projects progress, they attended mini-workshops (during course time) to improve their scientific literacy, citation management, research paper writing, and science communication skills (with attention paid to storyboarding, scripting, and video editing). The semester concludes with a "Climate Change Ecology Movie Premiere" so students can see each other's work on the big screen.

27.4 Using Remote Sensing to Teach Phenology

Measures of seasonal changes, or phenology, documented through remote sensing techniques, including sensors borne by satellites, aircraft, or drones or by fixed cameras, are rich phenological data resources that can be incorporated into classroom settings. Here, we introduce several remotely sensed phenological data resources and provide examples of how instructors are using them in their teaching.

27.4.1 PhenoCam in the Classroom

The PhenoCam Network, established in 2008, tracks vegetation phenology at 700 sites around the globe using automated high-resolution digital imagery across diverse landscapes (Richardson et al. 2018). Most participating sites use the StarDot NetCam, which records images every 30 min from sunrise to sunset. Images are then processed to estimate canopy greenness, at daily resolution. Current PhenoCam research addresses important questions related to global change and ecosystem functioning (Richardson 2023), aligning with the contemporary emphasis on global change in many higher education ecology and environmental science curricula. Phenology and its use as a sensitive indicator of vegetation response to climate change are made more accessible in higher education by the PhenoCam Network's open-access data policy. Here, we provide an overview of the data and software tools available to support the use of PhenoCam in higher education, highlighting a range of different classroom models and demonstrating the potential for using PhenoCam as a tool for developing higher-order cognitive skills.

27.4.1.1 PhenoCam Data Overview

PhenoCam images can be evaluated both qualitatively, through visual inspection, and quantitatively, through image analysis and statistical analysis of data derived from the images. The cameras record three-layer visible-wavelength images containing information about the red, green, and blue (RGB) color channels following the standard RGB three-color model. The intensity (or brightness) of each color channel can be extracted from the image for a user-defined region of interest (ROI), which might correspond to an individual tree crown or a multi-species canopy. From this data, the green chromatic coordinate (GCC), a quantitative measure of canopy greenness, is calculated as:

$$\text{GCC} = \frac{\text{G intensity}}{\text{R intensity} + \text{G intensity} + \text{B intensity}}$$

GCC is probably the most commonly used index derived from PhenoCam data (Richardson et al. 2018). Seasonal patterns in GCC typically align well with the Normalized Difference Vegetation Index, commonly used in satellite remote sensing. Time series of GCC characterize the overall seasonal trajectory of vegetation activity, from dormancy to green-up, and then from senescence back to dormancy. Phenological transition dates corresponding to the start ("greenness rising" date) and end ("greenness falling" date) of the growing season are then extracted from time series data using statistical methods. This data processing is carried out automatically each night on the PhenoCam server (PhenoCam.nau.edu), and those data are publicly available. Fully curated and quality-controlled data sets have also been periodically released and documented in peer-reviewed publications. For example, the first (v1.0) PhenoCam Dataset included an extensive array of color channel and GCC time series, as well as phenological transition dates, for 125 sites and 750 site-years of imagery (Richardson et al. 2018). A revised (v2.0) dataset included 400 sites and 1800 site-years of data (Seyednasrollah et al. 2019). The upcoming v3.0 dataset will include 750 sites and almost 5000 site-years of data. Addressing the need for more user-friendly data formats (some files in the previous datasets have almost 50 data columns), v3.0 will include new "simplified" GCC and transition date datafiles that will be better suited to educational use.

27.4.1.2 Tools to Facilitate PhenoCam Data Access

PhenoCam imagery is available in real time through the PhenoCam website, and provisional (not fully curated) data sets can be downloaded there as well. The PhenoCam Explorer website facilitates browsing and downloading of curated dataset releases (PhenoCam.nau.edu/PhenoCam_explorer/). GCC time series, transition dates, and site metadata can also be accessed through both a web-based API (PhenoCam.nau.edu/api/) and an RStudio (Posit Team 2023) interface (https://github.com/PhenoCam/PhenoCamapi). The *xROI* R package facilitates delineation and extraction of data for custom regions of interest (Seyednasrollah et al. 2019; github.com/bnasr/xROI). Finally, the *phenor* and *PhenoCamr* packages offer a phenology modeling framework that incorporates four phenological observation datasets, including data from the PhenoCam Network (Hufkens et al. 2018; Hufkens 2022; github.com/khufkens/phenor).

27.4.1.3 Example Analysis: Quantifying Ecosystem Greenness

The Ecosystem Ecology course at the University of Lethbridge leverages PhenoCam's real-time monitoring capacity and accessible data to teach students fundamental concepts of phenology. Specifically, PhenoCam datasets are used to assess the seasonality of ecosystem activity, and how it varies in time and across ecosystems, offering practical insights into the network's role in enhancing ecological understanding. Students use PhenoCam imagery and data to investigate differences in seasonality between sites that are superficially similar but differ in terms of species composition or climate regime. Examples include two grasslands with contrasting climate regimes (temperate versus Mediterranean, Fig. 27.2a, b), or two forests with similar climate regimes, but contrasting plant functional types (deciduous broadleaf versus evergreen needleleaf and deciduous needleleaf, Fig. 27.2c, d). This exercise expanded students' understanding of how environmental factors and plant functional types influence seasonal changes in ecosystem phenology, and hence its structure and function. PhenoCam's open-access platform, as well as web page functions that allow users to explore data (e.g., sites on a map browse site imagery or to access pictures recorded on specific dates), makes it easy

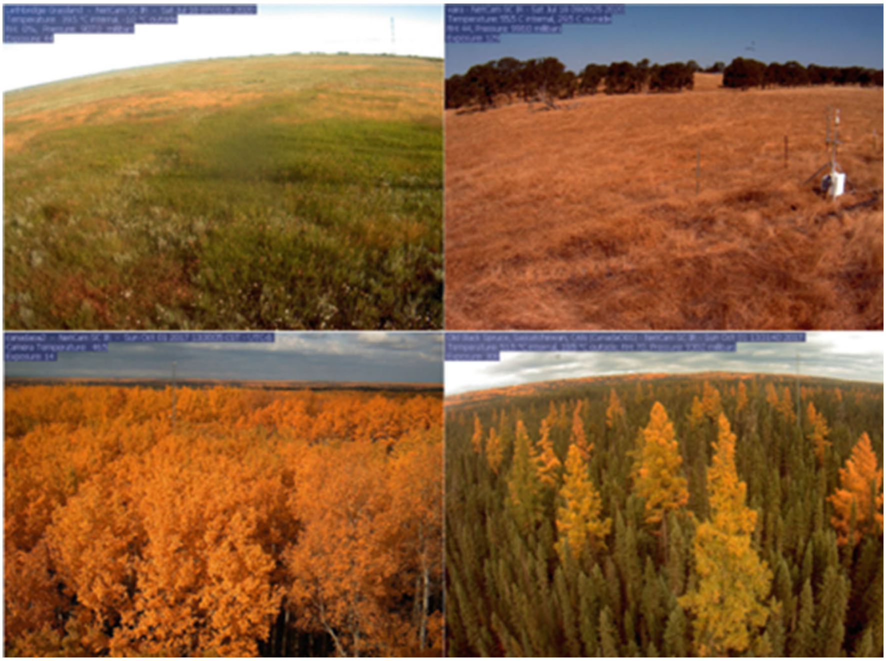

Fig. 27.2 PhenoCam images of ecosystems featured in an Ecosystem Ecology course, comparing grassland sites (top row) on the same day and year and boreal sites (bottom row) on the same day and the same years, providing insights into how phenological patterns vary in space and time

for students to explore patterns of spatiotemporal variation across ecosystems, work with real-world data and hone analytical skills, and advance their scientific literacy.

27.4.1.4 Example Analysis: PhenoCam and Big Data in Ecology

With over 80 million images in the PhenoCam archive, students at the post-secondary level have an opportunity to engage directly with a key example of "big data" in ecology. Students can capitalize on the enormous scientific value of publicly available, long-term datasets, while at the same time learning about the importance of reproducibility and replication, by being introduced to FAIR (findability, accessibility, interoperability, and reusability; Wilkinson et al. 2016) and open data, in support of open science and associated principles (transparent, inclusive, and democratic).

An instructor at Macalester College has utilized PhenoCam datasets at the college-level since 2019 to support these concepts. Key student objectives include analyzing PhenoCam time series data to extract start and end-of-season dates, identifying biotic and abiotic factors influencing growing season length, and overlaying EVI (the Enhanced Vegetation Index) and NDVI from satellite data, as well as tower-based CO_2 flux measurements of net ecosystem exchange, to align with PhenoCam data. Using the *PhenoCamr* package to download data, along with the PhenoCam Explorer interface, enables the methods employed in this course to help students achieve their objectives (Fig. 27.3) without requiring them to write code for data wrangling.

27.4.1.5 Example Analysis: Bioclimatology

The ability to access high-quality, spatially extensive, documented, and user-friendly data distinguishes the utilization of PhenoCam in higher education settings from other phenological data sources. Bioclimatology classes at the University of Wisconsin-Madison and Montana State University drew on these features of PhenoCam in exercises that leverage PhenoCam data to test hypotheses and investigate student-developed research questions about biosphere-atmosphere interactions. Course outcomes focus on simulating approaches (the scientific method) and workflows used by research scientists, thus contributing to career readiness, specifically students' preparedness for a research-based career. Incorporation of PhenoCam into this course setting promotes analytical skills, encourages critical thinking, enhances problem-solving, and facilitates effective communication of the outcomes of the data analysis—all essential components of higher-order cognitive processes.

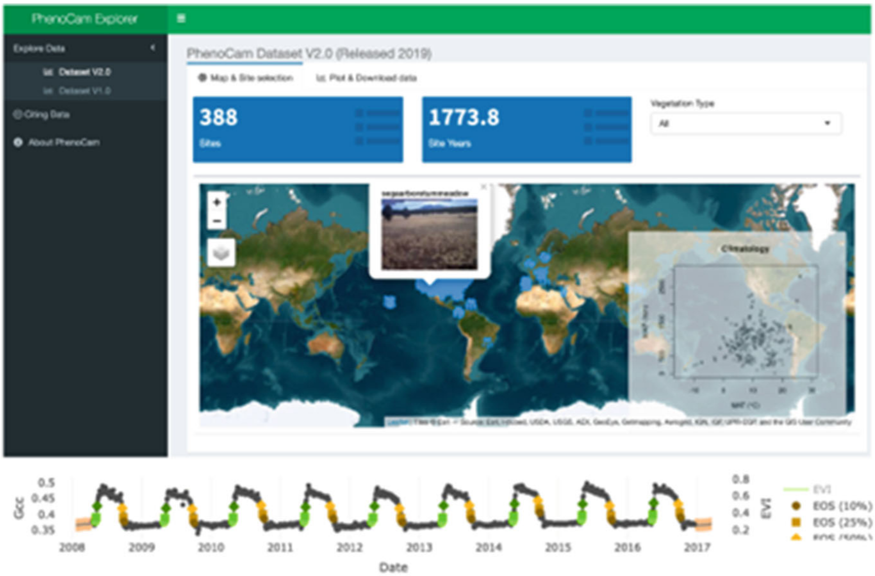

Fig. 27.3 PhenoCam Explorer Interface. This figure displays the PhenoCam Explorer website (PhenoCam.nau.edu/PhenoCam_explorer_prerelease/), offering an interactive interface to browse and download data from sites, including GCC time series, transition dates, and satellite data for each camera's location, including the Enhanced Vegetation Index (EVI) and the Normalized Difference Vegetation Index (NDVI) from the MODIS (MODerate resolution Imaging Spectroradi2meter) platform. The bottom graph shows 9 years of data from the *bartlettir* PhenoCam site, with black dots showing the measured GCC time series, and colored green and orange dots denoting start and end of season dates

27.4.2 Calculating and Comparing Annual Phenological Measures Derived from Satellite Sensors

Land surface phenology (de Beurs and Henebry 2004) is the phenology of vegetated landscapes observed using satellite remote sensing. Satellites capture images across broad swaths of the Earth's surface at regular intervals, allowing growth dynamics to be tracked at regional to global extents. In contrast to the phenology provided by ground-based camera systems, which often more closely match the scale and perspective of human observation, land surface phenology provides a top-down view of the vegetation canopy and an integrated, broad-scale measure of vegetation growth dynamics.

The foundation of land surface phenology consists of vegetation indices, which transform satellite-detected solar radiation reflected from the Earth's surface into metrics that contain ecologically meaningful information about plant presence, density, or health. One common phenology vegetation index is the normalized difference vegetation index (NDVI), which exploits the fact that healthy vegetation strongly reflects near-infrared (NIR) wavelengths and absorbs red wavelengths (Tucker 1979). NDVI is calculated as:

$$NDVI = \frac{NIR - red}{NIR + red}$$

This characteristic difference in reflectance is key for identifying vegetated areas on images taken from orbit. Land surface phenology is retrieved by assembling timeseries of NDVI or other vegetation indices and identifying transitions in the annual signal including the timing of green-up, the date and magnitude of peak growing season, and the beginning of senescence. At the landscape scale, these transitions are linked to terrestrial annual gross primary productivity and net primary productivity (Piao et al. 2007) and are indicators of integrated plant response to global climate change (Cleland et al. 2007).

Satellite-derived land surface phenology complements estimates of phenology provided by ground-based sensors, as demonstrated in the following exercise that compares the phenology of satellite and PhenoCam systems. Students are introduced to satellite imagery as an alternative source of phenological data and gain exposure to processing techniques using software that is either open-source or free for educational purposes.

This exercise guides students through the assembly of land surface phenology curves from Landsat data using Google Earth Engine, a popular analysis platform that features a web-based application programming interface, high-performance computational power, and a massive catalog of geospatial datasets (Gorelick et al. 2017). Third-party software solutions provide specialized analysis and visualization capabilities by integrating Google Earth Engine with statistical and geographic information system packages. This exercise uses two such customized solutions: *rgee* (Aybar et al. 2020), which links Google Earth Engine with R, and *LandsatTS* (Berner et al. 2023), an R package that accesses Google Earth Engine via *rgee* to process Landsat data for phenological analyses.

The exercise culminates with the creation of representative land surface phenology plots for two broadly different biomes. The plots allow students to see how the contrasting vegetation communities, environmental settings, and climatic conditions influence expressions of phenology across the landscape as recorded by Landsat satellites. Students are encouraged to compare and contrast the land surface phenology characterization with ground-based phenology data for sites that host an active PhenoCam (Fig. 27.2) to help answer a set of relevant questions. Because the graphical results are provided in the text, students will be able to participate in the activity even if all steps cannot be completed.

27.4.2.1 Comparison of Annual Phenological Curves

This exercise relies on R, RStudio, Google Earth Engine, and the R packages *rgee* and *LandsatTS* to produce land surface phenology profiles from Landsat timeseries.

Fig. 27.4 Examples of the PhenoCam field of view at (left) Kendall Grassland (Arizona, United States of America) and (right) Lac Clair Forest (Quebec, Canada)

It is adapted from the *LandsatTS* vignette (github.com/logan-berner/LandsatTS). It utilizes PhenoCam datasets for Kendall Grassland in Arizona, United States of America, and Lac Clair Forest in Quebec, Canada (Fig. 27.4). Additional R packages used for the assignment are *tidyverse* for data manipulation (Wickham et al. 2019), *sf* for handling spatial vector data (Pebesma 2018), and *data.table* for table functions (Barrett et al. 2024).

Important Prior to running this exercise, the following steps must be completed.

1. Obtain a Google Earth Engine account by registering at signup.earthengine.google.com with an existing Gmail or academic email account (.edu). Approval usually happens within 1–2 days.
2. Download and install R (r-project.org/).
3. Download and install RStudio (posit.co/downloads/).
4. Install *rgee* (github.com/r-spatial/rgee) and *LandsatTS* (github.com/logan-berner/LandsatTS) as packages in R.

1. Prepare the R environment

In RStudio, load the necessary processing packages.

```
library(sf)   # allows operations with point locations
library(tidyverse) # provides data manipulation tools
library(data.table) # provides table functions
```

Load and initialize rgee. Replace the email address shown here with one associated with a Google Drive and Google Earth Engine account.

```
library(rgee)
ee_Initialize(user = 'user@account.edu', drive = TRUE)
```

Load the *LandsatTS* package.

```
library(LandsatTS)
```

2. Define the points of interest over which to extract Landsat data

Create a feature geometry list using the latitude/longitude of Kendall Grassland and Lac Clair Forest.

```
points_sf <- st_sfc(sf::st_point(c(-109.9419, 31.7365)),
                    st_point(c(-71.6696, 46.9521)),
                    crs = 4326) %>%
st_sf() %>%
mutate(sample_id = c("Kendall Grassland",
                   "Lac Clair Forest"),
       region = c("Arizona", "Quebec"))
```

3. Process timeseries of Landsat data in Google Earth Engine

The following command directs Google Earth Engine to extract Landsat surface reflectance data over the points of interest for the specified time period. The resulting data are saved to the Google Drive associated with the user's Google Earth Engine account. If default settings are used (below), the output will be found in the top level of the Google Drive in the 'LandsatTS_export' folder ('My Drive > LandsatTS_export') with a file prefix of 'timeseries_'.

```
task_list <- lsat_export_ts(points_sf,
             start_date = '2004-01-01',
             end_date = '2023-12-31',
             start_doy = 1,
             end_doy = 365,
             drive_export_dir = 'LandsatTS_export',
             file_prefix = 'timeseries_')
```

4. Download Google Earth Engine file to the local system

The ee_drive_to_local command automatically downloads the resulting Google Earth Engine file from Google Drive to a temporary folder on the local system. Alternatively, the user can also open the Google Earth Engine folder associated with their account and manually complete the download. *Running this step before Google Earth Engine has finished processing and exporting the file will trigger an error; wait a minute or two before proceeding.*

```
temp_files <- map(task_list, ee_drive_to_local)
```

5. Compile and format the downloaded file

Compile all downloaded Landsat data files into a single file for subsequent analysis. Format the file by scaling band values, changing column names, and removing extraneous columns.

```
lsat.dt <- do.call("rbind", lapply(temp_files, fread))
lsat.dt <- lsat_format_data(lsat.dt)
```

6. Filter Landsat data to clear-sky acquisitions

Remove images with poor viewing geometry, high cloud cover, or snow cover, all of which can prevent the retrieval of high-quality data.

```
lsat.dt <- lsat_clean_data(lsat.dt,
                    geom.max = 15,
                    cloud.max = 80,
                    sza.max = 60,
                    filter.cfmask.snow = T)
```

7. Compute the vegetation index

Here we use the Normalized Difference Vegetation Index (NDVI), which is a measure of the photosynthetic capacity of green vegetation.

```
lsat.dt <- lsat_calc_spectral_index(lsat.dt, si='ndvi')
```

8. Display the land surface phenology at each site

This function iteratively fits curves to the extracted data to generate the typical phenology at each site and then plots the results (Fig. 27.5).

```
lsat.pheno.dt <- lsat_fit_phenological_curves(lsat.dt,
                 si = 'ndvi',
                      window.yrs = 7,
                      window.min.obs = 11,
                      si.min = 0,
                      spar = 0.6,
                      spl.fit.outfile = F,
                      progress = F)
```

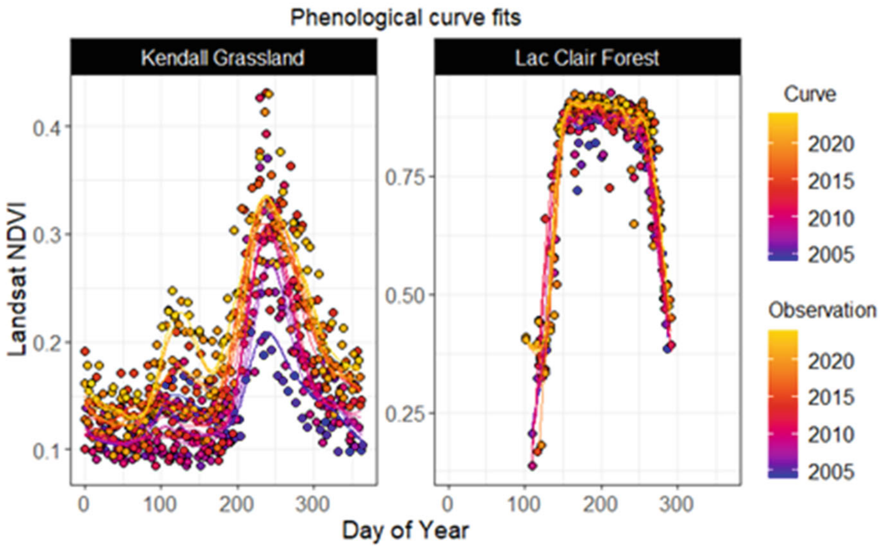

Fig. 27.5 Plots of the phenological curves for (left) Kendall Grassland and (right) Lac Clair Forest obtained from timeseries of Landsat surface reflectance data

9. Interpret the different phenology curves

After producing plots, students can discuss how and why the phenological profiles differ between the two sites. How do site characteristics–grasses versus deciduous vegetation; desert versus high-latitude climate regimes, including temperature, growing season length, and the timing and amount of rainfall; potential heterogeneity of vegetation species at each site–determine the individual expressions of plant growth across these landscapes? Students can compare and contrast these profiles as well as those derived from two PhenoCams. In what ways do the ground-based PhenoCam curves differ from the satellite ones? How does the landscape view of the satellites complement the more detailed perspective that the PhenoCams provide?

27.5 Phenological Data Fusion

Integrating ground-based observations, PhenoCam datasets, and satellite data offers students an opportunity to investigate phenology across multiple spatiotemporal scales (Richardson 2018; Morisette et al. 2021). Ground-based observations are often limited in their spatial coverage. Conversely, satellite data provide broad spatial coverage but lack the fine temporal resolution needed for detailed phenological assessments. The continuous temporal coverage provided by PhenoCam serves as a link across spatial scales, providing continuous temporal coverage of phenological change at organism-to-ecosystem levels (Klosterman et al. 2014). Integrating the various forms of information can offer a comprehensive approach, providing useful context for interpreting quantitative data as well as spatial patterns. This integrative approach can both enhance students' analytical skills and provide a complete perspective on the challenges and advantages associated with different observational methods.

27.5.1 Constructing and Testing Phenological Models

An assignment developed for an Ecological Systems Modeling course taught at Oregon State University in 2023 and 2024 provides an example of how multiple forms of phenological data can be integrated, visualized, and analyzed. The assignment incorporates in-situ phenological observations and gridded predictions of growing degree days (GDDs) and phenophases to address the following learning outcomes: (1) describe and implement the steps in developing, implementing, and validating an ecological systems model; (2) visualize and critically evaluate model predictions and potential sources of model error; and (3) describe how models may be applied towards understanding and solving real-world ecological problems. The version of the assignment described here can be found in Zenodo (zenodo.org/10632478).

The phenology model assignment consists of an R Markdown file that students complete within RStudio, which provides an interactive environment for writing and running R code (Gandrud 2015). R Markdown integrates descriptive text with R-code chunks into a reproducible workflow, which may facilitate student learning because instructions, results, plots, and answers to questions are contained within a single document (Baumer et al. 2014; Allaire et al. 2020). R packages used for the assignment included *rnpn* for accessing data from the USA National Phenology Network's API (Rosemartin et al. 2022), *terra* for working with raster data (Hijmans et al. 2023), *sf* for working with spatial features (Pebesma 2018), *dplyr* for data wrangling (Wickham et al. 2022), *ggplot2* for creating maps (Wickham 2016), and *equivalence* and *caret* for model validation (Kuhn 2008; Robinson 2016).

In the assignment, students visualize and statistically compare model-predicted and observed dates of phenophases of common lilac (*Syringa vulgaris*), a widely cultivated deciduous shrub, and of bagworm (*Thyridopteryx ephemeraeformis*), an insect pest that defoliates over 50 families of trees and shrubs in the eastern U.S. Model predictions were obtained from the USA National Phenology Network's map products (usanpn.org/data/maps), which include forecasts of annual growing degree-day (GDD) accumulations and the timing of important phenological events in insects and invasive plants across the contiguous U.S. (Crimmins et al. 2017, 2020). In-situ observations of lilac and bagworm phenophases from the U.S. are downloaded from the USA National Phenology Network's API using the *rnpn* package.

In the first exercise, students visualize and statistically evaluate the concordance between predicted vs. observed dates of lilac leaf-out (production of new leaves) for

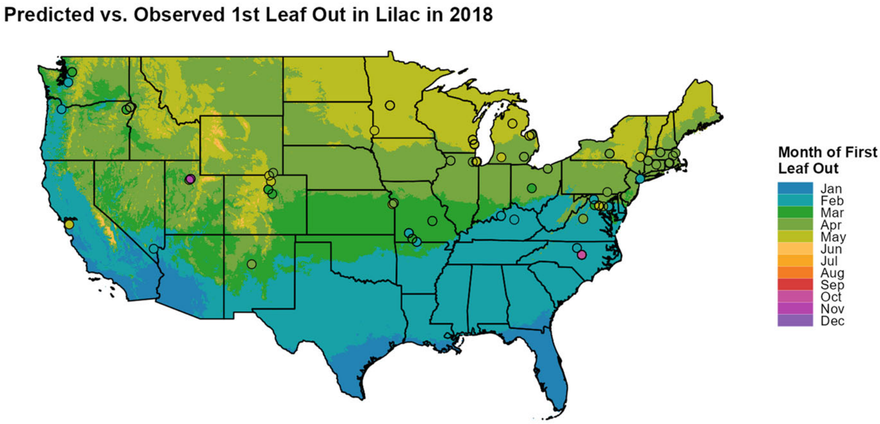

Fig. 27.6 A USA National Phenology Network map of model-predicted dates (underlying map) vs. observed dates (circles) of leaf out for common lilac in the contiguous U.S. for 2018. Predicted and observed dates were categorized into weeks and used the same color scheme to help students make cross-comparisons

the contiguous U.S. for 2018 (Fig. 27.6). They learn about potential drivers of geographic variation in predicted leaf-out dates, identify areas where predicted leaf-out dates were discordant with observed dates at 76 sites, and describe potential reasons for model discordance. For example, two observed leaf-out dates in Utah and North Carolina are much later than predicted dates, which could potentially be explained by observer error. Next, students conduct an equivalence test to evaluate whether predicted and observed dates (day of year) of leaf-out are statistically equivalent, which reveals evidence for model under-prediction. They discuss how the lilac phenological model might be adjusted to reduce model bias, such as calibrating the lower developmental threshold.

In the second exercise, students validate predictions of the appearance of bagworm caterpillars for 2022 using forecasts of annual growing GDD accumulations and 263 bagworm observations. Using a "for loop" in R, they calculate how many GDDs accumulate between March 1 and the date of bagworm observations for each site, and then use a Boolean integer (1 = yes, 0 = no) to indicate whether this value falls between 600 and 900 GDDs, the range of GDDs when bagworm is a caterpillar. Next, students calculate a confusion matrix to evaluate overall predictive performance and whether the model over- or under-predicts the appearance of bagworm caterpillars.

Students interpret confusion matrix results and discuss their implications for bagworm management. Effective control of bagworm depends on applying insecticide treatments to small caterpillars because chemicals become less effective as caterpillars increase in size. Model over-prediction, wherein caterpillars are predicted later than they were observed in the field, is more problematic than model under-prediction because decision-makers may miss the best opportunity to treat populations. Students find evidence of model under-predictions, meaning that caterpillars are predicted earlier than they were observed in the field in 2022. They brainstorm reasons to explain this finding, such as observers failing to notice and report very small caterpillars.

Ten questions are interspersed throughout the assignment to assess student learning outcomes and to practice their R coding skills. After completing questions, student “knit” the R Markdown file into an HTML file and a Microsoft Word document. The assignment will likely take students 1–1.5 h to complete, however, undergraduates may need more time than graduate students because they are less likely to have experience with using R and working with ecological data. One potential solution to this problem is to make questions that require writing R code optional (e.g., for extra credit) for undergraduates.

In summary, the phenological modeling assignment provides students with hands-on experience in visualizing and critically evaluating phenological model predictions and potential sources of error. Additionally, students learn some practical applications of phenological models, including their use in decision-support systems for integrated pest management.

27.6 Conclusions

Phenology is an ideal measure for engaging students in real-world data collection and analysis. Few subjects are more conducive or accessible for engaging diverse learners in meaningful and impactful science at such large scales and minimal cost. Examples of how instructors at higher education institutions have incorporated phenology into their courses abound. Our aim is that the examples shared here might inspire further adoption of phenological data collection and analysis.

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