

The Phenology Handbook

A guide to phenological monitoring for students, teachers, families, and nature enthusiasts



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Acknowledgments

Since the Spring of 2007 it has been our great pleasure to work with a wide variety of students, educators, scientists, and nature enthusiasts while developing the Phenology Stewardship Program at the University of California, Santa Barbara. We would like to express our gratitude to those who have contributed (and who are currently contributing) time and energy for field observations, classroom implementation, and community outreach. We thank the Phenology Stewards (UCSB undergraduates) who have helped to collect plant and avian phenological data at UCSB's Coal Oil Point Natural Reserve and to develop the methodologies and protocols that are presented in this handbook. Special thanks to the Phenology Stewardship graphic design team who helped develop this handbook, including Christopher Cosner, Karoleen Decastro, Vanessa Zucker, and Megan van den Bergh (illustrator).

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This Phenology Handbook is a work in progress, and will be updated continually through the spring and summer of 2008. We plan to increase the scope of the handbook by including and enhancing chapters that address the following topics:

- methods for using the herbarium to study historical phenology;
- a field guide to Coal Oil Point Natural Reserve, including species descriptions that work in coordination with the Phenophase Quick-Guide (see pages 38 - 40); and
- a phenology activity guide for teachers and students.

Updated versions of the Phenology Handbook will be posted on the UCSB Phenology Stewardship Program website, which is currently located at: <http://www.ucsbphenology.christophercosner.com>

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WHAT IS PHENOLOGY?

***P**HENOLOGY IS THE OBSERVATION AND MEASUREMENT OF EVENTS IN TIME*

The passing of the seasons is one of the most familiar phenomena on Earth. Consider, for example, the onset of spring in temperate climates. As winter ends, our surroundings burst with new life — forest canopies fill with vibrant greens, flocks of birds migrate in formation to northern breeding grounds, and brilliant wildflowers and their insect pollinators appear in rapid succession across hillsides, roadsides, lake margins, and fields. Similarly, as autumn approaches, the deciduous forest canopy progresses towards a colorful demise, birds navigate their return to southern wintering grounds, and many plants ripen their last fruits before the onset of winter.

Whether we live in urban or rural environments, there are constant reminders of the changing of the seasons. For example, many of us notice when the first wildflowers appear in the spring, when our favorite fruits are available in the local farmers' markets or supermarket, when trees change color or lose their leaves in the fall, when wildfire risk is highest due to the drying of our forests' fuels, or when frost first appears in the fall or winter. By studying the seasons in greater detail over the course of our lives, we can deepen our connection with, and understanding of, the landscapes we inhabit. We also develop our ability to observe and to measure the pace and the timing of the seasons, the onset and duration of which are beginning to shift with the changing climate.

Scientists refer to the study of the timing of seasonal biological activities as **phenology**. This term was first introduced in 1853 by the Belgian botanist Charles Morren and is derived from the Greek words *phaino*, meaning "to appear, to come into view" and *logos*, meaning "to study." Phenology is the science that measures the timing of life cycle events for plants, animals, and microbes, and detects how the environment influences the timing of those events. In the case of flowering plants, these life cycle events, or **phenophases**, include leaf budburst, first flower, last flower, first ripe fruit, and leaf shedding, among others. Phenophases commonly observed in animals include molting, mating, egg-laying or birthing, fledging, emergence from hibernation, and migration. Thus, **phenologists** record the dates that these events occur, and they study how environmental conditions such as temperature and precipitation affect their timing.

While the term **seasonality** is used to describe changes in the abiotic environment, such as the dates of the first and last frosts of the winter, or the date that ice melts in lakes or streams, the term **phenology** is reserved for describing the timing of biological activities.

The timing of phenological events can be quite sensitive to environmental conditions. For example, in a particularly warm and dry spring, leaf budburst and first flower might occur weeks earlier than usual, whereas in an exceptionally cool and wet spring they could be equally delayed. As a result, the timing of phenophases tends to vary among years based on patterns of weather, climate and resource availability. Phenological observations are therefore *integrative* measures of the condition of the physical, chemical, and biological environment. This environmental sensitivity means that phenological studies are simple and cost-effective ways to measure environmental changes, including climate change, over the long-term.

Weather is defined as the near-term atmospheric conditions of a region, such as temperature, precipitation, humidity, wind, and sunshine. The **climate** of a region, on the other hand, is characterized by the generally-prevailing weather conditions. For example, Santa Barbara, California is characterized by a Mediterranean climate – warm, dry summers and cool, moist winters. There are, however, daily and weekly changes in the weather that can rapidly change the temperature, sunshine, and wind conditions.

PHENOLOGICAL VARIATION

The timing and duration of phenophases within and among individuals, populations, and communities

Phenology is a science for all seasons, locations, and species. From the leafing, flowering, and fruiting times of plants to the molting, mating, and migration times of the animals they support, the phenological progression of an individual, a population, or an entire species may occur rapidly or slowly, and synchronously or asynchronously with other organisms. How, then, can we measure and compare phenological patterns for a wide variety of organisms that exhibit different phenophases and at different time scales? The answer lies in the scale of our observations and in the ways that we record and describe them.

Phenology, like all environmental sciences, uses quantitative methods to measure and to describe the occurrence of events and patterns in the natural world. Phenologists are interested in the dates that phenophases occur as well as in the pace of transitions between phenophases, and these observations can take place at multiple biological and geographical scales. For example, a phenologist can record the dates that a plant opens its first and last flowers (from which the duration of flowering can be calculated), as well as the number of flowers that are open each day or week during the flowering period. This can be done for one or many individuals of the same species in one population, for multiple populations of a species that occupies different habitats or locations, and for multiple populations of different species that coexist in one habitat.

Levels Of Biological Organization

The biological world can be observed at a variety of “scales” — ranging from long-distance observations to close-up and detailed views. Each scale generally requires a different set of tools, from satellites to magnifying glasses to microscopes. Phenology is one of the few sciences that routinely measure patterns at many of these scales. The levels of biological observation that are most important to the global and local study of phenology are shown below.

Biome

A group of co-occurring plant, animal, and microbial communities that live in the same type of climate, share a well-defined geographic area, are adapted to a particular substrate and level of nutrient cycling, and exhibit a recognizable set of dominant life forms and habitats.

Community

A group of co-occurring populations of different species, each of which interacts with some proportion of the other species.

Population

A collection of individuals of one species inhabiting the same general area or sharing a common environment.

Organism (Individual)

One member of a population or species that may or may not depend on other members of its population in order to survive.

*Remote sensing technologies allow for the detection of **geographically extensive** phenological patterns*

*Observational studies performed by on-the-ground phenologists provide **site intensive** documentation of phenological patterns*

Phenology Across Levels Of Biological Organization

Individual: An individual is one member of a population or species that may or may not depend on other members of its population to survive. Individuals of the same species within a community belong to the same “population”, and may exhibit great variation in the timing of their phenophases. The particular phenological pattern that an individual exhibits (e.g., the date of germination; the onset and duration of flowering; the average number of flowers open per day during the flowering season; and the time of seed dispersal) is usually due to both genetic and environmental influences.

The timing of an individual’s phenophases can have a profound effect on its reproductive success, as it is likely to determine whether: it survives to flower; flowers are pollinated; seeds are produced, ripened, and successfully dispersed; and whether most seeds will germinate and produce seedlings that survive to adulthood. Consequently, the timing of phenophases in plants – as in other animals – is subject to evolution by natural selection. If the climate changes gradually, and if populations contain enough genetic variation in phenological traits such as the date of first flower, they will be able to adapt as natural selection favors those phenophases that perform well under the new environmental conditions. Evolutionary biologists are concerned, however, that if climate change progresses too rapidly, many populations will not be able to adapt because they will not contain any genetic variants that perform well under the new conditions.

Population: A collection of individuals of one species inhabiting the same general area or sharing a common environment. The phenological patterns of individuals in a population are important because they determine: whether individuals are available for mating with each other; whether individuals compete for resources such as moisture in the soil or food; which individuals are exposed to (or escape from) flower- and seed-eating predators; and whether individuals can cooperate to deter herbivores or predators.

Species: Species is a collective term that usually refers either to one or to all of the populations of a given species. Populations of a given species may be large or small, closely spaced or highly isolated, and composed of individuals that occur in clumped, uniform, or random distributions. Where multiple populations of a given species are phenologically synchronized and not too far away from each other, the potential for migration and mating between populations is much higher than when they are phenologically mismatched. The exchange of individuals among populations can be very important, as it is one mechanism that can help to maintain genetic diversity within them.

Community: A community is a group of co-occurring populations of different species, each of which interacts with some proportion of the other species in the community. Some of the interactions are positive, in which both species benefit (examples include pollination and seed dispersal). Other interactions benefit one species but harm the other(s), including predator-prey interactions, host-parasite relationships, and harmful microbial infections of plants and animals. The phenology of interacting species is crucial to their survival, as the survival of interacting members will be strongly influenced by whether their phenophases overlap. For example, if a pollinator emerges from winter dormancy and its nectar sources aren’t flowering yet, both the pollinator and the plant on which it depends will suffer. The pollinator will have no food source, and the plant will not produce seeds.

Biome: A biome is a group of co-occurring plant, animal, and microbial communities that live in the same type of climate, share a well-defined geographic area, are adapted to a particular substrate and level of nutrient cycling, and exhibit a recognizable set of dominant life forms and habits. Examples include: deciduous forests, woodlands, coastal dunes, shrublands, tropical forests, boreal (subarctic) forests, mangroves, grasslands, and deserts.

As you can see, phenology can be described and measured at multiple levels of biological and geographical organization. Information from each of these levels provides fundamental knowledge about patterns and processes in nature. Phenological studies can inform us about the timing and duration of resource availability in ecological communities, including: when pollen and nectar are available to pollinators; when fruits are available to fruit-eating animals (including humans!); when leaves are available for herbivorous insects and mammals; and whether plants must compete with each other for the services of pollinators and seed dispersers. Phenological studies can help to inform agricultural planning, disease and pest control, and eco-tourism industries, as well as the anticipation of allergy seasons. They can also describe how populations, species, communities, and biomes are responding to changes in the regional and global climate. In short, phenological studies measure the pace of nature's clock, and in doing so can detect the changing pulse of the planet.

The first goal of this section is to demonstrate how variation in phenological patterns can be described and measured at multiple levels, including:

- within and among individuals;
- within and among populations;
- within a community of coexisting species; and
- across large geographic regions such as states, continents, hemispheres, and even the entire planet

The second goal is to help you understand how the phenological progression of an individual, population, or community can influence its ability to survive and to reproduce.

This background in phenological variation will help you to develop a framework for understanding the variation that you observe in your backyard, school yard, or natural area. It will also provide you with some terminology that will allow you more easily to communicate your observations with other phenologists. Although we use flowering phenology as our primary example, keep in mind that the principles presented in this section can easily be applied to other organisms that may or may not exhibit similar phenophases (e.g., birthing times of mammals, migration and egg-laying times of birds, spawning times of fish, and pollen producing times of non-flowering plants like Pine trees).

Phenological variation within and among individuals - flowering curves

Scientists have described over 250,000 species of flowering plants in the world. Although some species flower irregularly or continuously (mostly in tropical biomes where environmental conditions are more or less constant), most flowering plants in the temperate zone exhibit conspicuous flowering phenophases that start and stop at predictable times of the year. The timing of these phenophases, and especially the pace of flowering, is highly variable among individuals, populations, and species. While some species (or individuals or populations) produce only a few flowers over a short period of time, others produce many flowers over the course of months. These patterns can be captured by graphs of **flowering curves**, from which it is easy to visualize the dates of key phenophases and to make comparisons among individuals (**Figure 1**).

Notice in Figure 1 that the date of first flower is April 15, the date of peak flowering is May 6, and the date of last flower (defined as the date when the last flower opens) is June 10. This means that the duration of flowering was 8 weeks (or 56 days). If floral display surveys were conducted for more California Poppy individuals in the same population, the resulting flowering curves would reveal variation in flowering phenology (**Figure 2**).

Figure 2 shows three hypothetical flowering curves, each curve representing a different individual of California Poppy. First, notice the variation among the three individuals for the dates of first flower, peak flowering, and

last flower. The shapes of the three flowering curves also differ– the blue curve is the same shape as the black curve but shifted two weeks later, whereas the red curve exhibits a different shape altogether. Also notice that even though the red curve differs in shape from the black curve, the date of peak flowering is the same. Lastly, notice that the duration of flowering is shortest for the individual represented by the black curve and longest for the individual represented by the red curve. Overall, the flowering curves of these three individuals overlap, which means that these individuals might compete for pollination service. Alternatively, the simultaneous flowering of these plants might help to attract pollinators, as they will present a more conspicuous display of flowers and provide more nectar than an individual plant. The overlap in flowering times also means that pollinators could be transferring pollen among these plants.

If a phenologist's goal is to quantify and to summarize the phenological behavior of a population (such is often the case), a single graph that contains thirty or more flowering curves would be a bit overwhelming. Instead, the mean and variance of a phenophase of a population can be expressed in a different type of graph. In **Figure 3**, the mean date of first flower is April 8 for 30 individuals of the same California Poppy population in Santa Barbara. The error bars represent the variation among individuals within the population for date of first flower; there is a moderate amount of variation in this population (more about this shortly). If the pace and duration of flowering are tracked for each of these 30 individuals, the same graph could easily be constructed for other phenophases such as peak flowering and last flower.

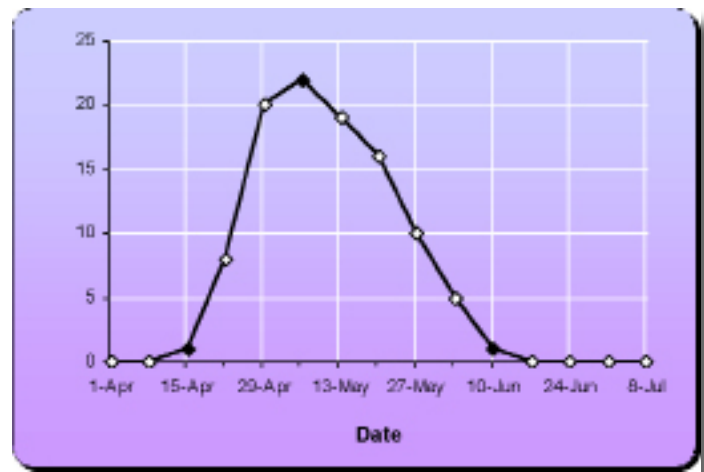


Figure 1. Flowering curve for one California Poppy individual that is located at Coal Oil Point Natural Reserve in Santa Barbara, CA. The dates of first flower, peak flowering, and last flower are marked by closed symbols. The y-axis should be labeled as “number of open flowers”.

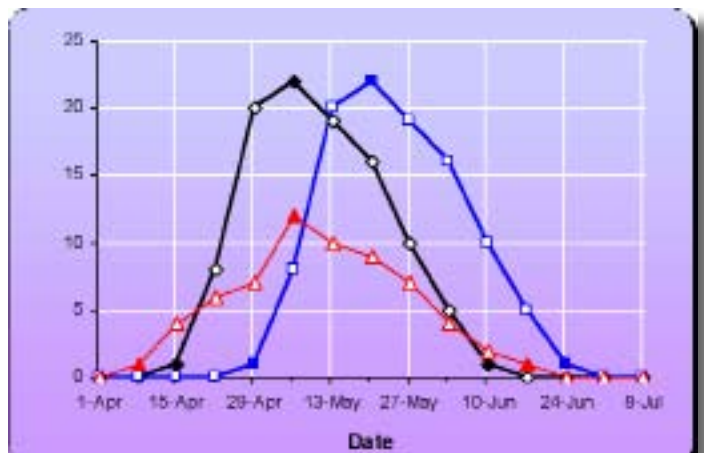


Figure 2. Flowering curves of three California Poppy individuals that are located at Coal Oil Point Natural Reserve in Santa Barbara, CA. Dates of first flower, peak flowering, and last flower are marked by closed symbols for each individual (the black curve is the same as in Figure 1). The y-axis should be labeled as “number of open flowers”.

Phenological variation within a population – what does it mean?

The variation in flowering phenology among individuals in this population of California Poppy could be due to different sources, including:

- *environmental factors* – the timing of an organism's phenophases can change dramatically as a direct response to environmental conditions such as temperature or the microhabitat in which each individual plant lives (e.g., in the shade of another plant vs. direct sunlight, in a sandy soil vs. a clay soil, highly exposed to cold winds vs. protected from them);
- *genetic factors* – the genetic composition of each individual (the flowering curves of siblings or other closely related individuals will tend to be more similar than the flowering curves of more distantly related individuals); or
- *a combination of environmental and genetic factors.*

While more detailed observations and experiments could reveal the relative importance of each of these *sources of variation* in shaping flowering patterns, we can also think of the *consequences of variation* in flowering patterns.

Patterns of mating and reproductive success in flowering plants – and therefore the long-term sustainability of a population – are largely dependent on the timing of flowering. For example, individuals that initiate flowering before pollinators are active in the spring are likely to suffer low reproductive success due to a lack of pollen transfer. Similarly, if the beginning and the end of the flowering season are characterized by only a few individuals that are flowering, the availability of pollen during these periods may be relatively low, even if pollinators are abundant. If individual plants cannot attract pollinators when population sizes are low (e.g., at the beginning and end of the flowering season), natural selection will favor individuals that flower synchronously (e.g., at the time of a population's peak flowering). In addition, during times of the season when only a few individuals are flowering, the probability of mating between close relatives increases, and this can reduce the genetic quality of the seeds produced.

On the other hand, if so many individuals of the same species flower at the same time that they compete for pollinators, then many of their flowers are likely to remain unpollinated. In this case, individuals that flower slightly “out of synch” (earlier or later) with the majority of their local population may benefit (have higher pollination success) because there is less competition for pollinators. In sum, variation in flowering patterns among individuals within populations will affect their visitation by both pollinators and seed dispersers, and this will affect the way that natural selection acts to favor particular phenophases.

Many plant biologists refer to plants as “phytometers” because their development and reproduction can provide excellent integrative information about ambient conditions.

Phenological variation among populations

Building upon this understanding of phenological variation within populations, we can continue to scale up our observations to compare phenological variation among populations. Let's suppose that students from San Diego, San Francisco, and Arcata each conduct a within-population study. The onset of spring typically arrives earliest at southern latitudes (San Diego) and progresses northward (Santa Barbara, then San Francisco, then Arcata), so the students hypothesize that California Poppies will start flowering earliest in San Diego, followed by the next northern location (Santa Barbara), and so on. The results of this hypothetical study are graphed in **Figure 4**.

There are two major aspects of phenological variation that are illustrated in Figure 4. First, notice that the students discovered a latitudinal trend in flowering times, just as they expected. This trend is also commonly observed along elevation gradients, where populations at higher elevations tend to flower later than populations at lower elevations. These phenological changes with latitude and elevation are commonly observed in a variety of plants and animals, and represent strong environmental regulation of biological activities, typically by tempera-

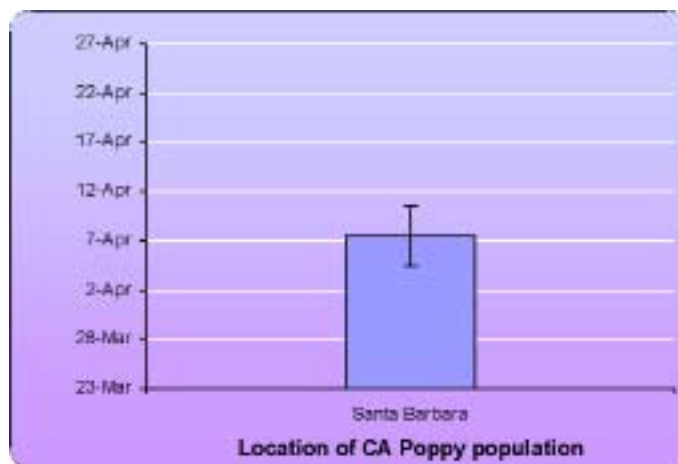


Figure 3. The mean date of first flower for 30 California Poppy individuals in the Santa Barbara population is April 8. Variation among individuals in the population is represented by the height of the error bars above and below the mean value.

ture. This general principle is described by Hopkin’s Law: the date of first flowering (and other phenophases) is delayed by approximately 4 days per degree latitude or 120 meters elevation (equivalent to 1 day per 100 feet elevation). While these trends reflect the sensitivity of phenophases to environmental factors, keep in mind that genetic factors also regulate the timing of phenophases and that the patterns we see in nature are largely the result of interactions between environmental and genetic factors.

Figure 4 also illustrates different levels of within-population variation – the San Francisco population exhibits the greatest amount of variation among individuals in first flowering date, whereas the Arcata population exhibits the least amount of variation. Another way to describe this pattern is that the Arcata population exhibits the greatest amount of synchrony for first flowering date. As we discussed earlier, the amount of synchrony within populations can have important short- and long-term consequences for pollination success, seed production, and seed quality. As you will see in the next section, phenological variation among coexisting species can have important consequences for community dynamics.

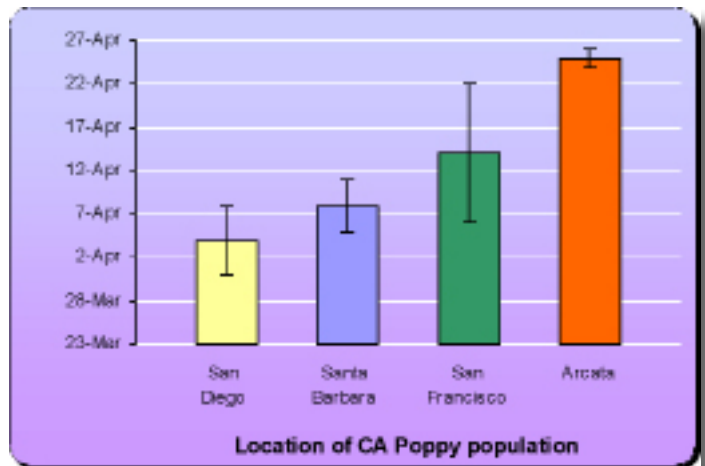


Figure 4. The mean date of first flower of California Poppy (for 30 individuals from each of four populations) increases with increasing latitude, from San Diego in the south to Arcata in the north. The Santa Barbara result is the same as in Figure 3. The y-axis should be labeled as “date of first flower”.

Phenological variation among coexisting species: community-level phenology

A brief visit to any habitat, whether it’s a backyard, school yard, or park, can reveal community-level phenology. The casual observer is likely to find some plant species that are flowering and other species that are not. Of the species that are flowering, some are likely to be just starting to flower (these plants will bear a large proportion of closed flower buds relative to the proportions of open flowers and developing fruits) and others are likely to be finishing up (these plants will exhibit a very low proportions of closed flower buds and open flowers and a very high proportion of developing fruits). The more attentive observer will notice the distribution of pollinating insect species among the flowering plants, noting whether particular insects prefer the flowers of certain plant species. Similarly, some species of birds might tend to spend more time visiting certain plant species, foraging for nectar (hummingbirds) or dispersing fruits and seeds (many songbirds).

A repeated visit a week or two later will reveal changes that have occurred in the phenology of the plant community, and probably in the abundance or assemblage of insect and bird species as well. **Community-level phenology is quantified as the change over time in the appearance, activities, interactions, or diversity of the assemblage of coexisting species in one habitat (Figure 5).**

Figure 5 depicts the phenology of a portion of a hypothetical ecological community. For each of the five species of flowering plants, the length of the red line represents the duration of each species’ flowering period. For example, the starting point of each line represents the date when the first individual plant in that population starts flowering, and the endpoint represents the date when the last plant produces its last flower. For insect pollina-

There are several ways to calculate variation among individuals that can be represented by the range bars shown in Figures 3 and 4. The most common estimate of variation is called the standard deviation. See the Activity Guide Chapter in this Handbook for instructions on how to calculate this and other measures of phenological variation.

tors (green lines), insectivorous birds (insect-eating; orange lines), and frugivorous birds (fruit-eating; blue lines), each line represents the start and end of foraging activity (pollinating, insect-eating, fruit-eating). In other words, the lines show the start date and the end date of all monitored individuals in the population.

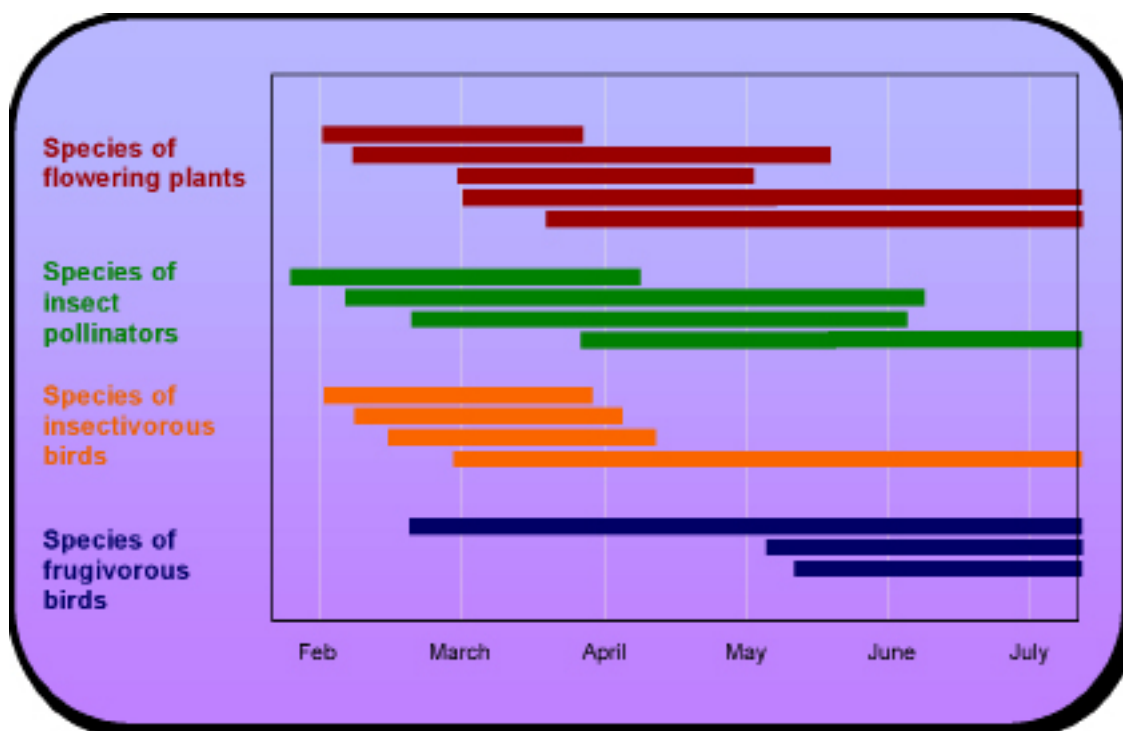


Figure 5. Graphical representation of the phenological progression of a biologically diverse community. Each horizontal line represents the timing and duration of a particular kind of phenological activity observed in a single species. For example, for flowering plants, each line may represent the duration of the flowering period of a given species. In this case, each line starts at the date of first flower among all monitored plants in the population, and the line ends at the date of the last flower produced by any of these plants. Similarly, for the species of insect pollinators, insectivorous birds, and frugivorous birds, the lines represent the first and last dates that any individual of these species is observed to be actively foraging. Drawing a vertical line across the graph at any date reveals the diversity and identity of coexisting (and potentially interacting) species; note that diversity and the composition of the community changes over the course of time.

Note that plants differ from animals in that, generally speaking, it is much more likely that individual plants can be monitored repeatedly within a growing season, recording the first and last flowering date of each individual plant. With this information, the start and end dates for the plant species in Figure 5 could, alternatively, represent the average dates of first and last flower, respectively. For example, we could calculate the average date of first flower if we observed this date in more than one distinct individual plant. It's much more difficult to do this for animals simply because they're highly mobile and it's difficult to identify different individuals.

Starting at the earliest date in February (you can impose a vertical line across the entire graph to help visualize this), one species of insect pollinator is active just before the first plant species begins to flower and before the first insectivorous bird species begins to forage. Moving the date to mid-March when four species of plants are flowering, there are three species of insect pollinators, four species of insectivorous birds, and one species of frugivorous bird that are actively foraging. Finally in late-July there are only two species of plants that are flowering, one species of insect pollinator, one species of insectivorous bird, and three species of frugivorous birds. Of these three time periods, biodiversity of the "active" community is highest in mid-March.

Community-level phenology - what does it tell us?

What does the phenology of ecological communities tell us beyond its approximate time schedule? To start, it describes the availability of resources in the community and sheds light on which species might be interacting most strongly with other species. For example, the two species of plants that are still flowering in July will be visited by only one species of insect pollinator; if this pollinator prefers to forage for pollen and nectar in one species over the other, then fruit and seed production of the neglected species is likely to suffer. As a more complex example, the abundance of insectivorous bird species is highest in March and the foraging activities of these birds is likely to decrease the abundance of insect pollinators. This may, in turn, reduce pollination services for the plants that are in flower at that time, which could result in many flowers being left unpollinated. This reduction in pollination could then lead to a decrease in the availability of ripe fruits for the three species of frugivorous birds that appear later in the spring. If three species of frugivorous birds are actively foraging for a limited supply of fruits, then competitive interactions among them are likely to be intense, and this could potentially affect the reproductive success of either individual birds or an entire population.

Overall, ecological communities are dynamic assemblages of coexisting species that interact both directly and indirectly over time. Thus, the phenology of communities provides a measure of their diversity and productivity, the combination of which can contribute to the long-term stability of the community.

Phenological variation among communities (across landscapes, continents, hemispheres, and the globe)

The detection of phenological patterns across ecological communities and across broad geographic scales plays an important role in our understanding of global environmental changes. The development of new remote sensing technologies (e.g., satellite-based observations), as well as new information-sharing and analytical technologies, in recent years has allowed for the integration of historically disparate environmental sciences (more about this later). The resulting multidisciplinary approach has led to the development of large databases that provide layers of information on physical, chemical, and biological processes across a variety of geographic scales. These



Phenology can also be examined at the level of the flower within an individual. This series of images of California Brittlebrush (*Encelia californica*) shows the phenological progression of one sunflower, from a young bud on the left to a withered flower on the right (a withered flower, also called a “spent” flower, usually indicates that the flower was pollinated and is maturing its seeds). Similar to the previous examples that quantify and describe the amount of variation of first flowering date, there can be variation among individuals, populations, and species for the rate at which individual flowers open, wilt, and mature seeds. Can you remember the three *sources of variation* that are likely to influence phenological traits?

You might be surprised to know that a sunflower is actually a collection of many small flowers (called an “inflorescence”)! Each of the large yellow “petals” is part of an individual “ray flower”, and each yellow strand in the middle is part of an individual “disk flower”. Notice in this phenological progression that ray flowers mature first, followed by the outermost disc flowers, and finally the innermost disc flowers. Can you detect the difference between fresh and wilted flowers on this sunflower inflorescence? This same inward progression is common to many species of sunflowers - take a close look the next time you see some in your yard, at the market, and at the florist’s shop!

efforts have helped to develop a stronger understanding of how environmental conditions, especially the climate system, affect phenological patterns among ecological communities and biomes. Some questions that have emerged focus on determining which community types are most sensitive to environmental change, which communities are the most imperiled, and how changes in one community can affect the productivity and diversity of another community.

SUMMARY - WHAT IS PHENOLOGY?

From individuals and populations to communities and biomes, the phenological attributes of living systems influence their ecological interactions and therefore the probability of persistence in the future. For example, if species that depend on each other (mutualists, such as a plant species and its pollinator) do not thrive at the same time (synchronously), then both species may suffer. The timing of an organism's phenophases can change dramatically as a direct response to environmental conditions, and this can have larger effects in the community. For example, warmer weather at the onset of spring can cause the seeds of many species to germinate earlier than they ordinarily would. Some individuals and species are more malleable (or "plastic") in this regard than others, and asynchrony that arises as a result can have cascading effects through the community. The productivity and sustainability of ecological communities, whether wild or farmed, can be greatly diminished when the phenophases of interdependent populations or species become asynchronous. With these concepts in mind, we can now provide a more precise definition of phenology: **Phenology is the study of the timing of recurring biological events, the interaction of biotic and abiotic forces that affect these events, and the interrelation among phases of the same or different species.**

SYNTHESIS - PHENOLOGICAL VARIATION

With the introduction above, you're now well aware of the ways in which the phenological schedule of an individual, population or species can affect its ability to persist in natural communities such as forests, fields, and streams, or in managed communities such as farms, local parks, or recreational areas.

For example, what are some ways in which an individual plant's flowering schedule may result in lower fruit production or seed quality compared to that of other members of the same population? Flowering when pollinators or potential mates are scarce — or when flower-eating insects are particularly abundant — will reduce pollination and fruit production. Alternatively, flowering at the same time as many close relatives can lead to reduced genetic quality of the seeds produced in the same way that mating between close relatives in humans and other animals can increase the risk of genetic diseases. Delaying flowering until late in the season, when the risk of drought (in deserts and in Mediterranean climates) or frost (in seasonal temperate climates) starts to increase may prevent any successful seed production at all. The risks associated with flowering at the "wrong" time are many and sometimes fatal.

With these ideas in mind, you should have no trouble providing answers to the following questions:

For a given plant species, how may populations that are spatially separated from each other benefit from being in phenological synchrony with each other?

- Unless populations are so isolated from each other that they never come in contact through seed dispersal or through the movement of pollen by wind or by animal-transfer, populations often benefit from receiving genetically distinct seeds or pollen from other populations. This increases a population's genetic diversity and may increase the probability that it can adapt to environmental change.

Within a given community, what are some additional ways in which one or more species are affected by the timing of the phenophases of other species?

- Pollinators that eat pollen (e.g., female bees and their offspring) will only have a food source if they are active during the flowering period of their favored plant species. Reciprocally, flowering plants that rely on animal pollinators will only produce fruits (and seeds) if they flower when their pollinators are abundant and searching for them.
- Nectar-eating birds, bees, and ants depend on the flowering time of their “prey”; plants that are attacked by these “nectar-robbers” will suffer reduced fruit and seed production, while plants that flower when such “thieves” are rare will enjoy higher reproduction (assuming that their pollinators are available!).
- Flower- and bud-eating beetles, bugs, moth and butterfly larvae, and other insects depend on the flowering schedules of their prey. So, not only does the phenology of plants affect their exposure to nectar-thieves, but it also affects their exposure to flower- and bud-eating species.
- The phenology of moth and butterfly larvae not only affect the plants that they eat, but it has strong effects on the survivorship and reproductive success of the birds that eat them.
- Pest-controlling insects and birds eat agricultural pests that, in turn, can destroy crops. A well-known example is the lady bug, a type of beetle that eats aphids, which — if not controlled — will attack young flowers, stems, and leaves. If pest-controlling animals (lady bugs, in this case) are not active in synchrony with their prey, an entire season of a crop can fail entirely.

In sum, the phenology of plants influences the abundances of the insects that eat or pollinate them as well as of the birds and small mammals that depend on them for fruits and seeds. The phenology of plant-eating insects and small mammals, in turn, affects the reproduction of their plant prey. The phenology of pollinating insects affects the reproductive success of the plants that they visit. And, the phenology of insectivorous birds affects the larvae on which they depend and the plants on which those larvae are found!

The answers to the above questions can have important implications both for wild species and for managed crops. The long-term viability of many wild plant populations depends on successful pollination, which can be limited if plants flower before or after pollinators are available. If fruit and seed production are diminished because of plant-pollinator asynchrony, food availability to frugivorous (fruit-eating) birds and mammals could be severely reduced. It is easy to imagine how food web dynamics in nature could be altered by asynchrony in the biological community. This is also true in the case of managed crops, where almost all of the farmed fruits that humans eat come from pollination services that are provided by insects. The synchrony of pollinator availability and flowering in farmed plants is therefore critical to our ability to produce food.

THE MODERN SCIENCE OF PHENOLOGY

The dawn of a new era in seasonal studies

Modern phenological studies are thought to have been initiated in Europe in the mid-18th century. Beginning in 1736, Robert Marsham kept detailed records of “Indications of Spring” on his family estate in Norfolk, Britain with the goal of improving timber production by learning more about the timing of plant and animal life cycles. His observations included the first occurrences of leafing, flowering and insect emergence. His descendents maintained these records until 1947, making it one of Europe’s longest phenological monitoring records. Though he was equipped with only a notebook and a writing utensil, the “modern” aspect of Marsham’s approach was the systematic nature of his records for many wild species in one ecosystem (27 phenophases for 20 plants and animals).

Phenology is an ancient science

Phenology is one of the earliest fields of science, studied by humans for millennia to predict the availability of food through the comings and goings of seasons. Early humans depended largely on their ability to locate, identify, and protect edible plants during all times of the growing season. This means that they had to be familiar with both the vegetative (stems, leaves, and roots) and the reproductive (flowers, fruits, seeds) units of the plants in their ecosystem so that they could identify them during all seasons. The same was true for agrarian societies, whose members also collected seeds and learned to maximize crop production by optimizing the timing of planting and harvesting. An adage common to some Native American tribes of eastern North America states that corn seeds should be planted in the spring soon after the leaves of nearby oak trees have reached a particular size (i.e., the size of a mouse's ear or a red squirrel's foot! *). This practice, based on generations of trial and error, predicts the earliest planting time so that the corn plants have enough time to fully mature before the end of the growing season; if corn seeds are planted before this time they run the risk of rotting in the ground. Although farming methodologies vary greatly today, the craft of maximizing crop production is no less important. With widespread loss of agricultural lands to urban development and a global human population size exceeding 6.6 billion, the timing of planting, harvesting, and crop rotations is critical to our ability to supply food for local and global demands.

* Russell, Howard S. 1980. Indian New England Before the Mayflower. University Press of New England. 284 pp. ISBN 0874511623

Similar approaches have been employed by people worldwide since Marsham's time — not necessarily to follow his lead or because their livelihood depends on it, but because they enjoy observing nature and predicting appearance dates each year. Phenological studies today can be just as simple, taking place in backyards, urban parks, or wilderness areas, or they can be very complex and employ advanced technologies and tools such as automated weather stations, inconspicuous video cameras, automated environmental sensors, and satellites, together revealing global and local seasonal patterns and the intricate mechanisms driving them.

Today's phenological studies: integrating scientific disciplines

Some of the most rigorous phenological studies performed today are carried out by environmental scientists representing a wide range of approaches, including population biologists, community ecologists, climatologists, hydrologists, and specialists in satellite-driven remote-sensing. The integration of scientific disciplines makes for particularly powerful studies because the *site intensive* nature of one tool (e.g., botanical inventories and detailed phenological studies) can complement the *geographically extensive* information provided by another (e.g., satellites). Let's consider this in more detail in the following example.

At the continental scale, sensors in NASA's MODIS satellites in space measure the amount of sunlight reflected from the earth's surface. Leaves reflect light that is particularly rich in wavelengths in the near-infrared portion of the light spectrum, which the human eye cannot see but that satellite sensors can measure. The reflectance of light from leaves is greatest in mid-summer when leaves are most abundant, and lowest in winter when grasslands, shrublands, and forest trees are mostly bare. Thus, satellites detect the onset of spring by detecting a rapid increase in the reflectance of infrared wavelengths — this phenomenon is called **green-up**. Alternatively, the senescence of leaves in the autumn leads to a decrease in reflectance, and this is called **brown-down**. By collecting these remotely-sensed data on a regular basis and on a large geographic scale, scientists can accurately measure the onset of spring growth across the entire Northern or Southern Hemisphere.

At the same time as green-up is detected around the world by satellites, plant-watchers on Earth can observe the fine details of this process. Families, students, nature enthusiasts, and professional botanists who regularly

visit a natural landscape can track green-up on a daily or weekly basis. By identifying which habitats and plant species are leafing out, we can identify the phenological events and species that contribute most to the infrared reflectance values observed from space (this process is called “**ground-truthing**”).

At an even finer spatial scale (e.g., from square miles to square meters), biogeochemical sensors can measure daily and seasonal fluctuations in temperature, precipitation, atmospheric gasses, sunlight, soil nutrients, stream flow, and other components of the abiotic environment upon which plants and animals require for growth. With these data on hand, scientists can determine the influence of environmental factors on phenological patterns.

The longest known phenological monitoring record comes from the Royal Court of Kyoto in Japan, where the onset of flowering for cherry trees has been recorded since 705 AD. Some wine-producing regions in Europe also boast records of blooming and harvest dates that extend back hundreds of years.

SUMMARY

Over the long-term, the timing and duration of green-up can be compared from year to year and from decade to decade to detect whether climatic variation affects the productivity or geographic distribution of natural plant communities. Scientific disciplines can be combined to investigate phenological patterns across both biological and geographical levels of organization. This integrated phenological research can provide layers of information spanning both space and time that reveal when and how different communities and biomes change as a function of climate change and other environmental conditions. Although remotely-sensed data can provide broad measures of global phenological patterns, ground truthing and biogeochemical monitoring are critical to our ability to identify the factors that drive phenological patterns within and among communities and biomes. The synthesis of information from multiple levels of biological and geographical scales is the best method by which we can discover broad ecological patterns and the processes that drive them.

In the following sections of this handbook, we will help you to develop the botanical tools and record-keeping methods needed to become an independent Phenology Steward who can contribute to the National Phenology Network’s growing community of ground-truthers.

Green-up refers to the progressive increase in plant growth at the beginning of spring. Springtime increases in plant growth can be tracked with great sensitivity by satellites, detecting and measuring the rate at which the earth’s vegetation produces its annual flush of leaves. From a weekly series of satellite images covering the Northern Hemisphere during the spring months, scientists can see that spring starts earlier at southerly latitudes and progresses northwards, and spring starts earlier at lower elevations and progresses upward in elevation. Intuitively this should make sense to many people – spring comes earlier in Southern California than it does in Northern California, and spring comes earlier in the valleys than it does in the mountains. Of course the intricate details of this pattern depend on the topography of the land as well as many physical, chemical, and biological factors, but the broad geographic patterns are simply remarkable: when reviewing the series of satellite images, it appears to scientists as though a green wave is progressing northward in latitude and upward in elevation! (In the Southern Hemisphere, the green wave progresses southward in latitude and upward in elevation).

Who participates in ground-truthing phenology?

- **botanists** exploring forests, fields, streamsides, and coastlines to monitor our natural biodiversity;
- **farmers** recording the growth of their crops (or the appearance of weeds!);
- **park rangers and land managers** who monitor the health of our forests;
- **livestock managers** who move cows and sheep among pastures so that the animals graze on plants of a particular seasonal age;
- **park visitors, hikers, and backpackers** interested in spying the springtime activities of plants and the animals that depend on them;
- **birdwatchers** observing the migrations of their favorite birds and keeping watch on the foods that they eat;
- **agriculturalists** concerned about the appearance of insect pests that eat our crops;
- **maple sugar harvesters** planning when to tap maple trees for their sap in the fall;
- **promoters of ecotourism** who need to predict the timing of optimum annual wildflower and autumn leaf-turning displays;
- **ecologists** who monitor rodents and other mammals that carry diseases such as Lyme Disease and Hanta virus, and whose populations grow and shrink with the availability of fresh, edible plant material;
- **fire fighters** concerned about the build-up of fuel (all growing plant material) that affects summertime wildfire risk;
- **physicians** interested in predicting the intensity of allergy seasons;
- **plant naturalists** interested in collecting wild species for herbs, spices, dyes, and medicinal uses;
- **home gardeners** aiming to predict the best time to sow vegetable seeds or to transplant seedlings; and
- **students** tracking the phenology of schoolyard gardens to start their own Phenology Diaries.

In short, with a little bit of botanical know-how, families, students, scientists, and any individual with an affection for plants can participate in phenological monitoring in their neighborhoods, backyards, and natural areas.

Although many people are familiar with four seasons (spring, summer, autumn, winter), some regions of the world experience a different number of seasons. In Australia, for example, aboriginals who have inhabited the continent for over 50,000 years have developed calendars based on the seasonal activities of plants and animals in relation to changes in temperature, wind, and rain patterns. These calendars actually note between 5 and 10 distinct seasons depending on which region of Australia is being described.

Keatley, M. and Fletcher T. 2003. Phenological data, networks and research: Australia. Pp. 22-44, In Phenology: An Integrative Environmental Science. Ed. M. Schwartz. Kluwer Academic Publishers. 563 pp. ISBN 1402015801

PHENOLOGY AND CLIMATE CHANGE

A (VERY) BRIEF OVERVIEW OF CLIMATE CHANGE

It is widely known that the Earth's climate system is changing rapidly. Although there is a range of opinions on how best to mitigate the consequences of climate change, there is strong agreement on how and why it is occurring. Here are just a few facts about changes in temperature, from the 2007 Assessment Report of the Intergovernmental Panel on Climate Change (IPCC):

- Global average surface temperatures have increased by 0.74°C during the last 100 years; this is the largest and fastest warming trend in the last millennium.
- The rate of warming has increased in recent decades. The most recent 50 years have warmed at nearly twice the rate seen in the previous 50 years, and 11 of the last 12 years have been the hottest in recorded history (since 1850).
- Land surfaces have warmed slightly faster than ocean surfaces, and the greatest rates of surface warming are continually found in mid- to high-latitude continental regions of the Northern Hemisphere.

These changes, and many others that are not described here, are largely attributable to the emission of greenhouse gases into the atmosphere and their continued accumulation, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases (e.g., hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride). There is no doubt in the scientific community that human activities such as industrialization, burning of fossil fuels, and deforestation have contributed to increased concentrations of greenhouse gases and therefore to global climate change.

There are multiple ways to define the **growing season** of a region, but most definitions point to the time of year that is favorable to plant growth. This metric can change depending on how cold-hardy the plants in a given habitat are, but a common definition is the time period between the beginning of spring and the occurrence of the first killing frosts of autumn, otherwise known as the frost-free season. The examples above show the effects of climate change on the physical world (e.g., snowpack, duration of lack and river ice, and the area of the arctic ice sheet), but climate change has similarly strong influences on the biological world. One major difference is that, while highly complex mathematical models have been quite successful in predicting the effects of climate change on physical global activities (such as ice melt), the effects on the biological world are immeasurably difficult to model and, as a result, are highly unpredictable.

CLIMATE CHANGE ON A SEASONAL TIME SCALE – THE CHANGING GROWING SEASON

In order to discuss the connections between climate change and phenology, we first need to understand how climate change is affecting the timing and intensity of the seasons. The term “global warming” often evokes images of unbearably hot summers. While it is true that summertime high temperatures are rising worldwide, it often surprises people to learn that in seasonal environments around the world – those characterized by cool or cold winters and warm or hot summers – winter is the most rapidly warming season. In fact, by many measures winters are warming at nearly twice the rate of summers. Where this occurs, winters are not only warmer, they are also shorter, and this change can be seen in several ways:

- The amount of time that lakes, rivers, and polar oceans are covered with ice during the winter is decreasing. In the Northern Hemisphere, observations of early-winter freezing dates for rivers and lakes over the last 150 years has found that freezing is becoming delayed at a rate of nearly 6 days per century. Ice “breakup”, in turn, is taking place earlier, at a rate of ~6.5 days per 100 years.

- Snow cover and snowpack have decreased in most regions of the world where they have been tracked by satellite, particularly in the Northern Hemisphere. Declines of snow cover in the mountains is particularly strong at lower elevations (this has been seen in both western North America and the Swiss Alps), where increases in April temperatures seem to be the most direct cause.
- Even the icepack of the arctic seas is melting rapidly; satellite imagery has detected that, over the last 30 years, the area covered by sea ice is declining at an annual rate of almost 3%. This decline is seen in both the winter and summer ice caps, with the rate of disappearance of the summer ice reaching nearly 7.5% per decade.
- The permafrost layer of the Arctic — the layer of soil that remains frozen year-round, regulating the drainage patterns and stability of the terrestrial biome — has been increasing in temperature since the 1980s. Its surface has increased by up to 3 °F (that's 5.4 °C), causing its lower levels to be disappearing (thawing and melting) at a rate of 2 – 4 centimeters per year!

One direct consequence of a warmer and shorter winter is the earlier onset of spring temperatures. Across the entire Northern Hemisphere, spring is arriving earlier at a pace of approximately 1.2 days per decade. Land surfaces are also retaining more heat during the summer, leading to persistent summer temperatures that linger into the fall. Thus, with regard to the temperatures that permit plants to grow, an earlier spring and a persisting summer means that the growing season is expanding (whether plants will receive enough rainfall to take advantage of these warmer temperatures is an unresolved question of great concern). Across Europe, for example, the growing season expanded 10.8 days during the period 1960-1999 (6 days toward an earlier spring, 4.8 days toward a persisting summer).

While these might seem like small changes, the natural world is actually responding in observable, dramatic, predictable (and in some cases, unpredictable), and potentially problematic ways. Summarizing more than 29,000 observational data series that demonstrate significant changes in physical and biological systems, the IPCC reported in 2007 that more than 89% (25,810) of those changes are in the direction expected as a response to climate change. In the biosphere, these changes tend to fall into two categories: responses in space and in time.

BIOLOGICAL RESPONSES TO CLIMATE CHANGE IN SPACE AND TIME – THE FINGERPRINT OF CLIMATE CHANGE

Geographic responses to climate change

On a spatial scale, many species of animals and plants have expanded their geographic ranges poleward in latitude (northward in the northern hemisphere; southward in the southern hemisphere) and upward in elevation over the last century, following shifting temperatures. As higher elevations experience more mild winters, for example, species from lower elevations may expand their range towards higher elevations because they can now tolerate the winters there. The same may be true across latitudes; species from lower latitudes (i.e., closer to the equator) may expand their range toward higher, or poleward, latitudes. These “range expansions” can be advantageous for species that can disperse easily, but they can threaten the existence of less mobile or more sensitive species. For instance, when one species expands its range into new territory, it may displace one or more species that have inhabited this territory for thousands or millions of years. If, in turn, the displaced species cannot migrate to new and suitable areas, they may become locally or globally extinct. Also, while some species may expand their ranges into higher elevations or latitudes in response to climate change, others will be forced to reduce their ranges as their habitats become too warm, too dry, or too extreme in their annual temperatures.

Furthermore, migration into new territory is often impossible, as habitat fragmentation due to human activities (such as the building of housing developments, golf courses, highways, or shopping malls) or the existence of natural barriers such as rivers or mountain ranges can prevent the movement (or **dispersal**) of seeds and fruits, and of young, pregnant or nursing animals.

Additionally, current and predicted rates of warming might outpace the dispersal rates of many organisms, especially for the thousands of plant species for which seed dispersal requires particular species of animals to eat their fruits. If their seed dispersers do not carry the seeds to other habitats, then plants will not be able to colonize new and potentially suitable habitats.

Lastly, food webs within ecological communities are likely to change when novel species colonize a habitat, potentially disrupting resource availability for many members of the community. For example, as the number and abundances of different species in an area change as species move in and out in response to climate change, the number and types of species competing for the same foods can increase. When this happens, competition for a rare food resource (such as ripe fruits or newly emerged insect larvae) can become particularly intense. Under these conditions, the risk of extinction is likely to increase for many species (recall our earlier example of frugivorous birds competing for ripening fruits in Figure 5).

Temporal responses to climate change

On a temporal scale, living organisms respond to the expanding or shifting growing season by changing their phenological schedules. Thousands of biological records spanning both the globe and the 20th century indicate a nearly ubiquitous shift in spring phenology toward earlier calendar dates. To summarize, organisms are tracking an earlier start to the growing season by emerging from dormancy earlier (mammals, insects), migrating earlier (birds, insects, mammals), developing new leaves and stems earlier (plants), and breeding earlier (mammals, insects, birds, plants). Not surprisingly, similar delays in autumn phenology are occurring due to a persisting summer—deciduous trees are shedding their leaves later than they used to, and birds and mammals are migrating later in the autumn than they used to.

As you can imagine, the consequences of phenological shifts will depend on the level of biological organization that we investigate. For a long-lived *individual* tree, for example, leafing out several days earlier each spring may allow it to get a rapid head start in its annual growth, especially if neighboring trees remain leafless, which would allow its leaves to receive a great deal of sunlight. On the other hand, if it produces its leaves earlier than any of the other members of its population, it may be particularly vulnerable to leaf-eating insects (e.g., moth and butterfly larvae, leaf miners, and leaf-cutting ants) simply because it will be a rare and limited resource for them.

The Intergovernmental Panel on Climate Change (IPCC)

After decades of scientific discussion about the possibility of global warming, in 1988 the World Meteorological Organization and the United Nations Environmental Programme created the Intergovernmental Panel on Climate Change (IPCC). The IPCC is a multidisciplinary scientific body that regularly brings together hundreds of experts from all regions of the world to assess the global climate system. Their efforts are broadly focused on two topics: the assessment and interpretation of scientific information, and the formulation of realistic response strategies at national and global levels. Their findings have been published in a series of ground-breaking Assessment Reports (1990, 1995, 2001, 2007) as well as in a handful of Special Reports examining topics in greater detail.

The IPCC's First Assessment Report in 1990 played a decisive role in the establishment of an international treaty for climate change mitigation in 1992, the United Nations Framework Convention on Climate Change (UNFCCC). Their Second Report provided key input for the negotiations of the Kyoto Protocol in 1997. The IPCC received the 2007 Nobel Peace Prize after the publication of its Fourth Assessment Report, which contained the strongest language to date concluding that "warming of the climate system is unequivocal" and that "there is very high confidence that the net effect of human activities since 1750 has been one of warming." You can learn more about the IPCC online at www.ipcc.ch

The effects of a phenological shift on a given *population* of a species will also depend on whether the other species on which it relies — for food, pollination, or seed dispersal — change with it. For example, if populations that benefit from each other respond differently to climate change (e.g., if a plant population flowers on average five days earlier but its pollinators haven't arrived), then one or both of them may exhibit population declines. On the other hand, if a population flowers early enough to “escape” one or more of its “natural enemies” (e.g., flower bud-eating beetle larvae), it may reap the benefits of high flower and fruit production.

At the *community* level, well, predictions are highly elusive. We've learned from radio-tracking and bird-banding efforts that birds are returning to spring and summer breeding grounds earlier and earlier, but the effects of these altered migration patterns on both the birds and the species with which they interact (as predators or as seed dispersers) are likely to be highly species- and community-specific. Nevertheless, there are several rules of thumb that probably apply.

First, the more specialized the relationship between species, the more vulnerable each of them are likely to be to the phenological effects of climate change. For example, plant species that are pollinated by only one species of pollinator are more vulnerable to losing these pollinator services than are species that are visited by a wide range of pollinator species. Similarly, insects that rely on a single plant species as their food source may experience severe population declines if their emergence times are mismatched with the growing or flowering season of their host plant.

Second, animals that habitually migrate between geographically distant biomes to complete distinct portions of their life cycles (e.g., growth and sexual maturation vs. breeding) are particularly vulnerable to the phenological effects of climate change simply because there are more inter-specific interactions that may be disrupted. Such species must continue to exhibit a phenological schedule that is viable given the co-occurring species and the climate in each of their “home” habitats. For example, species of birds that migrate over long distances must co-occur with their food sources (while avoiding their enemies) in the biome in which they grow and reach sexual maturity, and then, following migration to their breeding grounds, they must be in synchrony with the food sources that they feed to their newborns. Migratory animals must meet these demands while also avoiding the natural enemies that destroy them.

The fingerprint of climate change

These shifts in geographic range and phenology are what scientists call the “fingerprint of climate change.” What at first appears to be a situation where life is accommodating to climate change by altering the pace and duration of its annual cycle is actually quite worrisome — phenological schedules are changing rapidly and at different rates for co-dependent species such as plants and pollinators. There is an increasing number of reports in recent years of population crashes in the wild due to such asynchronous responses to climate change among co-dependent species, but we are only beginning to learn how widespread they are and in how many different kinds of organisms they occur.

A note about the worlds' oceans - data from IPCC's 2007 reports

Sea levels are on the rise worldwide, but not just because glaciers and sea ice are melting. In fact, melting glaciers and ocean ice account for only 28% and 15% of the rise in sea level, respectively. The most critical factor in rising sea levels is actually the warming of the ocean from solar radiation and the greenhouse effect. The oceans are absorbing over 80% of the heat added to the climate system, which leads to heat being dispersed vertically through the depths of the oceans. As a result, the average temperature of the “global ocean” has warmed to over 3000m deep, raising scientists' concerns over how oceanic processes such as circulation patterns (e.g., the North Atlantic Oscillation) will operate in the future. Not only this, but when water heats up, it expands — this “thermal expansion of the oceans” accounts for 57% of the total rise in sea level.

One consequence of asynchronous phenological responses to climate change among interacting species

The Dutch Pied Flycatcher (*Ficedula hypoleuca*) is a small passerine bird that migrates from Western Africa to Europe each spring. Upon its arrival at its northern breeding grounds it consumes caterpillars. The caterpillars have been responding to warmer spring temperatures by emerging as adults earlier in the spring, but some Flycatcher populations have not migrated earlier to keep pace. These mistimed Flycatcher populations have been in steep decline in recent years because of the asynchrony of their migration phenology with the phenology of their food source at its breeding grounds.



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PHENOLOGY NETWORKS

A GATEWAY TO DETECTING ENVIRONMENTAL CHANGE

Shortly after Robert Marsham initiated modern phenological surveys on his land in Britain, the Swedish botanist Carolus Linnaeus (1707-1778) revolutionized the field of phenology by conducting a study simultaneously in many locations. In 1750, Linnaeus, the scientist who invented the classification system still used today to name and to describe all plants and animals, selected multiple sites in Sweden where he recorded annually the dates of leafing, flowering, fruiting, and leaf fall for many species, along with the weather conditions at flowering. He described his methodology in his work *Philosophia Botanica* so that others could replicate the study. This was the first blueprint for the creation of a **phenology network**, which many scientists and citizens around the world then implemented at different geographic scales over the following decades and centuries.

The goal of a phenology network is to coordinate a group of people to monitor simultaneously phenological events across a wide geographic area and to share their information. Observers across a country or continent rely on a common set of definitions and protocols in order to standardize their observations across regions and for many different species. These standardized studies can have many uses—historically the most common goal has been to understand and to predict variation in the life cycles of plants and animals for agricultural applications. A practical knowledge of phenological patterns has also allowed hunters to predict game availability, enabled city and land managers to plan for resource use, and permitted societies to plan cultural events around natural phenomena.

Phenology networks blinked on and off throughout Europe and the world during the late-19th and 20th centuries. Many of them were phased out due to wars, a general decrease in their applicability, or a lack of government support (or a combination of these factors). Some successful networks, such as the Canadian effort that was initiated as early as 1890, proved their worth in the botanical or climatological sciences and then were expanded by either individual scientists or national meteorological agencies. Thus, the dominant trend was toward nationally-coordinated phenological observations, but there was an unfortunate lack of coordination among networks at the international level, especially across Europe. As a result, monitoring protocols have varied among networks and countries, and datasets have been difficult to merge, thereby limiting the scope of their studies.

The first notable exceptions to this lack of integration were the International Phenological Gardens (IPGs). The IPGs were established in several European countries in the late 1950's based on the growing need to predict agricultural seasons. Recognizing that genetically based differences in phenological events among plant populations collected from the wild can overwhelm the environmental signal obtained from phenological observations of local populations, scientists propagated clones of 14 species of trees and shrubs and sent them to gardens located from Italy to the Netherlands. More gardens were established in subsequent years, and over 50 of them are still being monitored today. With no genetic variation among gardens, each species, through its phenological development, has revealed substantial geographic variation in seasonality. Collectively, the phenological information provided by these gardens has led to the creation of climate maps as well as to predictive computer models for the improvement of agricultural practices. Even more, the International Phenological Gardens have played a critical role in detecting the effects of climate change on the phenology of plants. In fact, the study mentioned previously revealing a 10.8 day expansion of the European growing season was published by IPG scientists describing the phenology of their cloned trees and shrubs.

Recognizing the contemporary value of these data and of the remaining infrastructure of independently functioning phenology networks throughout Europe, the European Phenology Network (EPN) was established in

How does a clonal phenological garden work?

Earlier in this chapter you learned how scientists quantify phenological variation at a variety of biological and geographical scales. You also learned that the observed variation in phenology among individuals, population, and communities can be due to three sources of variation: environmental factors, genetic factors, or a combination of environmental and genetic factors. We can express this concept in the following mathematical equation:

$$V = G + E + G \times E$$

where V is the observed variation for a trait within a population (such as with date of first flower in our earlier examples), G is the amount of variation in the trait due to genetic differences among individuals (e.g., siblings tend to flower at a similar time, thereby reducing the amount of genetic variation within the population), E is the amount of variation in the trait due to the influence of the environment (e.g., warmer conditions typically induce earlier flowering), and $G \times E$ is the interaction between genetic and environmental factors (e.g., some genotypes [individuals] in the population are more sensitive to warm temperatures than other genotypes).

The scientists who established the International Phenological Gardens (IPGs) used this knowledge to their advantage. By planting cloned trees and shrubs in different regions of Europe, they caused all genetic variation among gardens to be zero. Based on the above equation, then, all observed variation between gardens in their phenological patterns must be due to environmental factors (E). This experimental approach is used often today by evolutionary ecologists and ecological geneticists who are interested in understanding the influences of genetic diversity and environmental change on ecological interactions (such as plant-pollinator and predator-prey interactions).

2000 by the Phenology Study Group of the International Society of Biometeorology. The EPN's goals were to create a platform from which to coordinate phenological monitoring efforts and to standardize observations across Europe to monitor more efficiently the changing climate. Other networks around the world have also developed or resurfaced over the past decade under the same context. Today, phenology networks exist in North and South America, Europe, East Asia and Australia.

PHENOLOGY NETWORKS AND THE CITIZEN SCIENTIST MOVEMENT

While the databases created by contemporary phenology networks are filled by *professional scientists* who observe and report the timing of seasonal events, some networks have invited ***citizen scientists*** to participate. These include nature enthusiasts, home gardeners, park docents, botanical garden staff, farmers, National Park rangers, families, teachers, and students. When people across a wide geographic area are trained to observe and record phenophases in their backyards, local parks, field stations, and nearby wild areas, the number of observations submitted to a database can increase dramatically. This process also engages the public so that they become more aware of nature and of the manifestations of climate change. The European Phenology Network, Nature's Calendar in Britain, Natuurkalender in Holland, and NatureWatch in Canada have each had great success in recruiting the public to report the timing of phenophases. The data are synthesized by scientists and results are reported in a variety of ways on the networks' websites. Recent efforts in the United States have led to the development of a nationwide phenology network that invites participation from professional and citizen scientists.

A BRIEF HISTORY OF PHENOLOGY IN THE UNITED STATES

A few attempts were made in the early 20th century to initiate coordinated phenological measurements in parts of the United States, but it wasn't until the mid-20th century that the concept took root. In the 1950's, motivated by the notion that the simultaneous monitoring of a widespread species could be used as an indicator for the progression of the agricultural growing season, Montana State University agricultural climatologist Dr. Joe M. Caprio started what would eventually become the nation's phenological legacy. Caprio sought observers across the Western US who would report to him the local timing of leafing and flowering of the Common Lilac, *Syringa vulgaris*. By 1957 he had recruited over 2500 volunteers in 12 western states, and within a decade he added two honeysuckle cultivars (*Lonicera tatarica* 'Arnold Red' and *L. korolkowii* 'Zabeli') to the observation program. Observa-



Figure 6. Locations in North America with five years or more of lilac phenology data, 1956-2001 (Québec stations not included). From Schwartz 2003.

Many cultures throughout history have used flowering times as cues for hunting and cultural activities. In the Pacific Northwest, the many nations comprising the Nuu-Chah-Nulth of western Vancouver Island have looked to the ripening of salmonberries (*Rubus spectabilis*) to alert them that anadromous sockeye salmon (those that migrate from saltwater to freshwater) are abundant in nearby streams. The Blackfoot of Alberta would time their annual mid-summer tribal ceremony to the ripening of Saskatoon berries (*Amelanchier alnifolia*), and reportedly would time their spring hunt for bison bulls to the flowering time of the Buffalo Bean plant (*Thermopsis rhombifolia*).

tions in this western US network continued through 1994 at which time Caprio retired and many of the observers dropped out as they aged and died, underscoring the fact that a phenological network is a living system that must be repopulated each generation to ensure its longevity.

Caprio's early success motivated two other researchers to initiate regional phenology networks in Nebraska (W. L. Colville, University of Nebraska) and in the Northeast (R. Hopp, University of Vermont) in the 1960's. Using the same approach as the International Phenological Gardens in Europe, these two networks recorded observations for a cloned cultivar of lilac, *Syringa chinensis* ('Red Rothomagensis') at about 300 sites. They also collected data on the aforementioned honeysuckle cultivars. Administration of these two networks was juggled for a couple of decades until funding was ultimately lost in 1986, after which University of Wisconsin-Milwaukee climatologist and geography professor Dr. Mark D. Schwartz contacted their volunteer networks to manage the remaining monitoring activities.



Figure 7. Phenological progression for the common Lilac, *Syringa vulgaris*. Leaf budburst (left) occurs early in the spring, the first flowers open about one month later (middle), and full flowering occurs a few weeks later (right). Photos courtesy Mark Schwartz and the USA NPN.

The data from the lilac and honeysuckle phenology networks have proven useful on many counts. Schwartz has developed sophisticated computer models capable of predicting the onset of spring across the United States from a combination of phenological and climatological data. The phenological data have also helped to demonstrate that spring in North America is arriving earlier than in the past, and Schwartz has estimated that the onset of spring is advancing by 1.2 days per decade across the Northern Hemisphere. There is even preliminary evidence that phenological schedules are, in some regions in the western U.S., strongly correlated with the size and frequency of wildfires during the subsequent “fire season”.

Schwartz and others have recently leveraged this phenological legacy in the U.S. to rally scientific and public interest around a national-level phenology network. **The USA National Phenology Network (USA-NPN)** is currently being designed and organized to engage federal agencies, environmental networks and field stations, educational institutions, and mass participation by citizen scientists. It is a nationwide collaboration among professional and citizen scientists designed to track the progression of the seasons.

THE USA NATIONAL PHENOLOGY NETWORK (NPN)

The vision of the USA NPN is to integrate available data from existing infrastructures (e.g., NASA's satellite imagery, National Weather Service Co-Op stations, National Park Service's annual inventories, and AmeriFlux's biogeochemical monitoring stations), while engaging citizen scientists across the country to monitor local organisms. The component of the NPN that is actively working to inform the American public and solicit their help is the Education, Citizen Science, & Outreach working group (ECSO).

The Education, Citizen Science & Outreach (ECSO) working group of the NPN

In the global campaign to reduce the factors that promote global warming, there are many organizations that provide citizens with opportunities to donate money or time with the goal of reducing energy use and green-

house gas emissions through education and outreach. There are only a few organizations, however, that invite citizens to contribute their time and energy toward scientific monitoring and the detection of local climate-related patterns. The ECSO working group of the NPN operates with the understanding that phenology, and the ability to measure and to record its progress over the seasons, is accessible to everyone in the country. The primary goal of ECSO programs is to bring together professional and citizen scientists, students, stewards of public and private lands, and outdoor enthusiasts to compile basic information on phenological responses to climate change; to study its nature, pace and its effects on ecosystem function; and to understand synchrony and ecological interactions among species.

The NPN's ECSO working group has designed a range of programs and products through which the public and scientific professionals can observe and interpret the phenological world on an unprecedented scale. Each program is designed to achieve one or more of the following objectives:

- To engage the public in long-term phenological data collection and analysis through both formal and informal science education programs;
- To engender self-directed, voluntary learning using inquiry-based approaches;
- To engage currently active land stewards, networks, and master naturalist programs in the collection and contribution of phenological data to the NPN;
- To provide training in the tools and applications of phenological studies to citizens and to scientists at all stages in their careers;
- To enhance opportunities for the public to interact with professional scientists;
- To promote novel tool development and collaboration among scientists representing historically distinct disciplines (e.g., climatology, hydrology, remote-sensing, engineering, ecology, population biology, and evolutionary ecology).

PROJECT BUDBURST – THE NPN'S FIELD CAMPAIGN FOR CITIZEN SCIENTISTS

This on-line educational and data-entry program is ECSO's flagship nationwide program for the public (<http://www.budburst.org>). The site went live on April 1, 2007, targeting students, nature enthusiasts, and their families. The site provides: information on the history and ecological significance of phenology; its link to climate change; materials for teachers and students; and an easy-to-use online utility for uploading botanical phenological data obtained in backyards, botanic gardens, nature preserves, and the wild. For the 2007 implementation of Project Budburst, 60 widespread and easily identifiable wild and cultivated species were targeted for observations throughout the U.S. Conveniently, the data management system allows users to enter phenological observations (including the dates of budburst, full leaf-out, first flower, peak flowering, and completion of flowering) for any species. By the end of the first field season for Project Budburst (June 2007) almost 1000 phenological observations were submitted from all over the country. The 2008 season of Project Budburst kicked off in January and is expected to attract a wider audience of citizen scientist participants. Project Budburst participants are now able to establish a user account at www.budburst.org, where they can upload as well as manage their data throughout the season.

Visit www.budburst.org today!

THE UCSB PHENOLOGY STEWARDSHIP PROGRAM

At the University of California, Santa Barbara (UCSB), we have designed a program to recruit and to engage local families, teachers, nature enthusiasts, and students at all levels in phenological monitoring. **The UCSB Phenology Stewardship Program** is a growing network of observers dedicated to tracking and recording seasonal biological events in the Santa Barbara region. With funding from UCSB's Coastal Fund, the Phenology Stewardship Program was initiated in the Spring of 2007 by PhD student Brian Haggerty and Professor of Ecology & Evolution Dr. Susan Mazer. Through a combination of scientific research, environmental education, and dynamic outreach presentations, their mission is to engage California residents in the collection of phenological data and the reporting of those observations to the Project Budburst online database.

The UCSB Phenology Stewardship Program provides internships for undergraduates in scientific research, environmental education, graphic design, and ecological mapping. The Program also provides training and teaching materials for K-12 teachers to bring phenological observation and its interpretation into the classroom and outdoor schoolyard or phenology garden. Activities also include the use of the herbarium at UCSB's Cheadle Center for Biodiversity and Ecological Restoration to demonstrate the usefulness of herbarium records for reconstructing historical flowering times and its relationship to climate, elevation, latitude, and habitat.

UCSB's Coal Oil Point Natural Reserve (COPNR) is the local site for phenological research, training, and outreach. Here, a series of Phenology Trails have been established that are tracked by undergraduate "Phenology Stewards" (research interns) who collect flowering data from 21 plant species along with the migration and residence times of shorebirds and passerines.

Look for the UCSB Phenology Stewardship Program online at www.Facebook.com and visit our preliminary web-site at: <http://www.uweb.ucsb.edu/~cmcosner/phenology/>



Figure 8. Images of UC Santa Barbara's Coal Oil Point Natural Reserve. On the left is a satellite image (from Google Earth) of a portion of the reserve; red lines mark the Phenology Trails that have been established in three habitats including foredune, backdune, and coastal bluff/scrub. The body of water in the upper-left corner is a portion of Devereaux Lagoon, where avian phenological surveys are conducted. On the right is a photograph (May 2007; courtesy Matt Wilson) of the backdune at Coal Oil Point. With the Pacific Ocean as a backdrop, flowering phenology of 21 plant species is monitored by Phenology Stewards (including the purple-flowered Beach Sand Verbena, *Abronia umbellata*, and the yellow-flowered California Poppy, *Eschscholzia californica*). Note the location of Santa Barbara (red dot) on the inset map of California.



The USA-National Phenology Network

The USA-NPN is being designed as a nationwide network that oversees regularly repeated phenological observations that are linked to local and national climatological and hydrological data, as well as to imagery or data obtained through remote sensing. These data, in turn, will be available for analysis using a variety of quantitative and geographic tools. The first objective of the USA-NPN is to establish a functional phenological monitoring network of stations distributed throughout the United States. Organizations such as biological field stations, agricultural extension stations, and National Parks, which already include biological monitoring as part of their current mission or ongoing activities, are particularly valuable institutional partners, as are schools and universities engaged in planting and monitoring local phenological gardens. Only with widespread engagement of the public, however, will the NPN be able to realize the kind of data-collecting power that will enable it to detect the species, communities, and biomes that are most sensitive to environmental change.



The USA-National Phenology Network will consist of four tiers representing varying levels of sampling intensity. The first tier (top of the pyramid) comprises the most intensively monitored sites, where multiple environmental parameters are already being recorded. The second tier represents existing networks of people and/or instruments, such as weather stations, national parks, national forests, and wildlife refuges. The third, even broader, tier includes members of the public and formal and informal educational groups. For example, Project Budburst, a national campaign to engage the public in phenological monitoring, was successfully launched in 2007 and expanded in 2008. At the base of the observation pyramid are remotely sensed data, which can provide wall-to-wall coverage of observations across the landscape. Finally, focused phenology networks with local to regional objectives are also being developed with the support and guidance of the National Coordinating Office of the USA-NPN, which was established in Tucson, Arizona in summer 2007 with long-term support from the U.S. Geological Survey and the University of Arizona.

Where to obtain more information about the USA National Phenology Network and ECSO:

The USA-NPN Plant Phenology Programs: www.uwm.edu/Dept/Geography/npn/

The USA-NPN National Coordinating Office: www.usanpn.org/

USA-NPN Native Species Observation Program: www.uwm.edu/Dept/Geography/npn/nativeintro.html

ECSO Contacts: www.usanpn.org/workinggroups/outreach.html
www.usanpn.org/about/contact.html

Project Budburst: www.budburst.org

PROTOCOLS FOR PHENOLOGICAL MONITORING

*I*NTRODUCTION

All phenological studies share one simple goal: to obtain precise dates of key life cycle events. There is, however, substantial variation among species in how they complete a given phenophase and this can complicate the process of identifying and assigning a date for a given phenophase. Consider the date of first flower — does a plant reach the phase of “first flower” when the petals of its first flower begin to become visible as the bud opens, or is it when the flower is open enough to see the anthers or stigma inside (the correct answer is the latter)? How do we determine this phenophase for different species whose flowers open in different ways or at different rates? Furthermore, not all flowers have the same reproductive structures inside, so our definition of first flower must also accommodate structural differences among species.

As another example, consider the spatial arrangement — or **architecture** — of the flowers produced by a plant. Some plants produce a single flower on each flowering stem whereas others produce loose or dense clusters (called **inflorescences**) of a few, of dozens, or of hundreds of flowers per stem. Within inflorescences of some species, the individual flowers may be so small that even a magnifying glass cannot make them clearly visible. How, then, should we quantify the date of first flower for a plant whose individual flowers we cannot even see!? The answers to these questions, and many more, are provided in this chapter.

The goal of this chapter is to provide definitions of phenophases for flowering plants so that observations can be standardized among observers. Given the tremendous variation in plant architecture among species, we have made an effort to facilitate the identification and recording of phenological information. First, we have aimed to minimize the number of definitions and to present them in a manner that is intuitive to all readers, regardless of their botanical experience. Second, we have identified several classes of plant architecture, each of which has its own set of protocols for the rapid identification and measurement of its phenophases. Most species of plants can easily be assigned to one of these architectural classes, so it will be a simple matter for readers to find the protocol that is most appropriate for the individual plant or species that they are observing. **We have condensed all phenophase definitions into a 3-page set of reference tables that we call the *Phenophase Quick-Guide*, which is located at the end of this chapter.**

The methods and definitions presented here have been tested by Stewards in the UCSB Phenology Stewardship Program and we’re confident that, with a little practice, even novices will soon be able to identify the phenophases of most species that they encounter. In this chapter we will consider general points, such as where and when to observe plant phenology, as well as specific points such as phenophase definitions by which phenologists can standardize their observations with other phenologists in the Santa Barbara region and across the country.

*P*LANT PHENOPHASES

Before we address general points about phenological monitoring such as site and plant selection, we will first remind the reader about plant phenophases. Although there is considerable variation among flowering plant species with regard to when and how rapidly seasonal events occur, the generalized plant phenological sequence can be summarized as follows:

- leaf budburst
- first full leaf (first leaf is fully expanded)

- entire plant leaf-out (all leaves on the plant are expanded)
- first flower
- peak flowering (largest floral display)
- last flower
- fruit maturity and seed dispersal
- leaf senescence (color change and abscission — the process of losing leaves at the end of the growing season)

Keep in mind that not all plants exhibit each of these phases, and not all plants complete phases in this order. Moreover, these phases can overlap substantially within a growing season both within and among individuals. For example, in contrast to deciduous trees and shrubs, evergreen species do not drop all of their leaves in the autumn nor do they exhibit the simultaneous production of new leaves in the spring (leaf budburst). Also, many wind pollinated plants such as birch and alder trees produce flowers before leaf budburst occurs—without leaves to break up the wind currents, pollen transport is much more efficient. Additionally, fruits often become fully ripe (and the seeds ready for dispersal) midway through the growing season before leaves have senesced and often before flowering has stopped. In Santa Barbara, California, where there is less seasonal change in climate relative to many other regions of the U.S., many species of plants flower for months at a time leading to overlap between leafing, flowering, and fruiting phenology. Keep this in mind as you continue reading and thinking about starting your own monitoring efforts.

A FEW CONSIDERATIONS ABOUT PHENOLOGICAL MONITORING

Consistency and accuracy are critical

The success of all phenological studies depends on two things: consistent observations, and accurate identifications of phenophases. Especially in the case of a phenology network where hundreds to thousands of observers are simultaneously recording the dates of phenophases for the same set of species, consistency is the key. Here we describe how to best establish and maintain your phenological studies, and later we provide you with the explicit instructions to accurately ascribe dates to phenophases.

Where To Do Phenological Monitoring

The short answer is: anywhere! Nature is all around us all the time, we just have to make a conscious effort to look. The first step is to become familiar with your natural surroundings by exploring the outdoors regularly and with a keen eye towards week-to-week and day-to-day changes in the abundances and diversity of plants and animals. Phenological observations can take place in urban, rural, and wild environments; parks and backcountry trails; schoolyards, backyards, and prison yards; and botanic gardens, zoos, and universities. Even along the roads and bike paths while commuting to and from work. The more you start looking, the more you will notice how nature is dynamic but far from random. Each year, the sequences in which plant species flower, mammals emerge from hibernation, insects emerge from dormancy, and birds migrate often occur in repeatable patterns.

The more appropriate answer to where to do phenological monitoring is: “It depends”. If your goals are simply to better acquaint yourself with the seasonality of your region, then anywhere will do—your neighborhood, outside your office building, or along the roadway or bike path on which you commute to work. If, however, your goals are to collect accurate phenological data to contribute to the Project Budburst database, then you’ll need to choose locations based on a few factors, including:

- the convenience of, and access to, the site — make sure that you are not trespassing and that it's a location that's easy to visit even when your weeks are hectic or your disposition is lazy;
- the permanence of the habitat — if that open space is slated for development in a couple months, it's best to look toward protected areas, parks, botanic gardens, and back and front yards; and
- the influence of human activity — make every effort to minimize this *source of variation*. If a city park is manicured to the point that you never see dried stems and fruits, or if shrubs are trimmed regularly so that leafing and flowering are constantly disrupted, go somewhere else. You may wish to avoid locations that you know are heavily watered, fertilized, or sprayed with chemicals because these activities impact phenology (and possibly your own health); at the very least, take note of these human-directed modifications of your plants' habitats so that you can include them when you contribute your observations (you'll have the opportunity to comment on these factors when uploading your data to the Project Budburst database).

When To Do Phenological Monitoring

The only thing that doesn't change about the natural world is that it is constantly changing! That means you can observe phenology during any time of the year. The spring and autumn are particularly rewarding periods because the biosphere changes so quickly, but even in the middle of winter or during the long days of summer the fine details of plant development can be surprising and fascinating. Currently, the national data base hosted at the Project Budburst website (www.budburst.org) is focused on spring green-up and flowering, and invites any careful observer across the U.S. to contribute phenological information from February through June each year. Consequently, throughout this Handbook, we focus on and encourage phenological monitoring of spring events.

The time schedule of a phenological study will depend on a few factors, including how rapidly the weather is changing, but can be generalized by the following example. Assume you are tracking the phenological status of a shrub in your backyard and it has dropped all of its leaves for the winter. It will remain dormant and leafless until it is warm enough to initiate springtime growth.

The next phenophase that you'll likely see is leaf budburst, so as winter beings to progress towards spring, every Thursday evening after work or school you take a close look at the status of the dormant buds. Just for fun you even start to measure the length or the circumference of a few buds on that shrub each week (mark them with a twist tie or string to revisit the same buds). As winter comes to an end and the temperature begins to warm, you increase the frequency of your observations to twice per week, say, Sunday and Thursday evenings. As spring approaches and you see the buds start to swell (you're still measuring them for fun and could even make a nice graph of their development through time), take a look every day after work until the first bud bursts open on the plant (don't forget to record the date!). This observation schedule, where observations increase in frequency as subsequent phenophases approach, is common to most phenological studies and can be repeated through the season for successive phenophases such as the full leaf expansion (typically just a day or two after leaf budburst!), first flower and fruit ripening.

This example demonstrates a few aspects about the consistency of phenological monitoring:

- Consistent observation intervals – With observations scheduled once weekly, then twice weekly, and then at daily intervals, you are certain to catch the exact date of each phenophase.
- Consistent time of day – This mostly helps to establish a regular schedule within your lifestyle. Suggestions include: just after breakfast, upon returning from school or work, and before or after a favorite television or radio program.

This example also illustrates how simple it is to make a more detailed study by tracking not just the date of the

phenophase but the rate of development leading up to it. This is particularly fun with flowering phenology. Once the first flower opens, maintain regular observations at a frequency of one to three times weekly and record the number of open flowers. Over the course of the flowering season you should see that the floral display, or the number of open flowers on the plant per survey, increases to a peak and then remains constant for a while before beginning to decrease. It is also interesting to keep notes on the diversity and abundance of pollinators that you observe visiting your plant(s).

In sum, consistent monitoring intervals are critical to ensuring that you catch the precise date that a phenological event occurs. There are many ways to increase the probability that you'll maintain a consistent monitoring effort, and we outline some of these ways in the following section.

Which Plant Species To Monitor

There are over 250,000 species of flowering plants in the world, so how do you choose which plants to monitor? Here we provide general advice on selecting plant species in your area as well as some specific ideas on which plants to look for.

General advice for appropriate plant species for phenological monitoring

The most general suggestion we can make is start monitoring any plant that you've learned to identify and for which you know the common or the scientific (latin) name! The first step is to familiarize yourself with your natural surroundings and begin to observe day-to-day and week-to-week changes in the appearances of plants. Choose plants where you spend the majority of your time, typically around your home, school, work place, and grocery store. Don't be shy! Get into the habit of recording brief observations about a few plant species each week—do the leaves look green and healthy or brown and withered? Are there flower buds, open flowers, and/or developing fruits on the plant? What do they look like? Are there insects that visit or that live on the plants, and if so, what do they look like and approximately how many are there each week? By taking a few minutes a few times per week to record your observations (and to compare to your records from weeks past), you're sure to develop a keen eye for the pace of plant phenology.

Community-Based Decision

Plant species can be chosen in a number of ways for phenological monitoring. To start, consider this basic question: What is the native habitat(s) and plant community in your region, and which are the dominant native plant species? To answer this question you can visit native plant nurseries, botanical gardens, or state parks in your region and ask staff members or docents to help you to identify native plant species that can be found locally. You may also take local hikes with a published field guide of your region's native plants, enroll in a botany or horticulture class at a community college, or contact your county extension service. The immediate Santa Barbara region is fortunate to include several distinct habitats—coastal dune, coastal sage scrub and wetlands on the coastal plain (where the majority of people live), and chaparral and riparian (streamside) communities in the surrounding mountains. It is simple to conduct online searches of these (and other) habitats to discover the names and appearances of the dominant plants in each of them. You can then head into those habitats for a hike or a picnic to identify plant species.

Phenology-Based Decision

Species of plants can also be chosen for phenological monitoring based on their seasonal phenology. Choose a couple of species of wildflowers that bloom in the spring, a shrub that flowers in early summer, a shrub that flowers in late summer, and another herbaceous plant that flowers in the fall. Then, during the winter revisit

your summer-flowering shrubs to check for dormant leaf buds. By following this scheme, you will become tuned-in to the both the seasonality and the phenology of your region.

Specific Advice For Appropriate Plant Species For Phenological Monitoring

This Phenology Handbook has been created based on phenological research and monitoring conducted in the major habitat types in the Santa Barbara region. Most of this research has taken place at UCSB's Coal Oil Point Natural Reserve which is characterized by coastal dune and coastal bluff vegetation. Below is a list of 21 species of plants that the UCSB Phenology Stewardship Program has been monitoring at this reserve since spring of 2007. Many of these plants are available (seasonally) for purchase at local nurseries, the Santa Barbara Botanic Garden, and at plant sales held by local organizations. They can be easily added to residential or workplace landscapes, facilitating their phenological monitoring. Some of these plant species are also described in detail in the "Field Guide to Coal Oil Point Natural Reserve" chapter of this Handbook.

FAMILY	SCIENTIFIC NAME	COMMON NAME
Anacardiaceae	<i>Toxicodendron diversilobum</i>	Poison Oak
Asteraceae	<i>Ambrosia chamissonis</i>	Beach Bur
Asteraceae	<i>Anaphalis margaritacea</i>	Everlasting
Asteraceae	<i>Encelia californica</i>	California Brittlebrush
Asteraceae	<i>Isocoma menziesii</i>	Coast Goldenbush
Asteraceae	<i>Malacothrix saxatilis</i>	Seacliff Daisy
Brassicaceae	<i>Cakile maritima</i>	Sea Rocket
Caprifoliaceae	<i>Sambucus mexicana</i>	Elderberry
Chenopodiaceae	<i>Atriplex lentiformis</i>	Quailbush
Convolvulaceae	<i>Calystegia soldanella</i>	Beach Morning Glory
Fabaceae	<i>Lupinus arboreus</i>	Bush Lupine
Hydrophyllaceae	<i>Phacelia ramosissima</i>	Branching Phacelia
Nyctaginaceae	<i>Abronia umbellata</i>	Beach Sand Verbena
Onagraceae	<i>Camissonia cheiranthifolia</i>	Beach Evening Primrose
Onagraceae	<i>Epilobium canum</i>	California Fuchsia
Onagraceae	<i>Oenothera elata</i>	Hooker's Evening Primrose
Papaveraceae	<i>Eschscholzia californica</i>	California Poppy
Polygonaceae	<i>Eriogonum parviflorum</i>	Seacliff Buckwheat
Scrophulariaceae	<i>Antirrhinum nuttallianum</i>	Nuttall's Snapdragon
Scrophulariaceae	<i>Scrophularia californica</i>	California Figwort
Solanaceae	<i>Solanum douglassii</i>	Douglas's Nightshade

Table 1. List of plant species that have been monitored at Coal Oil Point Natural Reserve (in Santa Barbara, California) by the UCSB Phenology Stewardship Program since Spring of 2007. Two of these species (in bold) are also on the targeted species list for Project Budburst.

There are also many species of plants on which we are focusing the attention of phenologists across the country for participation in Project Budburst. The full list of targeted plant species is available (and is also broken down by each state, including California) in the "Participate" section of the Project Budburst website (www.budburst.org).

It's interesting to visit the species lists of other phenology networks worldwide which invite participation by citizen scientists. There you will be able to find lists of species that are monitored throughout Europe and Canada, many of which are also found in the U.S. A particularly rewarding research exercise for teachers and students (or families with young scientists) is to determine: (1) which plant species monitored in these other phenology networks are also found in the U.S. and in the students' region, and (2) how the phenology of the species found in the students' region compares with the phenology of the same plant species monitored by citizen scientists in the other networks.

NatureWatch (Canada): <http://www.frogwatch.ca/english/>

Nature's Calendar (UK): <http://www.naturescalendar.org.uk/>

Natuurkalender (Netherlands): <http://www.natuurkalender.nl/index.asp> (Translation via Google)

The European Phenology Network: <http://www.dow.wau.nl/msa/epn/index.asp>

Accumulating and comparing phenological data

This brings us to an important point about the nature of collecting phenological data. Given that all flowering plants exhibit at least a few of the above phenophases (first, peak, and last flower), and given that pollination and fertilization events occur prior to most fruit and seed maturation, it is ideal to track each individual plant through its entire annual cycle and record the dates of all of its phenophases. This approach, when repeated for many individuals of the same species, enables us to compare their phenological progression in different locations or habitats and eventually, across years and decades.

For instance, imagine that you have monitored the flowering duration of the California Poppies in your home garden (calculated as the number of days between the appearances of the first and last flowers). Imagine that you have also recorded the first and last flowering dates of 30 additional Poppy plants on a nearby hiking trail, noting the approximate elevations of each plant. With these simple records, it would then be possible to ask specific questions about this species, such as:

- Do all California Poppies flower for the same duration, or do early-flowering individuals get a head start on the season and flower for a longer duration than later-flowering individuals?
- Do individuals growing at low elevations flower earlier and/or longer than high-elevation individuals found at high elevations?
- Do poppies that may be subject to urban heat-island effects flower earlier than those in natural habitats?
- Do garden-grown Poppies flower longer than wild Poppies, possibly because environmental factors such as summer drought or herbivory shorten the flowering period in the wild?

As many species of plants continue to initiate flowering earlier in the season as a phenological response to climate change, these questions are important to ecologists and agricultural specialists seeking to understand how plants respond to changes in climate and how they will balance different environmental pressures.

***P*HENOPHASE DEFINITIONS**

Phenological monitoring is facilitated by first noting two features of all flowering plants:

- Floral architecture or inflorescence type - are flowers clustered in inflorescences, or are they borne singly?
- Habit - is the plant herbaceous (non-woody) or woody? Is the plant a shrub or a tree?

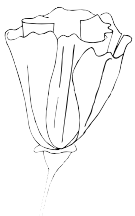
We've written phenophase definitions based on combinations of architecture and habit. **When determining the date of a phenophase, simply determine the habit and flowering architecture of your plant and locate the appropriate cell in the Phenophase Quick-Guide.**

FLOWERING ARCHITECTURE

Whether a plant produces solitary flowers or inflorescences will change the way that flowering phenophases are determined and recorded. See the Phenophase Quick-Guide and the list below to examine these effects. Below are illustrations of the major inflorescence types that you are likely to encounter. **Once you identify the inflorescence type of your targeted species, simply find the appropriate cell in the Quick-Guide to find the quick definition of each leafing or flowering phenophase.**

To help orient you when examining flowers on an unfamiliar plant, the following illustrations show a variety of floral displays you may encounter. Compare the illustrations to the photos in the "Field Guide to Coal Oil Point Natural Reserve" in this Handbook, and to photos in other field guides, to feel more comfortable in the field. To help simplify your experiences in the field we have categorized inflorescences by general appearance. Once you identify the inflorescence type of your targeted species, simply find the appropriate cell in the Phenophase Quick-Guide to find the quick definition of each leafing or flowering phenophase.

SOLITARY FLOWERS



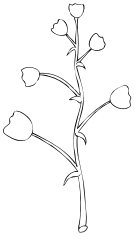
Solitary flowers are borne singly on stems. The California Poppy, *Eschscholzia californica*, is an example.

SPIKE-LIKE INFLORESCENCES



Spike

Elongated inflorescence in which flowers are arranged in a linear manner along the stem and are attached directly to the main stem (pedicels, or stems connecting flowers to the stem, are absent). Flowering typically begins at the base of the spike and progresses upward.



Raceme

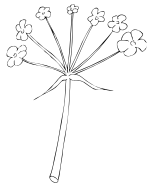
Elongated inflorescence in which flowers are attached to the main stem by pedicels. Flowering typically begins at the base of the raceme and progresses upward.



Panicle

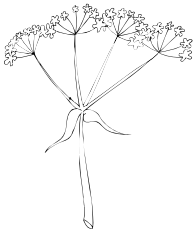
Elongated and branching spike-like inflorescence. Each flower is attached to a branch by a pedicel, and each branch is similar to a small raceme. A panicle is essentially a compound raceme inflorescence. Flowering variably begins at the base of the panicle and progresses upward.

UMBEL-LIKE INFLORESCENCES



UMBEL

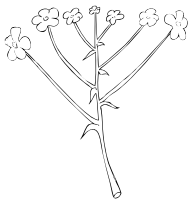
The pedicels of umbelliferous flowers attach to the stem at a common point, like the struts of an umbrella. Flowering progression is variable but often starts at the outer edges and progress either concentrically toward the center or as a wave across the umbel.



COMPOUND UMBEL

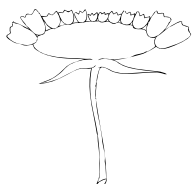
An umbel of umbels. The pedicels of umbelliferous flowers attach at a common point, and the stems (peduncles) of each umbel is attached at a common point. The progression of flowering is highly variable.

OTHER TYPES OF INFLORESCENCES



CORYMB

Not a true umbel, but often appears as umbel-like and flat-topped in the field. Actually a raceme where the lowest flowers have elongated pedicels. The lowest flowers on the main stem typically begin flowering first.



HEAD

A dense cluster of small flowers on a head-like stalk. All plants in the Sunflower family (Asteraceae) produce head inflorescences. Flowering typically begins at the outer edges of the head ("disk") and progresses concentrically toward the center.



Scorpioid cyme

Essentially a raceme inflorescence that is coiled. Flowering begins with the lowest flowers on the stem and progresses upward as the inflorescence uncoils to an erect spike-like structure. The open flowers are typically found at the apex of the coil.

Catkin

Catkins are hanging spikes, typically found on trees.

HABIT

The habit of a plant is its characteristic appearance and growth form. Plant habits that are common to the temperate zone include:

- **Herbaceous** – A non-woody flowering plant that can be annual, biennial, or perennial; the stems remain flexible and relatively soft. Examples in the Santa Barbara region include wildflowers such as Lupine and California Poppy, grasses, and many culinary herbs such as cilantro, parsley, and basil.
- **Forb** – herbaceous flowering plants, excluding grasses. Typically used when referring to wildflowers. We use this term in the Phenophase Quick-Guide.
- **Shrub** – A woody perennial plant, typically with multiple main stems. Shrubs can be evergreen or deciduous, and height is commonly <5m. Common examples in the Santa Barbara region include Poison Oak, Lemonade Berry, Ceanothus, Manzanita, and Coyote Bush.
- **Tree** – A woody perennial plant, typically with one main stem (tree trunk) and height >3m. Common examples in the Santa Barbara area include Eucalyptus, oaks, Sycamore, California Bay, and pines.

The habit of your targeted plant will have a strong effect on how you record its leafing and flowering phenophases. **In forbs, the very first appearance of the phenophase (e.g., first flower or leaf) marks the onset of a given phenophase, just as you'd expect.** In shrubs and trees, however, we must accommodate their vastly larger size and number of branches. **Consequently, the onset of a given phenophase in shrubs and trees is marked by the appearance of the phenophase in three different locations (branches for leafing phases, inflorescences for flowering phases) before we record it.** Once you identify the habit of your targeted species, simply find the appropriate cell in the Quick-Guide to find the quick definition of each leafing or flowering phenophase.

See the Phenophase Quick-Guide to find precise definitions of phenophases given a species' combination of flowering architecture and habit.

A note about fruits

Fortunately, the “rules” of phenological development of fruits are more or less independent of inflorescence architecture, habit, and developmental pattern. All pollinated flowers develop into seed-containing fruits, given enough resources and time. There are many kinds of fruits, each of which becomes ready for dispersal in a different way. For example, berries and other fleshy fruits are removed by animals when ripe; capsules and legumes split open to release their seeds when dry; and winged fruits, which often are dispersed by wind while still containing their seeds. Monitoring the timing of fruit maturity or ripening requires that you be able to identify when the seeds are dispersable, whether by animals or wind or gravity. Hints include noting when fruits appear to have been removed (or drop to the ground when soft), when fruits change color from unripe (usually green) to ripe-and-ready (often black, red, orange, or yellow), when capsules split open to reveal the seeds inside, and when the wind carries fruits (or winged seeds) away from their maternal plant.

PHENOPHASE QUICK-GUIDE

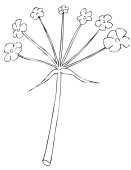
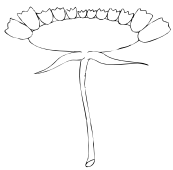
When determining the date of a phenophase, simply determine the habit and flowering architecture of your plant and find the appropriate cell in the table of phenophase definitions. We have provided three tables of phenophase definitions: leafing phenophases, first flower, and last flower.

DEFINITIONS OF LEAFING PHENOPHASES

	Leaf budburst		First full leaf		Entire plant leaf-out	
	Simple leaf	Compound leaf	Simple leaf	Compound leaf	Simple leaf	Compound leaf
Habit						
Forb	Not applicable (forbs don't produce dormant winter buds)	Not applicable	The date on which the first leaf has expanded to its final size (can be tricky when leaves take a long time to fully expand)	The date on which the first leaf has fully expanded; the midrib has reached its final length (individual leaflets need not be fully expanded)	The date on which all leaves have fully expanded. Be aware that plants with indeterminate (continuous) growth may continue to produce leaves throughout the season.	The date on which all leaves have fully expanded. Be aware that plants with indeterminate (continuous) growth may continue to produce leaves throughout the season.
Shrub or Tree	The date on which the third bud "bursts", revealing green leafy tissue	The date on which the third bud "bursts", revealing green leafy tissue	The date on which the third leaf has fully expanded, and the pedicels are visible	The date on which the third leaf has fully expanded; the midrib has reached its final length (individual leaflets need not be fully expanded)	The date on which all leaves on the plant have fully expanded. Be aware that plants with indeterminate (continuous) growth may continue to produce leaves throughout the season.	The date on which all leaves on the plant have fully expanded. Be aware that plants with indeterminate (continuous) growth may continue to produce leaves throughout the season.

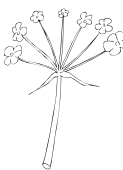
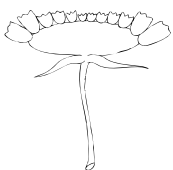
DEFINITIONS OF FIRST FLOWER

Note that a flower is considered to be “open” as soon as the petals open far enough to reveal the reproductive structures (anthers and/or stigmas) inside.

	Inflorescence Type				
	Solitary Flower	Spike-like inflorescences	Umbel-like inflorescences	Heads	Cymes
					
Habit					
Forb	The date on which the first flower on the plant opens	The date on which the first flower opens on any spike	The date on which the first flower opens on any umbel	The date on which the first <i>disk flower</i> opens in any head	The date on which the first flower opens on any cyme
Shrub or Tree	The date on which the third flower on the plant opens	The date on which at least one flower has opened on three spikes	The date on which at least one flower has opened on three umbels	The date on which at least one <i>disk flower</i> has opened in three heads	The date on which at least one flower has opened on three cymes

DEFINITIONS OF LAST FLOWER

Note that a flower is considered to be “open” as soon as the petals open far enough to reveal the reproductive structures (anthers and/or stigmas) inside.

	Inflorescence Type				
	Solitary Flower	Spike-like inflorescences	Umbel-like inflorescences	Heads	Cymes
					
Habit					
Forb	The date on which the last flower has opened on the plant; any remaining buds remain closed	The date on which the last flower has opened on the plant; any remaining buds remain closed	The date on which the last flower has opened on the plant; any remaining buds remain closed	The date on which the last disk flower opens in any head on the plant (look for the last-opening disk flowers towards the center of the head)	The date on which the last flower has opened on the plant; any remaining buds remain closed
Shrub or Tree	The date on which the last flower has opened on the plant; any remaining buds remain closed	The date on which the last flower has opened on the plant; any remaining buds remain closed	The date on which the last flower has opened on the plant; any remaining buds remain closed	The date on which the last disk flower opens in any head on the plant (look for the last-opening disk flowers towards the center of the head)	The date on which the last flower has opened on the plant; any remaining buds remain closed