Phenology Lecture #3
Phenological responses to environmental change: Examples and potential outcomes
Slide Notes

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Slide 1: phenological responses to environmental change: examples and potential outcomes
This lecture uses a series of case studies to introduce students to topics regularly addressed by phenological research community.

Note to instructors: More phenology educational materials and activities are available online***,*** including lesson plans for advanced undergraduate or graduate seminars; lesson plans for undergraduate laboratory activities; and phenological activities for use in informal educational settings. To learn more and to download materials, visit the Education section of the California Phenology Project website (www.usanpn.org/cpp/education) or the USA National Phenology Network (www.usanpn.org/education).

Slide 2: introduction to the biological significance of phenology
This slide serves to remind students that phenological processes are key components of almost all organisms' evolution and ecology. The quote comes from an article written by Jessica Forrest and Abraham Miller-Rushing in 2010. This article was part of a special themed issue of the journal *Philosophical Transactions of the Royal Society, B,* called "***The role of phenology in ecology and evolution***", which includes several review and primary articles focusing on the biological significance of phenology. The slides that follow provide evidence in support of Forrest and Miller-Rushing's (2010) statement.

Slide 3: outline
The lecture begins by discussing the biological significance of phenology, and then presents examples of phenological responses to climate change. The slides that follow introduce the concept of **phenological mismatches**, a topic of great interest among biologists and resource managers. The last portion of the lecture describes studies documenting three widely predicted, long-term phenological responses to climate change (geographic range shifts, evolutionary adaptation, and extinction).

Slide 4: importance of matching the timing of life-history events with environmental conditions
Plants and animals have many requirements for survival. For example, they must avoid unfavorable environmental conditions and times of the year when resources are scarce. Moreover, interactions with predators and/or pathogens may dramatically affect survival. So if possible, numerous organisms try to minimize their interactions with these antagonists.

Potential Question for Students: What are some examples of harsh conditions that organisms avoid? What are some resources that may be scarce at certain times of the year? Can anyone describe any interactions with antagonists that have a seasonal component?

Slide 5: importance of matching the timing of life-history events with environmental conditions

Many phenological traits have evolved over many generations in response to these requirements for survival. Organisms may time their phenological schedules such that environmentally vulnerable phenophases coincide with favorable climatic conditions. Organisms may also time their phenological schedules so that phenophases with high resource demands coincide with times of year associated with relatively high resource availability. Organisms may also evolve to schedule phenophases that interact with mutualistic partners (e.g., pollinators) to co-occur with key mutualists.

Slide 6: example of ecological significance of phenology in sunflowers

A study conducted by Pilson (2000) provides an excellent example of how an individual's phenological schedule affects its overall fitness. Sunflowers (and all members of the daisy family) produce clusters of tiny flowers called "head inflorescences". Each "sunflower" that you see is actually an inflorescence composed of dozens of individual flowers (which are visible in this photo). When sunflower inflorescences bloom, their tiny flowers are very appetizing to a number of insect herbivores, including the sunflower bud moth (*Suleima heliantha*).

Slide 7: phenology and herbivory

Herbivore presence is associated with plant phenology in sunflowers. This figure from Pilson (2000) shows that individuals whose inflorescences bloom early in the season *and* late in the season contain fewer herbivorous moths than those whose inflorescences bloom in the middle of the season.

Slide 8: phenology, herbivory, and fitness

The timing of flowering affects fitness in sunflowers, as is shown in this slide. Herbivore damage has a significant negative effect on individual fitness. Pilson (2000) excluded herbivores from some inflorescences (black circles) and left other inflorescences alone (open circles). Uncovered inflorescences (open circles) that bloomed while *Suleima* moths were most abundant produced significantly fewer seeds inflorescences that were protected from herbivores.

Slide 9: revisit the outline

The next part of the lecture focuses on biological responses to climate change. These responses have been documented using manipulative studies, shown to vary among taxa, and may also influence the human population. We'll look at three case studies in detail to see how scientific researchers have demonstrated phenological responses to climate change.

Slide 10: Sherry et al. (2007) - manipulative studies have shown that even short-term climate change can affect flowering phenology

The next few slides describe a manipulative study focusing on several prairie plant species that occur in the mid-western United States.

Slides 11 and 12: Sherry et al. (2007) - manipulative studies have shown that even short-term climate change can affect flowering phenology

These slides describe the experimental design of this study.

- The researchers planted 12 plant species into experimental plots
- The researchers used the equipment pictured in this slide to manipulate temperature and precipitation regimes experienced by plants in each plot
- The researchers monitored the flowering and fruiting phenology of the 12 prairie species for one year

Each plot was subjected to one of the following four experimental treatments:

1. Ambient temperature, ambient precipitation (control treatment)
2. Warmed temperature, ambient precipitation
3. Ambient temperature, doubled precipitation
4. Warmed temperature, doubled precipitation

Slides 13-16: serial views of Figure 1 from Sherry et al. (2007)

This figure is revealed in increments in slides 13 through 16. The figure shows changes in the onset of flowering (A, **Slide 13**) and fruiting (B, **Slide 14**) (in days) in response to the experimental treatments. Slides 13 and 14 show the responses of all 12 species to the warming treatments. The x-axis shows the number of days that a species' phenophase differed from that of the control treatment. For example, in Slide 13, species with bars extending to the right (*Andropogan, Schizachyrium,* and *Ambrosia*) exhibited delayed flowering. Species with colored bars extending to the left (all other taxa) exhibited accelerated flowering. **Slide 15** shows the species responses to the warming + DP treatment. DP stands for "doubled precipitation".

Species are listed in the order buds were first observed in control plots, beginning in March with *Viola* and ending in late August with *Ambrosia*. A positive value indicates earlier flowering or fruiting than the control; a negative value indicates later flowering or fruiting than the control. For the warming and warming plus DP treatments, the differences in flowering and fruiting from the control are significant for all species except *Erigeron (*green bar*)* ($P < 0.05$).

In the DP treatment (**Slide 16**), there were no significant differences in the onset of flowering and fruiting from the control. Data are means (± SE) for advanced or delayed phenology, respectively.

Slides 17-20: serial views of Figure 2 from Sherry et al. (2007)

This figure shows the effects of warming on the timing of the onset and duration of reproduction in the 12 prairie species studied by Sherry et al. (2007). The entire reproductive period is composed of three phases (budding, flowering, and fruiting). The green bars represent plants in the control plots, the red bars indicate the warmed plots, and blue diamonds indicate the mean starting date of flowering for each species in each treatment.

The dotted vertical line indicates the peak summer temperature as defined by the maximum temperature of the regression curve.

Panicum (shown in **Slide 18**) showed a strong response to warming. Students may enjoy discussing some implications of this observation.

Some potential questions to ask students include: Would *Panicum* be able to adapt to a warming climate? Why or why not? How might the phenological shift observed here influence organisms that rely on *Panicum* for food?

Erigeron (shown on **Slide 19**) does not show a response to warming.

Some potential questions to ask students include:
What are some implications of this observation? Would you expect *Erigeron* to adapt to a changing climate? How might a disruption in the degree of overlap among species influence organisms that are higher up in the food chain? If these other organisms are plant mutualists (e.g., pollinators or seed dispersal agents), how may this affect the ability of plant populations to survive and adapt to environmental change?

Slides 21-22: phenological responses of different taxa
Sherry et al. (2007) showed that plants respond to environmental change, even in the short term. But a question that might follow is: "how do other taxa respond to climate change?"

Meta-analysis is a statistical approach that combines the results of several studies that test similar hypotheses. Scientists often use meta-analyses to look for broad trends that may exist on a very large scale. Parmesan (2007) conducted a meta-analysis to ask the simple question "Do different groups of organisms respond in similar ways to climate change?"

Slide 23: figure from Parmesan (2007)
This figure shows that phenological responses to climate change appear to vary greatly both within and among taxa. Amphibian phenology, in particular, appears to be quite sensitive to climate change.

Potential questions to ask students: Which organisms' phenological responses have been the most studied (as of 2007)? Which organisms' phenological responses may require more study to understand? How might interacting species (plants-pollinators; predator-prey) respond to climate change?

Slide 24: revisit the outline
Most studies of phenology have focused on wild plant and animal communities, but a growing body of research investigates the potential effects of phenological shifts on processes that directly influence the human population.

Slide 25: examples of phenological events that influence the human population
The timing of festivals (e.g., the Cherry Blossom Festival in Washington, D.C.), crop harvests, ecotourism events (e.g., wine tasting, whale watching), and even pest outbreaks (e.g., pine bark beetles attacking forest trees) are examples of seasonal activities that may regularly affect people's lives and well-being.

Slide 26-27: pollen-allergies affect millions of people worldwide
Ragweed (*Ambrosia* sp.) is a common allergen in the United States. Many people experience **seasonal** ragweed allergies, which are induced by ragweed flowering. Pollen counts for this plant are even published daily, as is shown in this map.

Slide 28: the duration of the ragweed allergy season has increased as a function of climate
This figure shows the change in the length (days) of the ragweed pollen season from 1995 to 2009 as a function of frost-free days, and delays in the time of first frost during the fall, for 10 central North American locations (eight in the United States and two in Canada). As temperature has increased in North America, so has the length of the ragweed allergy season.

Slide 29: revisit the outline
We know that phenological schedules have shifted in response to climate change. Moreover, studies have demonstrated that phenological responses differ among species. So the potential for climate change to result in species "mismatches" has long been an area of intense interest among phenologists and natural resource managers. This section of the lecture defines mismatches and provides an example of a trophic mismatch between a bird species and its food source.

Slides 30-32: phenological mismatched defined
Phenological mismatches occur when the timing of the availability of an important resource (such as food) changes in response to climate, **BUT** the timing of the demand for said resource does not change. The figure reproduced from Stenseth and Mysterud (2002) provides a comparison of "phenological match" versus a "phenological mismatch".

Slides 33-36: serial presentation of a trophic mismatch between the pied-fly catcher and its food source (Both et al. 2006)
In response to climate change, the winter moth and the leaves of its primary larval food source, the English oak, are emerging earlier in the season than in the past. The pied flycatcher, a migratory bird that feeds on the winter moth, however, has not shifted its migration time. This mismatch has led to steep (>90%) population declines in the nine populations studied by Both et al. (2006).

Slide 37: revisit the outline
The remaining portion of the presentation focuses on three potential long-term outcomes of phenological change: geographic range shifts, adaptation, and extinction. These outcomes have been widely predicted by numerous independent researchers. We'll use a series of case studies to learn how scientists investigate whether these outcomes are occurring in wild populations.

Slides 38-39: geographic range shifts (Jepsen 2011)
The geographic ranges of some species may change in response to climate change. This slide introduces a study conducted by Jepsen et al. (2011), which documents the range shift of a forest insect pest and relates this range shift to novel phenological matching between the pest and its food source.

The area indicated by a blue bracket on the map of Norway in **Slide 38** shows the former range of the pest species (the spring umber moth) in black horizontal lines near southern Norway. The species has moved north, however, the green circle on **Slide 39** shows the part of northern Norway where the study was conducted.

Slides 40-41: introduction to the pest and its food source
The scarce umber moth is one of SEVERAL pests that feed on the young leaves of birch trees in northern Scandinavian birch forests. Defoliation of these trees can be quite severe.

Slide 42: evidence of increasing temperatures at Jepsen et al.'s (2011) study sites in northern Norway
Over the past 30 years, temperatures have risen at the researchers' study sites.

Slides 43-45: evidence that the scarce umber moth encroachment in northern Norway

- The left side of the figure shows the current known distribution of the scarce umber moth in Norway.

- The map on the right side of the figure shows the 12 sites in the study region (coastal districts of Tromso) where moth populations have been monitored since 1999.

- The middle portion of the figure shows population trajectories per site (the number of larvae on 100 branches of mountain birch) for two forest pest species (solid line: scarce umber moth, hatched line: winter moth).

- In recent years, **scarce umber moths** (solid lines) have become increasingly abundant at the southern coastal study sites relative to northern sites.

Slide 46: warming and increased matching of pest-plant phenological schedules
The researchers raised moth eggs and birch branches in climate chambers set to different temperatures. Their results show that as temperatures increase, the timing of moth egg hatching and birch leaf emergence become more and more synchronous. The finding that

warming contributes to increased phenological matching, suggests that phenological shifts have allowed the umber moth populations to move northward.

Slide 47-48: changes in elevation in response to climate change
Some species may migrate to higher elevations where mild temperatures may prevail, despite changing climate. This may be already happening. In a recent study published in the journal *Science*, Chen et al. (2011) estimate that species are shifting on average ~11m in elevation per decade.

Slide 49: revisit the outline
Evolutionary adaptation is another potential response to climate change. If phenological schedules can evolve in response to changing environmental conditions, then plant and animal species may be able to survive and persist as the climate warms.

Slides 51-54: brief explanation of natural selection
These slides serve to remind students about the evolutionary process of natural selection. Phenological traits may evolve in response to climate change if there is genetically based variation in phenological schedules among individuals in populations and if reproductive fitness varies among individuals in the population. If selection consistently favors individuals with particular trait values, this may lead to changes in trait values over multiple generations. The concepts described above are presented graphically in the presentation.

Some potential questions to ask students include: Have any of the studies described thus far (e.g., Sherry et al. 2007, Parmesan 2007) shown an evolutionary response to climate change? Why or why not?

Slides 55-56: Franks et al. (2007) detected rapid evolution of a phenological trait in response to a climate fluctuation
The researchers collected field mustard (*Brassica rapa*) seeds from a single site. This site underwent a severe, extended drought period in the late 1990's and early 2000's.

Seeds collected in 1997 were designated as grown in a "wet environment" (before drought occurred). Seeds collected in 2004 were designated as grown in a "dry environment" (after extended drought).

It should be noted here that the seeds were collected from the exact same site and thus originate from the same population.

Slides 57-58: Franks et al. (2007) detected rapid evolution of a phenological trait in response to a climate fluctuation
Because flowering time is genetically determined (at least in part) in field mustard, the researchers could grow the plants in common environments to determine whether adaptive evolution of this trait had occurred over the seven-year interval between seed collection events.

The researchers grew plants from both collection environments (wet and dry), and wet x dry hybrids in two different common environments (a wet growing environment and a dry growing environment).

Slide 59: Franks et al. (2007) detected rapid evolution of a phenological trait in response to a climate fluctuation
They found that flowering time had significantly accelerated in the seven-year interval between collections. Interestingly, this study showed that a phenological trait could evolve in a relatively short period of time in response to a climate shift.

Slide 60: revisit the outline
Another potential response to global climate change is extinction. Documented studies showing unambiguous links between climate change, phenological shifts, and species extinction are lacking. Studies have shown, however, that certain populations whose phenological schedules have not shifted in response to climate change are declining.

Slides 61 -63: extinction risk and phenology – the example of migratory birds in Europe
Moller et al. (2008) took advantage of the fact that spring migration times and demographic trends of 100 European bird species have been closely monitored for over 50 years. They found that species that did not adjust the timing of their spring migration are currently in decline. This trend is shown in **Slide 63**. This suggests that these species that cannot evolve or shift their geographic ranges in response to climate change face a high extinction risk.

Slide 64: outline
This slide serves to remind students of the topics presented in the lecture. A list of the peer-reviewed journal articles discussed during different parts of the lecture is also provided.

Slides 65-66: references
These slides provide full citation information for the articles discussed in this lecture.