Annual Report Vol. 41 (2018)

For everything there was a season: phenological shifts in the Tetons

Trevor Bloom[1,2,*], Corinna Riginos[1,3], Donal O'Leary[4]

1 The Nature Conservancy, Lander, WY
2 Northern Rockies Conservation Cooperative, Jackson, WY
3 Department of Zoology & Physiology, University of Wyoming, Laramie, WY
4 Department of Geographical Sciences, University of Maryland, College Park, MD
* Author for correspondence: trevor.bloom@tnc.org

Abstract Around the world, phenology — the timing of ecological events — is shifting as the climate warms. This can lead to a variety of consequences for individual species and entire ecological communities. Grand Teton National Park biologists have identified this topic ("effect of earlier plant flowering on pollinators and wildlife") as one of their priority research needs. We assembled phenological observations of first flowering dates for 49 species collected by Frank Craighead, Jr. in the 1970s, before significant warming occurred. In 2016 we began standardized phenological observations of these same species, plus an additional 61 for a total of 110 species, in the same locations. First flowering date for 65% of the species with historic records correlated significantly with mean spring temperature; these species are therefore expected to flower earlier now than in the 1970s. Early spring flowers had the largest shifts in phenology, emerging an average of 21 days earlier now relative to the 1970s. Yet not all species are emerging earlier. In particular, phenology of late summer/early fall flowering plants was largely unchanged. In 2017, we initiated pollinator collections at our key phenology sites. Additional years of observations will allow us to better understand plant-pollinator interactions and identify potential phenological mismatches.

Introduction

Climate change is a significant threat to biodiversity (Monahan and Fisichelli, 2014; Parmesan and Yohe, 2003). In the Rocky Mountains, climatic changes such as the earlier arrival of spring snowmelt (Hall et al., 2015) and advancing spring onset (Ault et al., 2015; Monahan et al., 2016; Monahan and Fisichelli, 2014) are leading to changes in plant and animal interactions (Armstrong et al., 2016; Dillon, 2011; Kearns et al., 1998; Middleton et al., 2013), plant reproductive success (Inouye, 2008), and disturbances such as more wildfire (Bloom et al., 2018*b*; O'Leary et al., 2016). Around the world, many species' phenologies are shifting as global and local climates warm (Inouye, 2008; Parmesan and Yohe, 2003). Examples of phenological traits include when plants leaf out, first flower, or reach peak flowering; when insects emerge, metamorphose, pollinate, and reproduce; or when migrating birds arrive in breeding grounds. Although some species' phenologies are closely linked to temperature and climatic events such as snow melt (O'Leary et al., 2018; Sherwood et al., 2017; Willis et al., 2008), other species' phenologies can be driven by day-length cues (Coppack et al., 2003; Dawson et al., 2001; Gwinner, 1990). As the climate warms, this can result in phenological mismatches or novel synchronies between species pairs (Deacy et al., 2017; Kearns et al., 1998). Observed shifts in phenology are often the first signs that climate change is impacting natural populations and may be an early warning of future population declines or local extinctions (Willis et al., 2008). Plants that shift phenology in response to changing temperatures may fare better under a warming climate (Willis et al., 2008).

One approach to understanding the impacts of anthropogenic climate change on phenology is to compare current-day phenological events with the timing of those events in historic records that pre-date the influence of climate change. Detailed historic phenology data are rare, but in GTNP we have the opportunity to capitalize on data gathered by ecologist Frank Craighead, Jr. in the 1970s. These data served as the basis of his popular book *For Everything There is a Season* Craighead Jr (1994), which gives a week-by-week account of ecological events that are likely to be occurring in the Grand Teton-Yellowstone area. Similar phenology notes have been used to compare past and present patterns in a handful of other locations around the United States. These include Thoreau's notes from Massachusetts (see Miller-Rushing et al., 2012 for a synthesis of findings), Aldo Leopold's notes from Wisconsin (Bradley et al., 1999), and the notes of the Smiley brothers in New York (Cook et al., 2008).

Within the Greater Yellowstone Ecosystem (GYE) and GTNP, there is currently little understanding of how climate change is affecting plant and animal phenology or potential asynchronies between these guilds. One study used remotely-sensed data to conclude that more rapid spring green-up is negatively impacting migratory elk populations in the GYE (Middleton et al., 2013). Others are showing that warming temperatures in GTNP may impact plant nectar production and pollinator resources (Debinski et al., 2014; Dillon, 2011; Sprayberry et al., 2016; Monahan et al., 2016). While these studies are indicative of changes that are occurring, a more detailed understanding of how plant phenology is changing at the species level — and what it means for the myriad species that depend on these plants in the GYE — is needed in order for managers to anticipate and mitigate impacts of these changes (UW-NPS, 2017).

Our primary research question is: 1) how has plant phenology, on a species level, shifted now relative to the 1970s in the Tetons? Additional research questions include 2) what climate variables (e.g. spring temperature, precipitation as snow, timing of snowmelt) are most closely related with plant flowering times and pollinator emergence? 3) What are the plasticity and predicted future flowering times for ecologically important plant species in the Tetons? 4) And importantly, what are the likely consequences of current and future changes in plant phenology for key pollinators (e.g. bumblebees, hummingbirds, butterflies) and other wildlife (e.g. sage-grouse, bears)? Ultimately we aim to better understand ecological relationships and assist in the mitigation of climate change impacts on the plants and wildlife of the GYE. We also seek to increase public involvement and understanding of climate change and science-based decision making through engagement in our citizen science project, Wildflower Watch.

Methods

Historical collections

We retrieved hand-written notes, entered these into digital form, and quality-controlled nearly 800 observations that Frank Craighead Jr. made of plant flowering and fruiting dates in 1974-1979 and 1988. During each of these year's spring or summer seasons, Craighead made near-daily observations of phenological events. His notes include 258 species of flowering plants, although not every plant was observed every year. We categorized plant observations representing first presence of leaves, first presence of buds, first flower, peak flower, and occurrence of fruits or seeds. The vast majority of the observations were of first flowering date, and we have therefore focused our analyses on this phenological event. Most of Craighead's observations were made in Grand Teton National Park near Blacktail Butte (Figure 1); we focus analyses on data from this location, excluding other locations he visited. All data were sorted by species, year, and ecological event. We identified 49 species that had at least three observations from the 1970s. We are working to expand the historic dataset to include herbarium records and additional historic phenology notes.

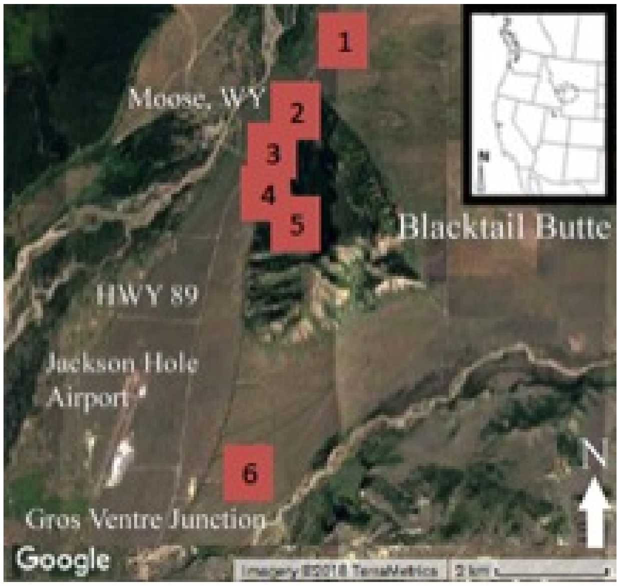

Figure 1. Six primary sites for observations of phenology of >100 species of flowering plants and as well as pollinators within Grand Teton National Park. Pollinators and phenophases for each plant species were collected in at least one of six site locations encompassing a diversity of habitats.

Name	Habitat	Location
1) Craighead Cabin	Sagebrush steppe	43.6645, -110.6857
2) Lower Blacktail Forest	Mixed conifer	43.6606, -110.6969
3) Lower Blacktail Sage	Sagebrush steppe	43.6587, -110.6991
4) Blacktail Butte Aspen	Aspen grove	43.6564, -110.6974
5) Upper Blacktail Butte	Montane forest	43.6518, -110.6929
6) Gros Ventre junction	Sagebrush steppe	43.5819, -110.7185

Table 1. Collection sites mapped in Figure 1.

Contemporary observations

In spring 2016, we initiated contemporary observations of the 49 species for which we had at least three years of historic data, plus an additional 61 common or ecologically important species that we decided were valuable for study (Table S1). We are focusing our observations on the areas near Craighead's home in the sagebrush steppe vegetation towards the summit of Blacktail Butte, located near Moose, Wyoming in GTNP (Figure 1). Craighead's notes and surviving relatives indicate that he walked this 2.7 km path regularly as he made his phenological observations. Blacktail Butte is an isolated outcrop of vegetated limestone with elevations ranging from 1,990-2,343 m, centered between the Beartooth-Absaroka Range to the north, the Gros Ventre Range to the east, the Snake River Range to the south, and the Teton Range to the west. The location and topographic variation of the formation means that it harbors a great diversity of microclimates, plants, and wildlife.

Along this path, we identified six key phenology sites representing a gradient of ecosystem types, from the dry, exposed sagebrush flats near Craighead's home, through an aspen woodland, and up to a montane stream waterway (Figure 1, Table 1). During our twice-weekly observations in spring 2016, 2017, and 2018, we visited each site to record the presence or absence of each species and its phenological phase (phenophase) including vegetative, budding, flowering, peak flower, fruiting, and senescence/withering. We defined peak flower as the duration of time when at least 50% of inflorescences are open in flower, as opposed to buds (Primack et al., 2004). While we do not have historic data on all of these phenological stages, it is important to begin tracking changes in all of these parameters, as peak flowering date and seeding/fruiting date have important consequences for species of birds, mammals, and insects that feed upon plant resources such as nectar and fruits (Aldridge et al., 2011; Deacy et al., 2017; Dillon, 2011; Kearns et al., 1998). We also captured coarse-scale weather observations, naturalist observations, and hundreds of photographs. In 2017-2018, over 95% of observations were made by a single researcher, Bloom, minimizing observer effects. The year 2016, which was a pilot year, may be removed from the dataset after additional years of observation are added.

Micro-climate monitoring

Starting in spring 2018, we designed and deployed an array of climate stations across the entire Jackson Hole valley. As of Fall 2018, we have deployed a total of 48 Onset HOBO 8K Pendant Temperature Data Loggers across 39 independent sites. Most of these sensors are recording ambient air temperature. Each sensor is set to record temperature once ever 60 minutes for approximately 200 continuous days – after which we download all data and reset the sensors to continue recording. The six key phenology sites (Figure 1) each contain a "climate station." Each climate station contains a pair of sensors – one in the air, one in the ground. The air sensors are placed in a solar radiation shield and mounted 50cm above the ground on a fence post or small tree to capture ambient air temperature. The ground sensors are buried 5cm under the ground and tethered to the air sensor post with a 1-meter cord. The furthest southern climate station is located in the Cache Creek drainage of the Bridger Teton National Forest. The furthest north station is Pilgrim Creek, GTNP, where it is paired with a phenocam (https://phenocam.sr.unh.edu/webcam/sites/grandteton/). Additional climate stations are located at the Miller Butte phenocam on the National Elk Refuge and near Gros Ventre junction.

The majority of the sensors, 36, are located in an array up the full elevation gradient of Blacktail Butte (Figure 2). We aim to capture a high (<10m) resolution of microclimate – including multiple topographic aspects, cold air drainages, ride tops, and the summit across a diverse range of ecosystems.

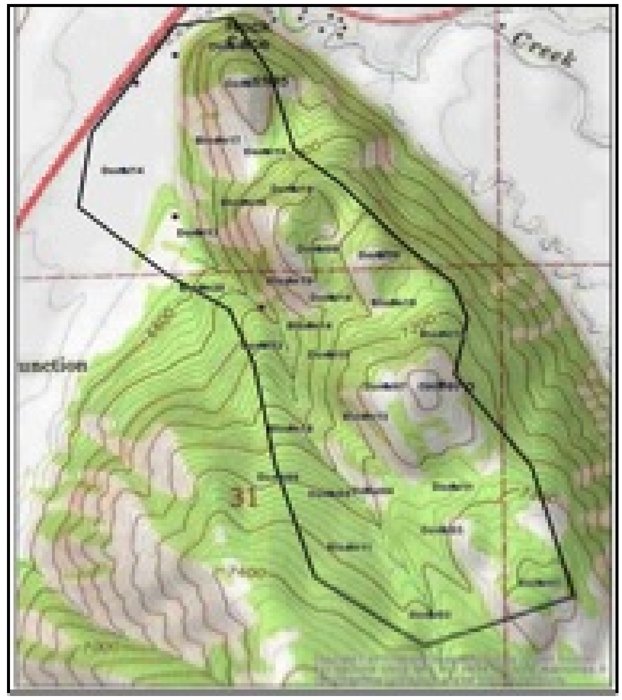

Figure 2. Close up view of northern Blacktail Butte where we have installed 38 total climate sensors (there are eight additional sensors located outside Blacktail Butte). Each station contains at least one temperature sensor at ambient air. Certain climate stations located at each of the six core phenology sites include a temperature sensor in the soil, pollinator collections, and game cameras for wildlife sightings and snow depth validation.

Phenology and climate analyses

Temperatures averaged across of all of Teton County were derived from the Parameter elevation Regression on Independent Slopes Model (PRISM) dataset (PRISM Climate Group 2018). We used these data to analyze the trends in minimum, mean, and maximum temperatures averaged across Teton County from 1970 to present. We also extracted mean spring temperature (March, April, May) to regress against phenological data. For each species, we calculated the Julian day (0-365) for the first flower for each year from the combined historic and contemporary dataset. We used a linear regression to analyze first flower date as a function of mean spring temperature. All analyses were performed in R (R Core Team 2018). In addition to these individual species analyses, we also categorized plants into functional groups to further analyze how flowering times have shifted. We defined functional groups as early flowering species (first flower before June 15), mid-summer flowering species (first flower between June 15-July 31), late summer flowers (first flower after August 1), berry species and invasive species. For each functional group, we calculated the mean first flower date for both the historic (1970s) and contemporary (2016-2018) records, to calculate the shift in flowering times.

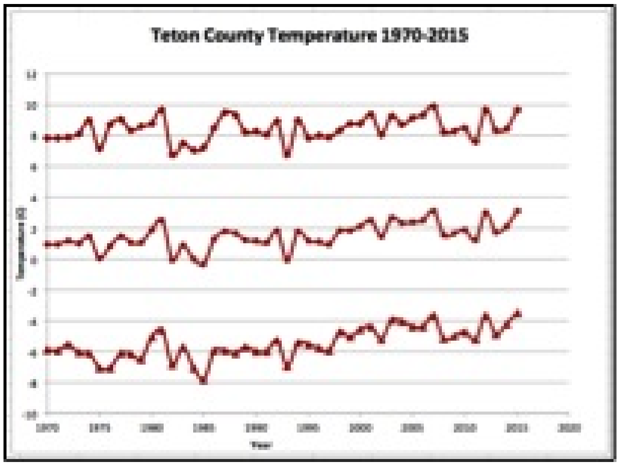

Figure 3. Teton County has experienced substantial warming in the past 40 years, evident in maximum (top line), mean (center line), and minimum (bottom line) temperatures displayed above. Most notably, minimum temperatures have risen more than 2°C since the 1970s.

Pollinator collections

In 2018 we collaborated with the University of Wyoming/AMK Ranch to engage undergraduate students to sample pollinators at our sites. At each of the six key phenology sites, we placed three different colored pan cups (blue, white, and yellow) and 1 blue vane trap to capture pollinators. The pan cups contained soapy water used as a surfactant. Pollinator collection traps were deployed June 3-August 5, 2018. During this time period, traps were set out once a week (typically Thursdays) for 24-hour periods to capture relative abundances and emergence curves for the pollinators collected. Collaborators from the University of Wyoming are currently working to identify all insects collected over the summer field season. The most abundant pollinators are from the orders Hymenoptera, Coleoptera, and Lepidoptera. Full results are not available yet and will be reported in the future.

Preliminary Results

Climate monitoring

Analysis of historic climate data in Teton County reveals a gradual, yet variable, increase in temperature since the 1970s, especially in minimum temperatures, which have risen more than 2 degrees Celsius in the past 40 years (Figure 3). We are currently analyzing the first full year of HOBO data to extract climate variables such as daily high and low temperatures, cumulative growing degree days (Richardson et al., 1975; Tuhkanen, 1980), and snowmelt timing (Lundquist and Lott, 2008). Snowmelt timing can be identified easily – as snow is a powerful insulator and thus the sensor records a constant temperature until the snow melts and a diurnal temperature cycle is clearly observed (Figure 4). This method improves upon existing remote-sensing based data (O'Leary et al., 2017) by allowing for a daily snow-presence reading that is free of cloud interference and a spatial precision of <1m. However, the presence of anomalous snowpack conditions (e.g. a large wind drift, or snow clearing by an herbivore in search of forage) may influence such local snowmelt timing observations.

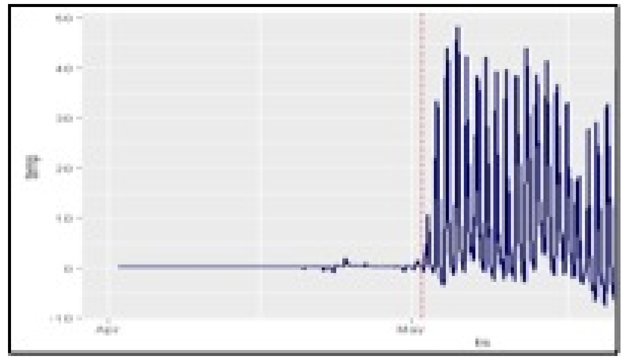

Figure 4. The exact time of snowmelt (dotted red line) is characterized by a flat line (temperature logger insulated by snow) followed by the return of a daily high and low temperature cycle.

Temperature sensitivity

The majority of plants, for which we have at least three years of historic data and at least 2 years of contemporary data (n=49), exhibited a statistically significant sensitivity to spring temperatures. First flowering date for 65% of these species was negatively correlated with mean spring temperatures, meaning warmer temperatures related to earlier flowering times (Figure 5). Some species had remarkably tight correlations with mean spring temperature (e.g.

Epilobium angustifolium; *Hydrophyllum capitatum*; *Potentilla gracilis*). Other species did not show much relationship at all with temperature (e.g. *Prunella vulgaris*; *Prunus virginiana*; *Shepherdia canadensis*).

The slope of these regressions also varied. Species with particularly steep slopes – indicating high sensitivity to mean spring temperature – were *Orogenia linearifolia*, *Viola adunca*, *Lomatium ambiguum*, *Galium boreale*, *Geum triflorum*, *Taraxacum officinale*, and *Arnica cordifolia*.

Changes in mean first flowering date

Although we have only two or three years of contemporary observations depending on the species, these data indicate that most wildflower species today are flowering weeks earlier than observed by Craighead in the 1970s (Figures 5 and S1). Early flowering species such as yellowbells (*Fritillaria pudica*) and arrowleaf balsamroot (*Balsamorhiza sagttata*) show the largest effect and are emerging ∼21 days earlier. Midsummer flowers such as sticky geranium (*Geranium viscosissimum*) are emerging ∼11 days earlier. Late season flowers like Engelman aster (*Eucephalus engelmannii*) do not appear to have changed their first flower timing. Nonnative species such as musk thistle (*Carduus nutans*) are emerging ∼11 days earlier today.

Berries, such as huckleberries (*Vaccinium* spp.) and service berries (*Amelianchier alnifolia*), are important food sources for many animals. As a group, berry species are emerging an average of ∼9 days earlier today than observed by Craighead. Yet not all species are shifting. For example chokecherry (*Prunus virginiana*) has maintained a constant first flowering date of approximately June 9 (Julian day 160) since 1974.

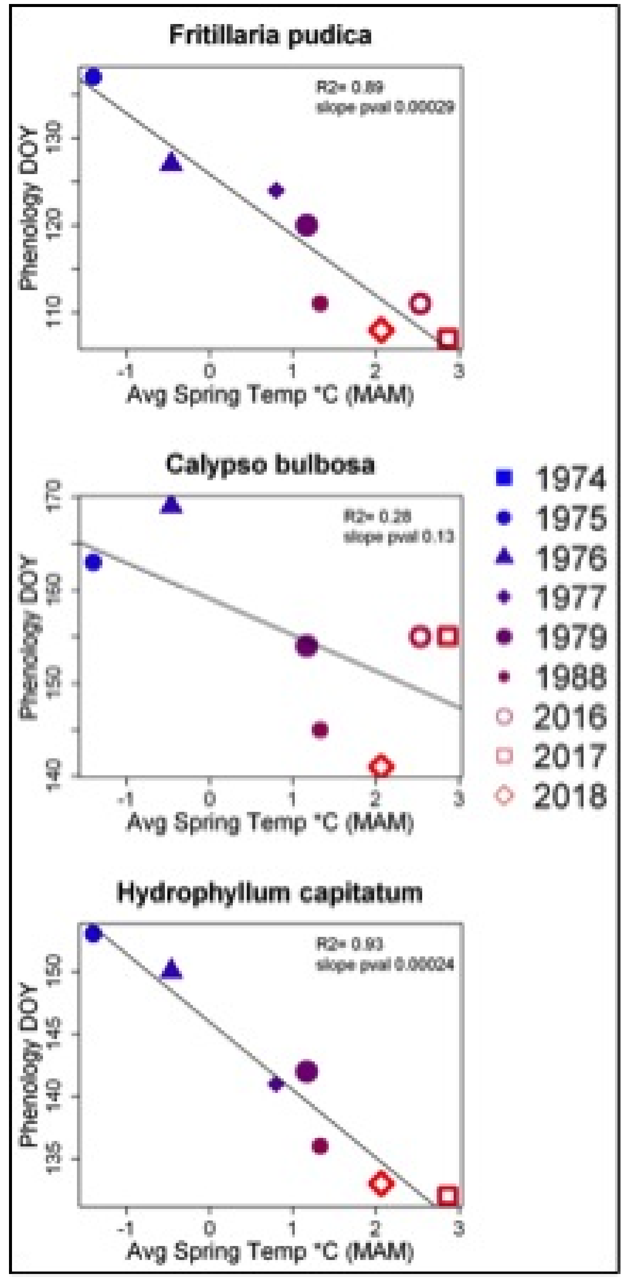

Figure 5. The date of first flower ("phenology Day of Year") as a function of mean spring temp (March, April, May) using phenology observations from 1974-1979, 1988 and 2016-2018 for three representative species. Observations made by Frank Craighead are indicated by a solid symbol, and observations made by authors are hollow. Higher average spring temperatures are correlated with earlier flowering dates for most, but not all, plant species in Grand Teton National Park.

Discussion

As climate warms, the timing of seasonal ecological events is shifting causing cascading effects on entire ecosystems (Butt et al., 2015; Hughes, 2012; Middleton et al., 2013; Miller-Rushing et al., 2010). Our preliminary results demonstrate that individual plant species in the Tetons region respond differently to temperature cues. Previous research has demonstrated that plants whose phenology is more plastic to temperature shifts fare better under a warming climate, whereas those that do not rapidly adapt may experience declines in abundance and even local extinction events (Willis et al., 2008). We have already observed that many species are flowering earlier now than they were in the 1970s. It is likely that the phenology of certain plants are no longer lining up in timing with other important ecological events such as the arrival of migratory birds and the pollination habits of insects (Mayor et al., 2017; McKinney et al., 2012; Singer and Parmesan, 2010).

For example, the first flowering date of western serviceberry (*Amelanchier alnifolia*) is tightly correlated with spring temperature (R^2=0.915), whereas the phenology of chokecherry (*Prunus viginiana*) shows little to no relationship (R^2=0.127). These two shrubs fill similar ecological niches and their fruits are important food sources for migratory birds and bears before hibernation. Given that chokecherry is less plastic in response to variation in temperature, we expect this species to be more vulnerable to climate change than serviceberry and that it could experience population declines over the coming decades. This could have negative consequences for herbivore species that consume chokecherry berries.

These variations among species in plasticity to temperature changes are not surprising, since it is well-established that other factors beyond spring temperatures can affect phenology. Snowmelt timing may be a more important driver of phenology than temperature for many species, particularly within these mountainous ecosystems where snowpack is a dominant climatic control (O'Leary et al., 2018; Sherwood et al., 2017). This may explain why we found that early spring flowers which emerge soon after the snow melts are shifting their flowering dates much more in response to climate change than plants that bloom later in the summer. Other potential drivers of phenology include day length, precipitation as rain, growing degree days, drought, and grazing by herbivores (Wolf et al., 2017).

We are building the historic data set to include data on when certain plants began to bloom, when migratory birds arrived, and when bears exited hibernation. Changes in these patterns can signal changes in the "health" of the ecosystem. Such large shifts in flowering time as we are observing in the Tetons may result in large phenological mismatches or novel synchronizations between plants, pollinators, and foragers (Deacy et al., 2017; Debinski et al., 2014).

Certain organisms, including migratory birds, respond seasonally to the length of the day, rather than the temperature (Coppack et al., 2003; Dawson et al., 2001; Gwinner, 1990). Thus they base their annual migration patterns to arrive at the same time each year to a certain region or habitat. In the Colorado Rockies, broadtail hummingbirds are arriving the same time each year, yet flowers are blooming earlier, thus they are missing peak nectar availability resulting in reduced brooding success (McKinney et al., 2012). Our early data already suggest that berries that make up a large portion of bears' diets are now fruiting in late summer rather than the fall, when bears need them most. With less natural food to eat, this may cause bears to seek out human food more. Also novel synchronies can occur when foragers or pollinators gain access to novel food resources during different times of the year (Deacy et al., 2017). With greater knowledge of the problem, managers can take actions to prevent some of these problems.

Teton County has experienced substantial warming over the past forty years, in line with the rest of the region and country. This trend in increasing air temperature is expected to continue for the next several decades (Pachauri et al., 2014). Given the relationship between mean spring temperature and first flowering date we have shown, we can expect many flowering species to bloom earlier in the future, possibly having cascading effects on the entire ecosystem. Assessing the plasticity of certain species to increases in temperature may help managers mitigate impacts of climate change. Our study will help to reveal these patterns, providing valuable insight on management decisions such as revegetation or assisted migration plans in the GYE.

Citizen science and outreach

As a complement to our research program, we also aim to increase overall science literacy and awareness of climate change through continued outreach efforts. The reputation of Frank Craighead, a renowned biologist in the GYE and long-time resident of the Tetons, and the accessibility of our field sites, lend this project perfectly to citizen science and community engagement in climate change research. Citizen science, which engages non-professional scientists in one or more stages of scientific research, has made substantial contributions to scientific understanding and conservation management (McKinney et al., 2012) and is an effective form of science outreach.

In spring 2018 we launched Wildflower Watch, a citizen science project where volunteers collect phenology observations on approximately a dozen wildflower species in several location in Jackson Hole. We expanded partnerships to include more volunteers from diverse backgrounds and created a total of five phenology walks in Jackson Hole – Blacktail Butte, The Murie Center, Kelly Elementary, AMK Ranch and Cache Creek. We published a booklet of instructions using photos, diagrams, maps of collection sites, and step by step instructions for making field observations (Supplementary Materials: Wildflower Watch). We utilize the Nature's Notebook application, and all citizen science data is automatically uploaded to the USA National Phenology Network database.

In 2018, 271 volunteers uploaded a total of 4,728 observations to the USA National Phenological Network (USANPN) database using the Nature's Notebook application. This is a huge increase in participation from our 2017 pilot year where volunteers collected 102 observations. Most were one-time participants, yet many citizen scientists returned to the field repeatedly over the course of the season. We partnered with educational organizations including the Teton Science Schools and Kelly Elementary to bring hundreds of students of all ages into the field to participate as citizen scientists. We also partnered with Bridger Teton National Forest, Friends of Pathways, and Jackson Hole Wildlife Foundation to create a citizen science collaborative project at Cache Creek – the most popular trail system in the Jackson Hole region.

Preliminary examinations indicate that our citizen scientists are accurately collecting phenology data on target taxa that do not greatly differ from the observations of our primary researchers. Our efforts have proven the feasibility of a successful citizen science project in the Tetons, and we plan to grow our program over the coming years. By combining the Wildflower Watch program with the Nature's Notebook application, our volunteers automatically record their observations in a permanent, cloud-based repository which offers many data visualization and interpretation tools for citizen scientists and educators to explore.

Future Work

Historic and contemporary phenology

In order to build a contemporary phenology database to compare with the existing Craighead observations, we envision a continuation of the twice-weekly phenology observations for an additional 1-3 years. This will allow us to compare contemporary phenology with historic data with ten years of recorded observations for most species. This database will also serve as a new highly systematic baseline for the phenology of common plant species and pollinators found in GTNP.

In support of this analysis, we have started gathering additional historical data by accessing the herbarium records of local flowering plants. This will expand the scope of historical data to other locations in GTNP, to additional species, and to more years from the past. Furthermore, this will allow us to examine changes in a broader set of phenological stages, which will likely reveal more clear patterns on the regional effect of climate change (Calinger et al., 2013). Much of the Craighead data are observations of first flowering date, while herbarium specimens can provide data on peak flowering date, fruiting, and seeding. We will compile, georeference (Bloom et al., 2018*a*), and datamine all relevant records for our focal species from GTNP, Bridger Teton National Forest, the Murie Collections, and the Consortium of the Rocky Mountain Herbaria. We will also continue to seek out other sources by word of mouth. Often individuals have made their own phenological observations over the years, and these informal data sources can be valuable and rich (Primack et al., 2004). For example in 2018, Teton Science Schools staff provided us with the phenological notes of their founder, Ted Major, from the 1970s. We are working on digitizing and datamining these records.

We will continue to gather contemporary phenology data at our study sites for at least one more season, ideally more. This will allow us to answer robustly the question of whether and how much earlier plants are flowering now than in the past. We are also assembling a broader set of climatic data (e.g. growing degree days, snowmelt timing, precipitation as rain) to include in phenology modeling. This may allow us to better model other phenology indicators (e.g. peak flower, fruiting) with greater accuracy than using spring air temperature alone, particularly for late-blooming species that have weak phenological relationships with spring air temperature.

Novel climate analyses

Our plot-based observations of phenology combined with the fine-scale data from our numerous climate stations will be used together to better understand the links between phenology and climate – and how these shift under global warming. This dataset will support spatial models of species-specific spring greening. Essentially if we can determine the specific mechanisms (temperature, growing degree days, snowmelt timing etc.) that drive phenology for specific species, we can use these metrics to train models of landscape level phenology. By serving as source data for model fitting and ground-truthing observations for post-hoc validation, our observations will improve our understanding of phenology of the GYE beyond the Blacktail Butte study area.

Cascading effects

We plan to continue monitoring of pollinators and create abundance emergence curves for important functional groups such as bumble bees (*Bombus* spp.) and butterflies (*Lepidoptera* spp.), following principles and protocols described in Sprayberry et al. (2016) and Bloom et al. (2018*a*). We will link insect abundance and emergence with the phenology of flowering host plants, in an attempt to identify potential mismatches or novel synchronies.

In winter 2018-2019 we will deploy game cameras at each of the six primary phenology sites shown in Figure 1. This may allow us to observe animal behavior including preferred forage species for important wildlife species such as moose, elk, mule deer, grizzly, and black bears. In addition, each game camera will be set up to capture snow-depth and snowmelt timing. A 2-meter measuring stick will be placed upright from bare ground in the field of view of the camera to capture snow depth on a daily basis.

Restoration and continued outreach

We are working closely with key partners to expand the utility of our research to inform restoration of federal lands. In Grand Teton National Park, we are communicating with ecologist Kelly McCloskey to address park priorities. Beginning in 2019, we hope to inform GTNP when and where to collect seeds (at the key phenophase) for native plants to then be reseeded elsewhere in the park, including the Kelly Hayfields restoration project.

Over the long term, we aim to build species distribution models, informed by our data, to predict the composition of future plant communities at these sites and also to detect species that may be at risk of local extinctions due to climate change. We are also working with Bridger Teton National Forest officials to inform the update of the Regional Forest Plan to include climate change. As always, we are working hard to nurture and grow Wildflower Watch – blossoming to include more citizen scientists from diverse backgrounds. We will continue our relationship with Teton Science Schools to build curricula around Wildflower Watch to increase science literacy and connect people with nature. Working with Bridger Teton National Forest, Jackson Hole Wildlife Foundation, and Friends of Pathways, we will grow the Cache Creek program to engage an ever-broader audience in the issue of climate change and its impacts on natural communities. Together, our research and citizen science aim to advance our understanding of climate change's impacts on the ecology of the Tetons, to inform management practices, and to foster a more engaged and educated citizenship.

Acknowledgements

Thank you to the UW-NPS Research Station administration and summer staff, as well as Geneva Chong, Raylene McCalman, and Rachael Mayer for assistance in the field and project guidance. Funding was generously provided the Community Foundation of Jackson Hole, UW-NPS Small Grants Program, United States Forest Service, U.S. Geological Survey, the Meg and Bert Raynes Wildlife Fund, and private donations from over 40 donors. We gratefully appreciate our administrators at The Nature Conservancy and The Northern Rockies Conservation Cooperative. We extend gratitude to our amazing citizen science volunteers. Finally thank you to the helpful staff of Grand Teton National Park and Bridger Teton National Forest.

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Supplemental Materials

Table S1. Species List.

Scientific name	Common name
Acer glabrum	mountain maple
Achillea millefolium	yarrow
Aconitum columbianum	monkshood
Actaea rubra	red baneberry
Agastache urticifolia	Cat mint
Alnus rubra	Red alder
Amelanchier alnifolia	Serviceberry
Antennaria rosea	Pussytoes
Arctostaphylos uva-ursi	kinnikinnick
Arnica cordifolia	heartleaf arnica
Artemisia tridentata	Big Sage Brush
Balsamorhiza sagittata	arrowleaf balsamroot
Bromus tectorum	Cheatgrass
Calochortus nuttallii	Sego Lily
Calypso bulbosa	fairy slipper
Campanula rotundifolia	harebell
Carduus nutans	musk thistle
Castelleja miniata	Giant red Indian Paintbrush
Castilleja linariifolia	Wyoming indian paintbrush
Castilleja sulphurea	Yellow sulphuric paintbrush
Centaurea stoebe	Spotted Knapweed
Chamerion angustifolium	fireweed
Cirsium arvense	Canada Thistle
Cirsium foliosum	elk thistle
Claytonia lanceolata	spring beauty
Clematis hirsutissima	hairy clematis; sugarbowl
Collinsia parviflora	blue eyed mary (tiny blue flowers)
Comandra umbellata	Pale comandra
Corallorhiza striata	Striped coralroot
Crepis acuminata	tapertip hawksbeard
Delphinium nelsonii	larkspur

Continued on next page

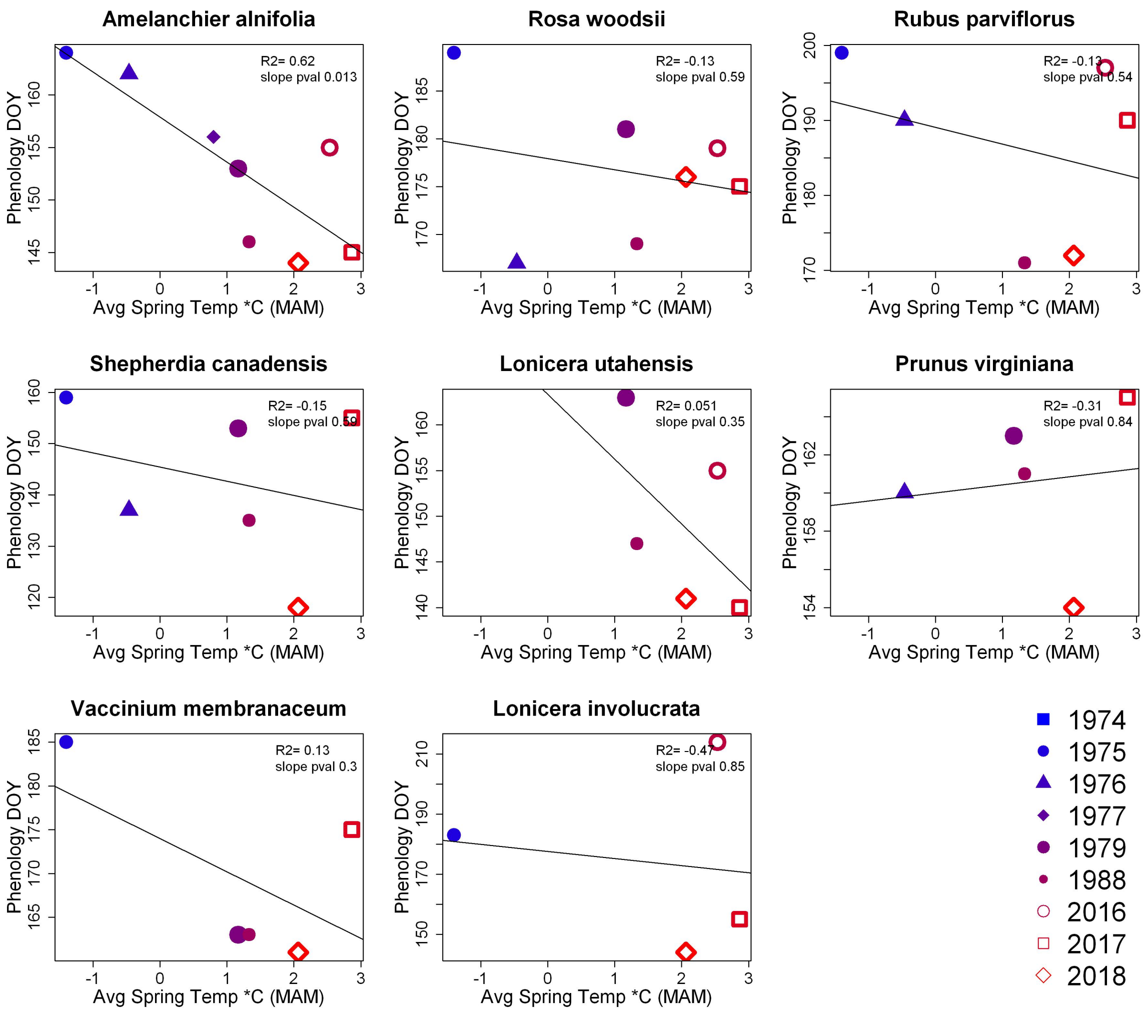
Scientific name	Common name
Delphinium occidentale	Tall larkspur
Disporum trachycarpa	fairy bells
Dodecatheon pauciflorum	shooting star
Eremogone congesta	ballhead sandwort
Ericameria nauseosa	rubber rabbit brush
Eriogonum umbullatum	sulfer-flower buckwheat
Eucephalus engelmannii	Engelmann aster
Fragaria vesca	woodland strawberry
Frasera speciosa	green gentian
Fritillaria atropurpurea	leopard lily; spotted fritillary
Fritillaria pudica	yellow fritillaria
Galium boreale	Northern bedstraw
Geranium viscosissimum	sticky purple geranium
Geum triflorum	old man's whiskers; prairie smoke
Gilia aggregata	scarlet gilia
Grindelia subalpina	Gumweed
Helianthella uniflora	one flower sunflower
Heracleum maximum	cow parsnip
Heuchera villosa	Alumroot
Hydrophyllum capitatum	waterleaf; ballhead waterleaf
Iliamna rivularis	Holly Hock
Linaria dalmatica	YELLOW toadflax
Linum lewisii	Lewis/blue/prairie flax
Lithophragma parviflorum	star flower
Lithospermum incisum	narrowleaf stoneseed
Lomatium triternatum	desert parsley
Lonicera involucrata	Black twinberry
Lonicera utahensis	Utah honeysuckle
Lupinus argenteus	silvery lupine
Lupinus sericeus	silky lupine
Mahonia repens	creeping barberry; Oregon grape
Mahonia repens	Oregon grape
Maianthemum racemosa	feathery false lily of the valley

Continued on next page

Scientific name	Common name
Maianthemum stellatum	wild lily of the valley
Medicago sativa	Alfalfa
Melilotus officianalis	Sweet Yellow Clover
Mertensia ciliata	mountain bluebelle
Mimulus guttatus	Yellow monkey flower
Noccaea montana	Alpine penny cress
Opuntia fragilis	Fragile prickley pear
Orobanche ludoviciana	Broomrape Artemesia parasite
Orogenia linearifolia	Snow Drops, Indian potato
Penstemon cyaneus	large flowered blue penstemon
Penstemon procerus	Small flowered blue penstemon
Perideridia gairdneri	gardners yamha; common yampha
Phlox hoodii	Hood’s phlox
Phlox longifolia	long-leaved phlox
Populus balsamifera	Cottonwood
Populus tremuloides	Aspen
Potentilla arguta	tall white cinquefoild
Potentilla gracilis	slender yellow cinquefoil
Prunus virginiana	black chokecherry
Purshia tridentata	antelope bitterbrush
Ranunculus glaberrimus	sagebrush buttercup
Ranunculus jovis	Utah buttercup
Ribes lacustre	prickly current
Rosa woodsii	woods’ rose
Rubus idaeus	Rasberry
Rubus parviflorus	thimble berry
Rudbeckia occidentalis	Western Cone Flower
Sambuccus sp.	Elderberry
Sedum stenopetalum	spearleaf stonecrop; yellow stonecrop
Senecio integerrimus	Western Groundsel
Shepherdia canadensis	buffalo berry
Silene vulgaris	Bladder campion, white
Solidago canadensis	Golden rod

Continued on next page

Scientific name	Common name
Streptopus amplexifolius	Twisted Stalk
Symphoricaros oreophilus	mountain snowberry
Symphyotrichum ascendens	Longleaf Aster
Taraxacum officinale	dandelion
Thalictrum occidentale	Western Meadowrue
Tragopogon dubius	yellow salsify
Triflorum pratense	Red clover, cowgrass (introduced)
Vaccinium membranaceum	huckleberry
Valeriana occidentalis	Common valerian
Viola adunca	early blue violet, or hookedspur violet
Viola nuttallii	yellow violet;
Wyethia amplexicaulis	mule’s ear
Zigadenus elegans	Death camas



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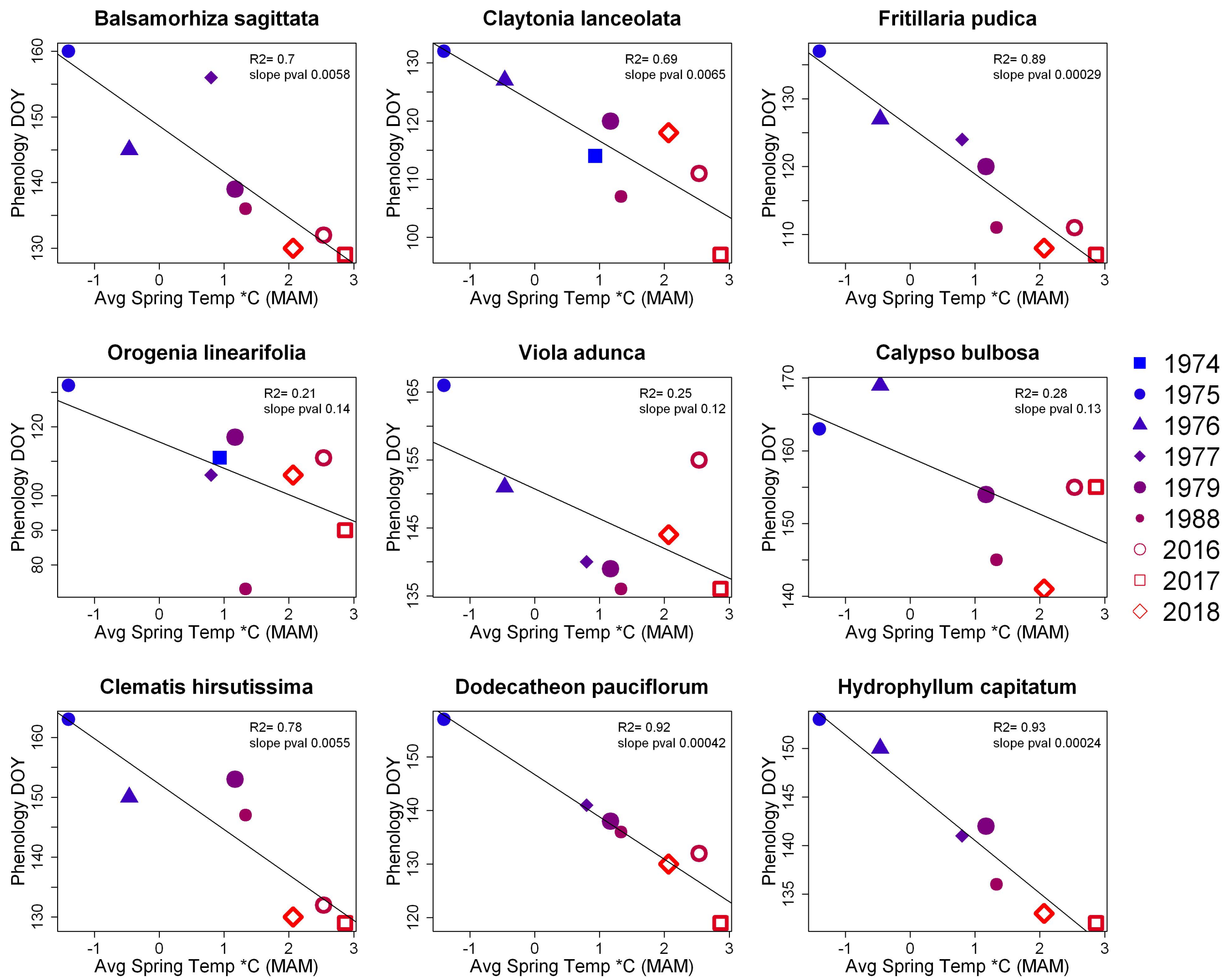

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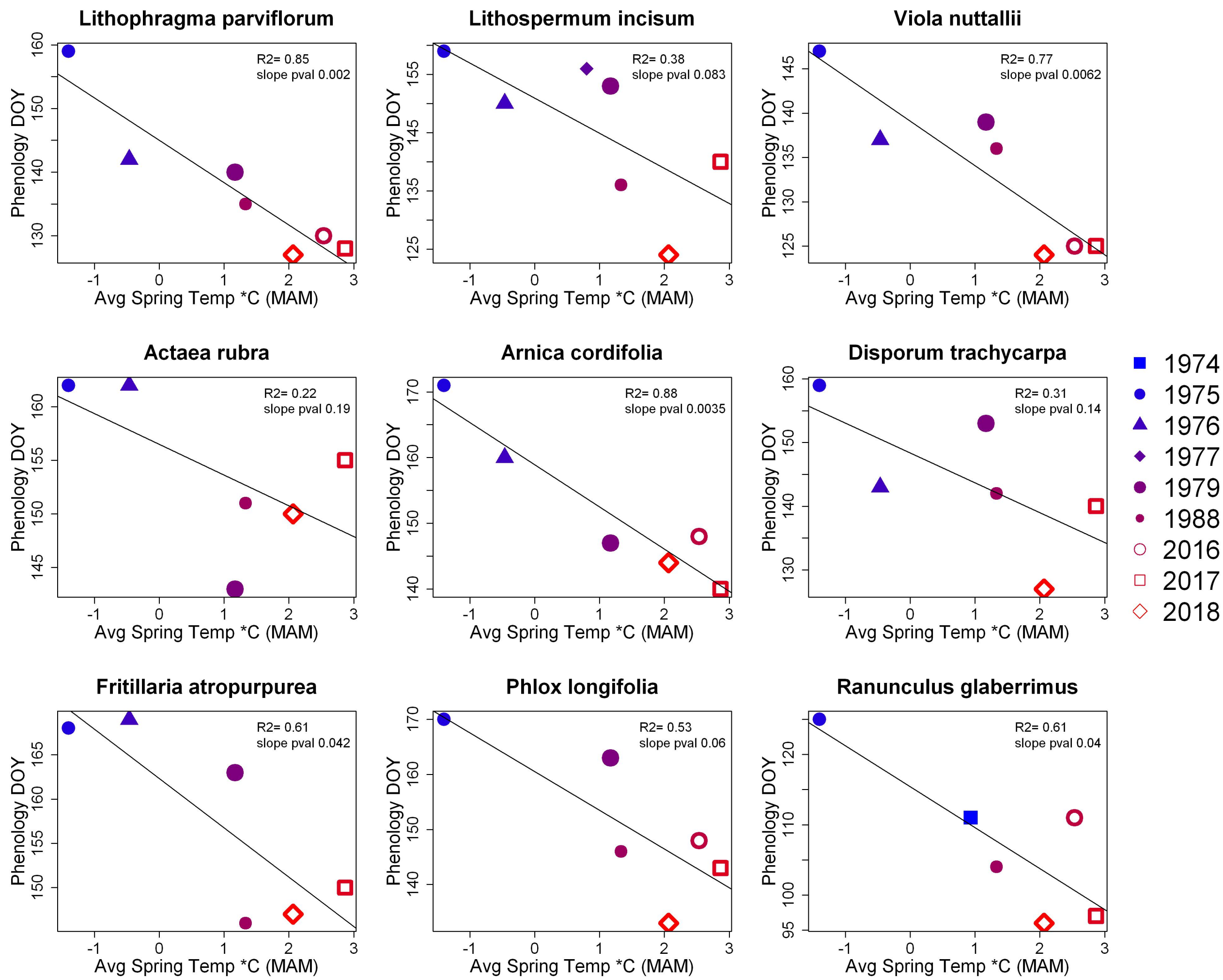

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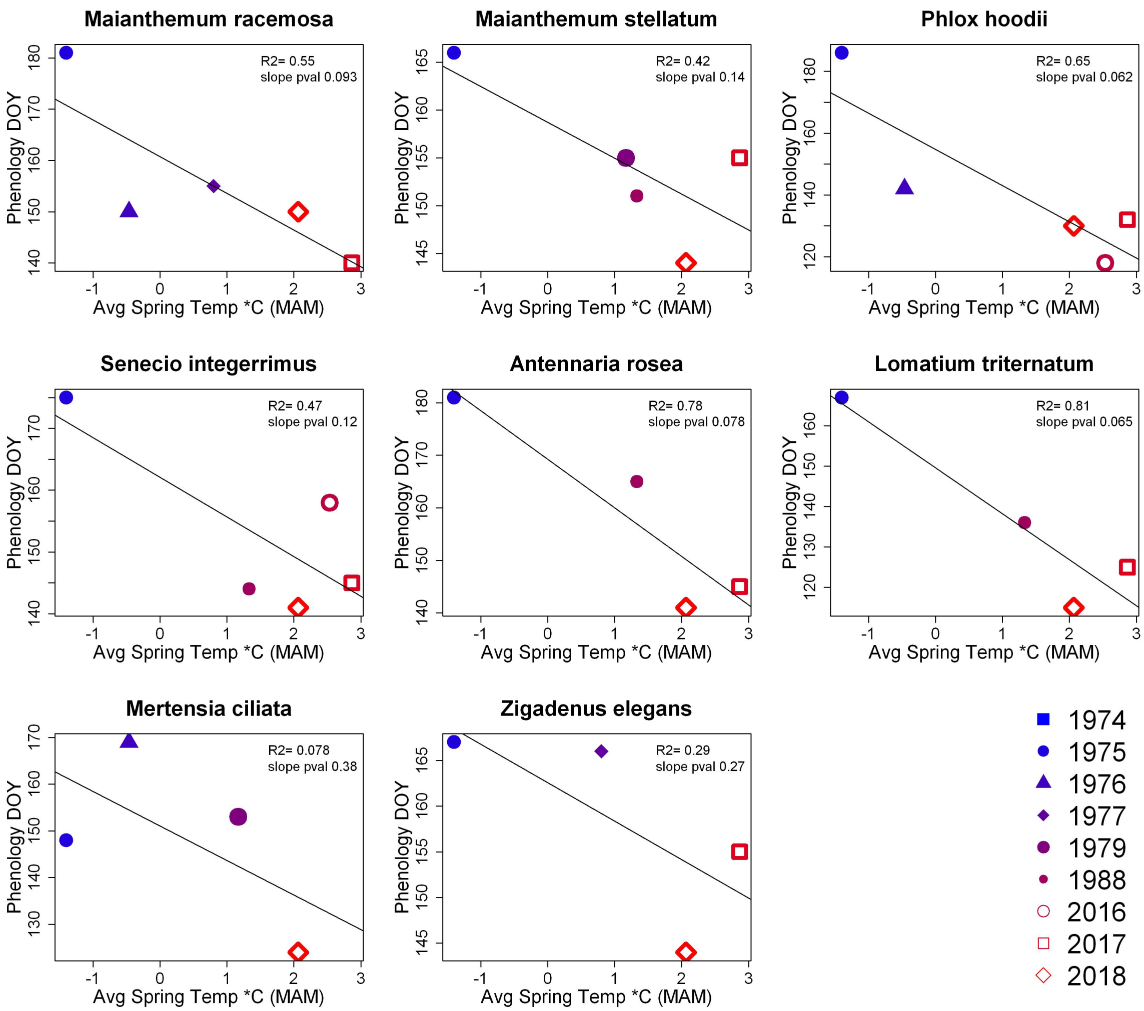

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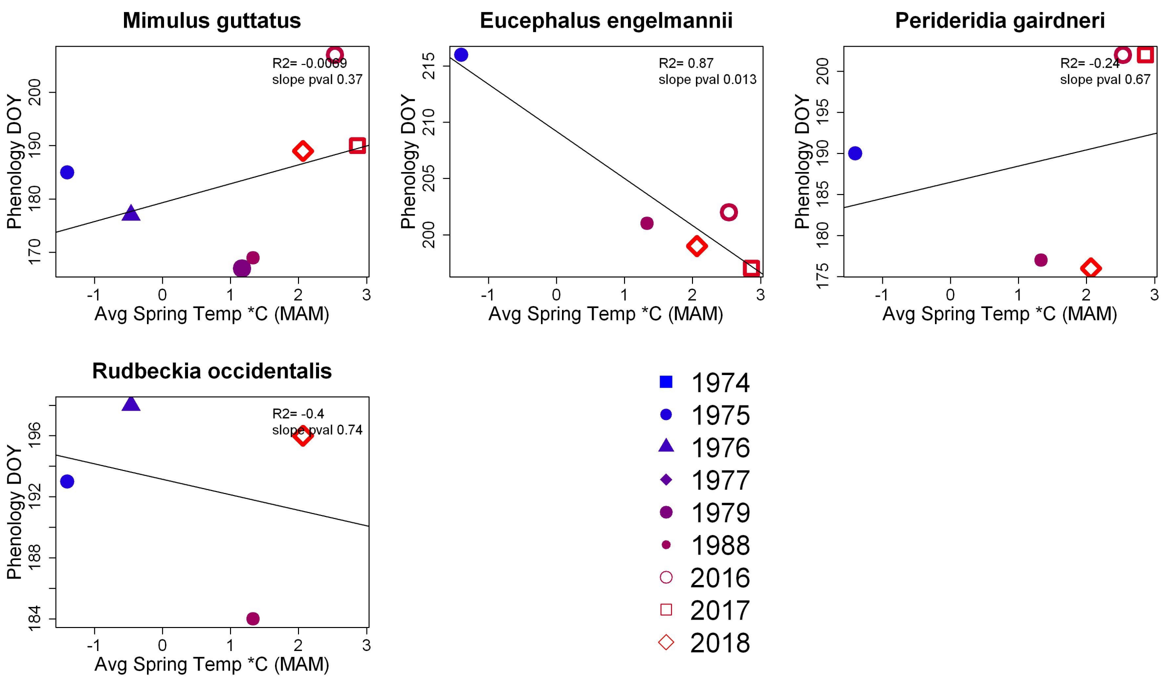

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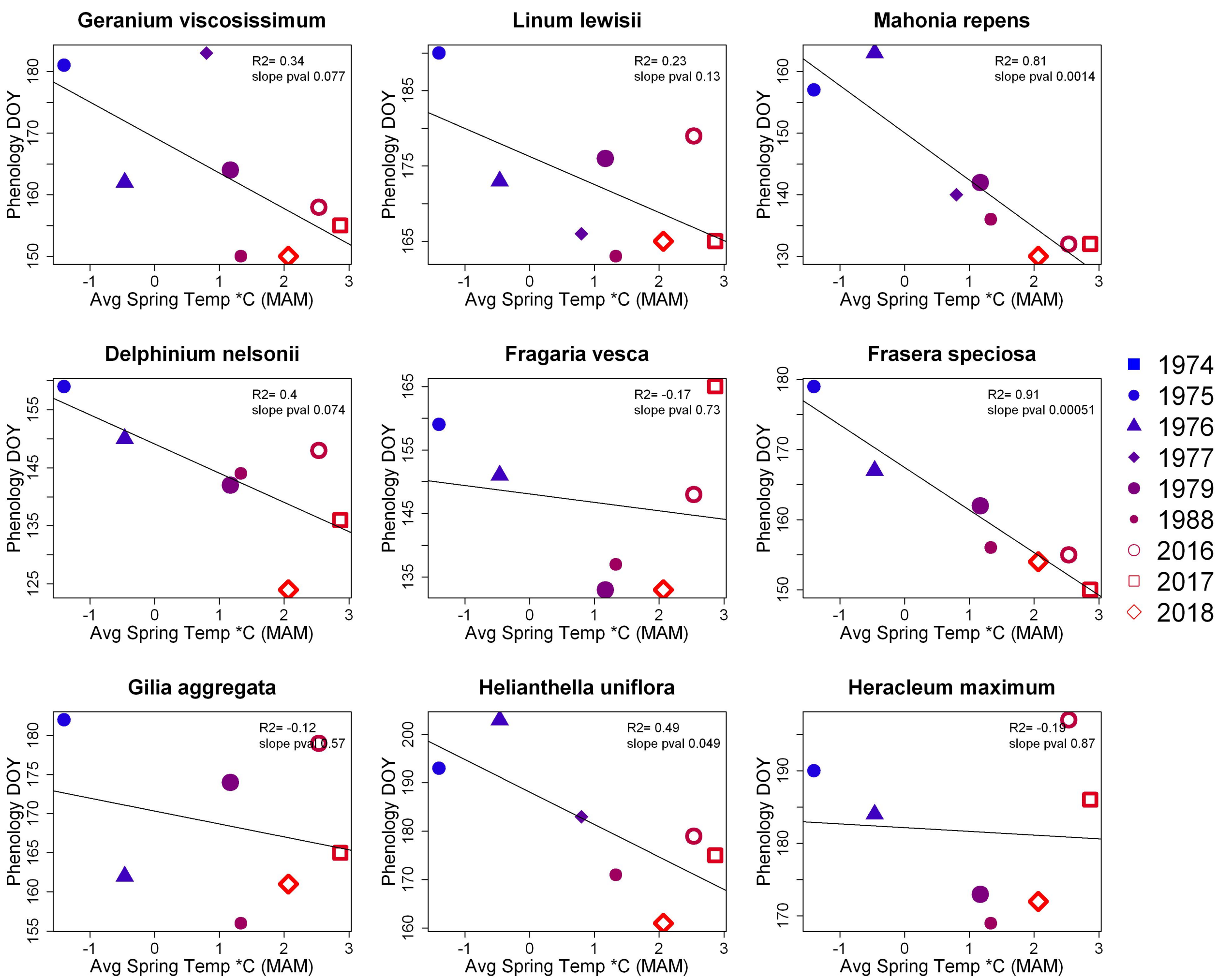

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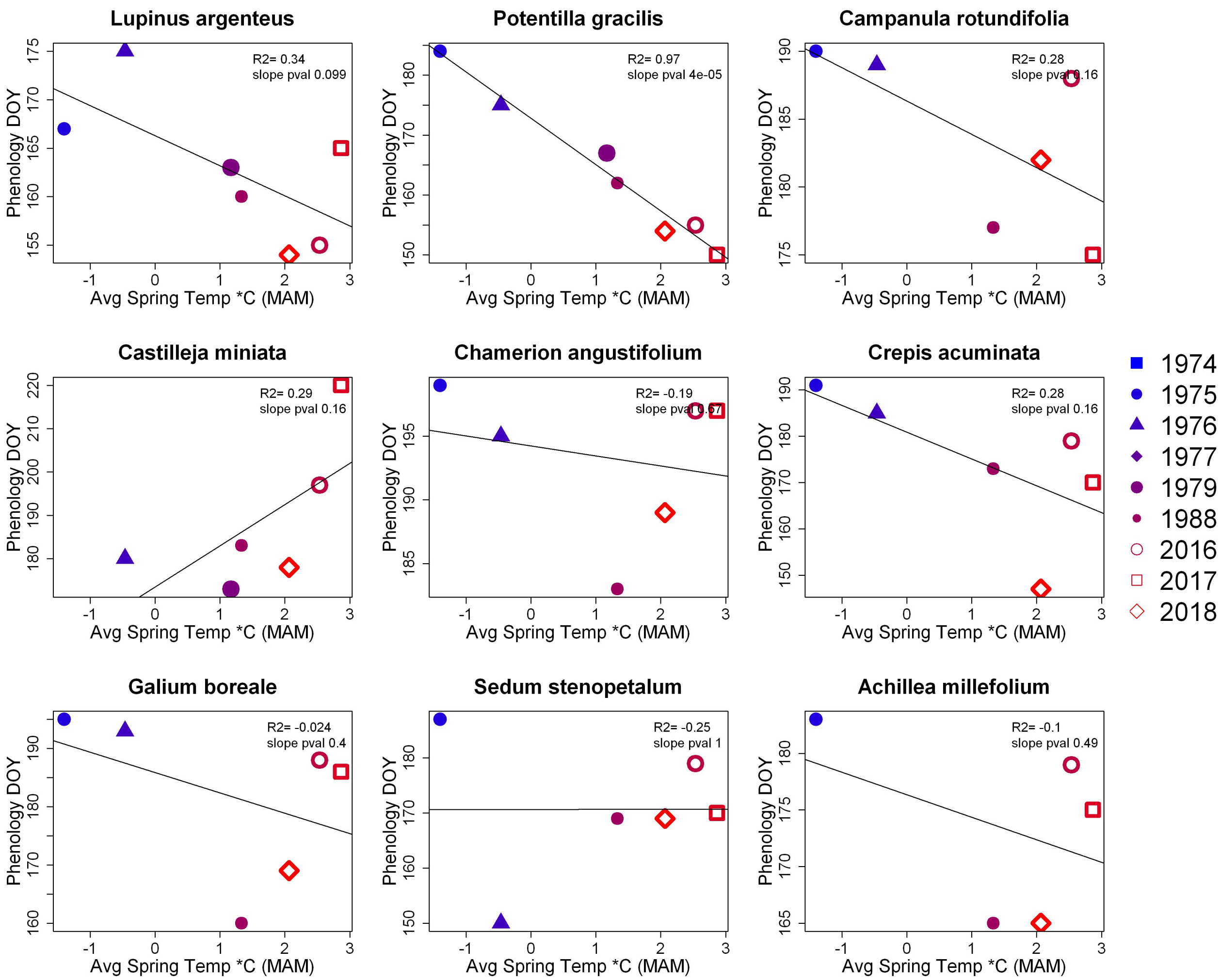

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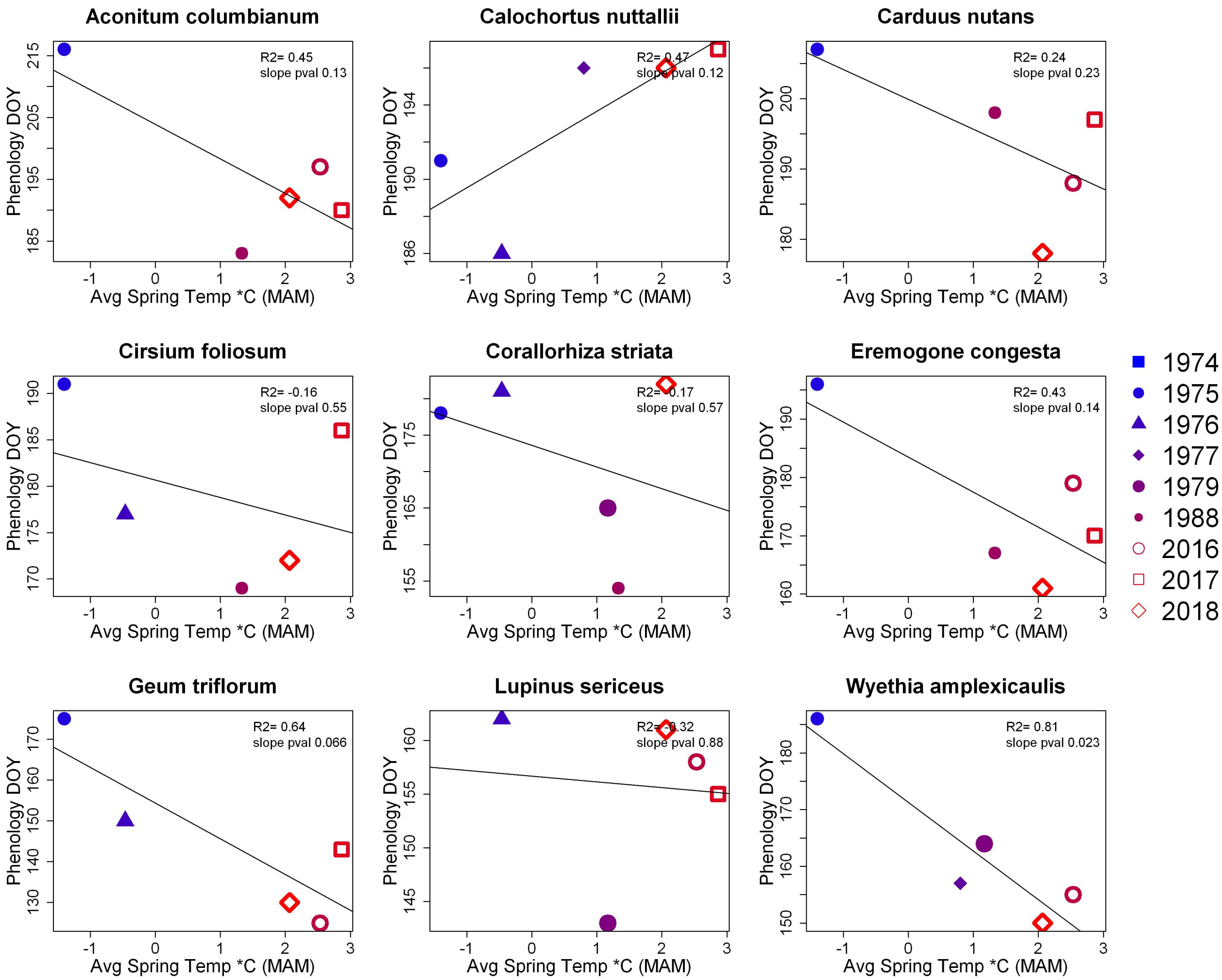

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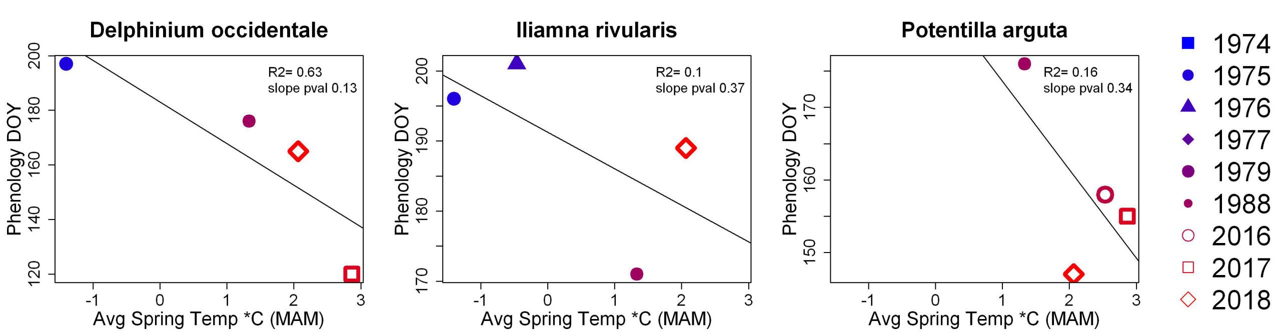

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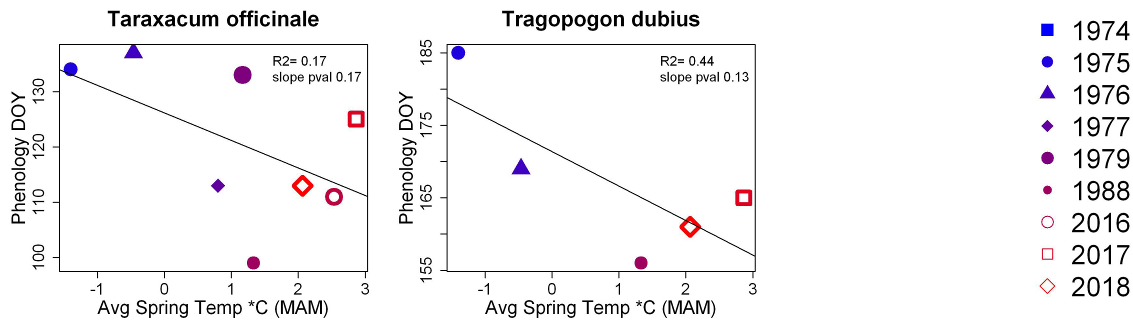

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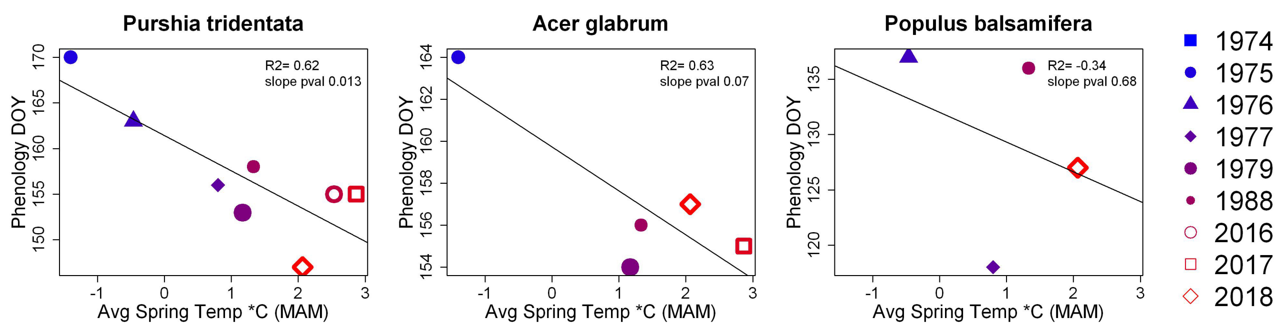


Supplemental Materials, Figures S1 (cont.)

Wildflower Watch

A Project of The Nature Conservancy in Wyoming and the Northern Rockies Conservation Cooperative

Field Guide for Citizen Scientists

The Nature Conservancy Wyoming

Northern Rockies Conservation Cooperative

Hello and welcome, wildflower and nature enthusiasts!

This booklet contains everything you need to begin collecting valuable data on the effects of climate on the seasonal timing of flowering plants in the Tetons. It will also teach you about local plants and their behavior in this amazing region. Even more importantly, you'll be assisting The Nature Conservancy in an important scientific study. Thank you for taking the time to join us.

Nature's Cycles

Timing is everything. This is true within your own life, and in the natural community around you. In the spring, winter snow melts and wildflowers begin to bloom, including our state flower the Wyoming Indian Paintbrush. At the same time, bears begin to emerge from hibernation, the males often several weeks before the females. Migratory birds begin to flock north and spread out to their respective summer homes, and the bison, elk, mule deer, and moose start giving birth to their young. All the amazing wildlife we have in our region are dependent on ample plant-based food to nourish themselves and their offspring before the fall frost arrives and withers the leaves, foreshadowing another winter.

New Threats

Climate change is one of the biggest threats facing the natural diversity of Earth and the wildlife of the Tetons. Snow is melting earlier each year, and spring temperatures continue to break record highs—leading to changes in plant and animal interactions and causing more disturbances such as wildfires. We already know from previous studies that increased temperatures have altered natural patterns worldwide, shifted the flowering season in parts of the Rocky Mountains forward by up to a month. Despite these changes in blooming, many birds still arrive at the same time each year because their migration habits are tied to the length of the day, instead of the temperature or snow. These mismatches in timing could have serious consequences. For example, what if migratory hummingbirds arrive after the best nectar-producing plants have bloomed? What if bears' favorite berries are ripe in the summer rather than the fall when bears need them most as they fatten for winter?

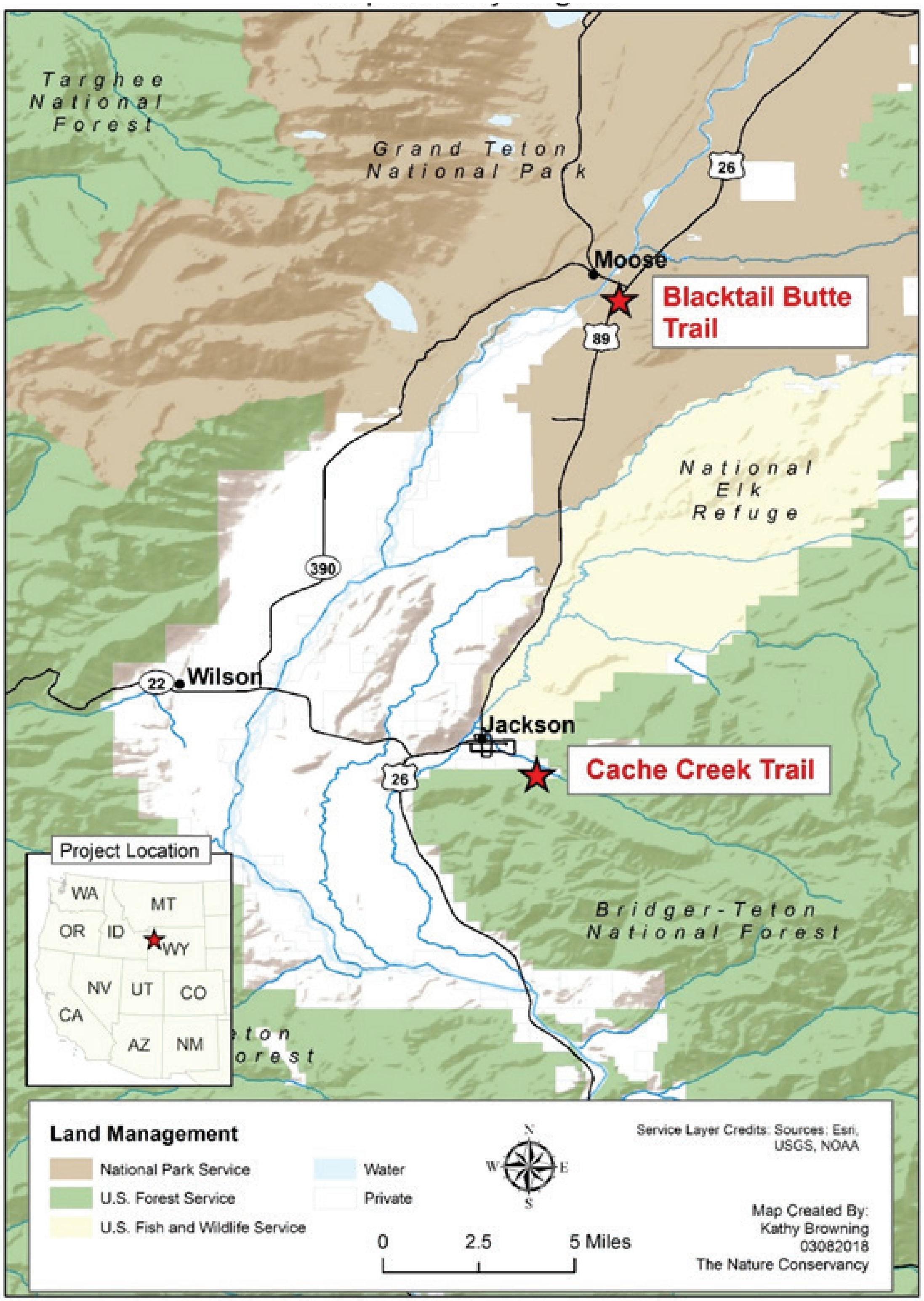
Building on a Legacy

This project builds on the legacy of a local and internationally renowned biologist, Frank Craighead. Frank and his identical twin brother, John, were extraordinarily progressive biologists who defined their career in the Greater Yellowstone Ecosystem. Among many achievements, they invented radio tracking animals (telemetry) as part of their research on grizzly bears; this method soon was adopted for use across the world. Both Frank and John have since passed away but their legacy lives on. One of Frank's legacies is the detailed notes he kept on everything he saw in the outdoors around his home in Moose, Wyoming from 1975-79 and 1988. Frank's notes included when certain plants began to bloom, when migratory birds arrived, and when bears first started being seen in spring. This study of timing of biological events is known as phenology. Frank used these notes to write the popular book, *For Everything There is a Season: The Sequence of Natural Events in the Grand Teton-Yellowstone Area*. We are building on his legacy by conducting contemporary field observations, nearly 50 years later, to compare the timing of current ecological events to historic data. We hope that this project will continue to illuminate changes over many years to come.

What Can You Do?

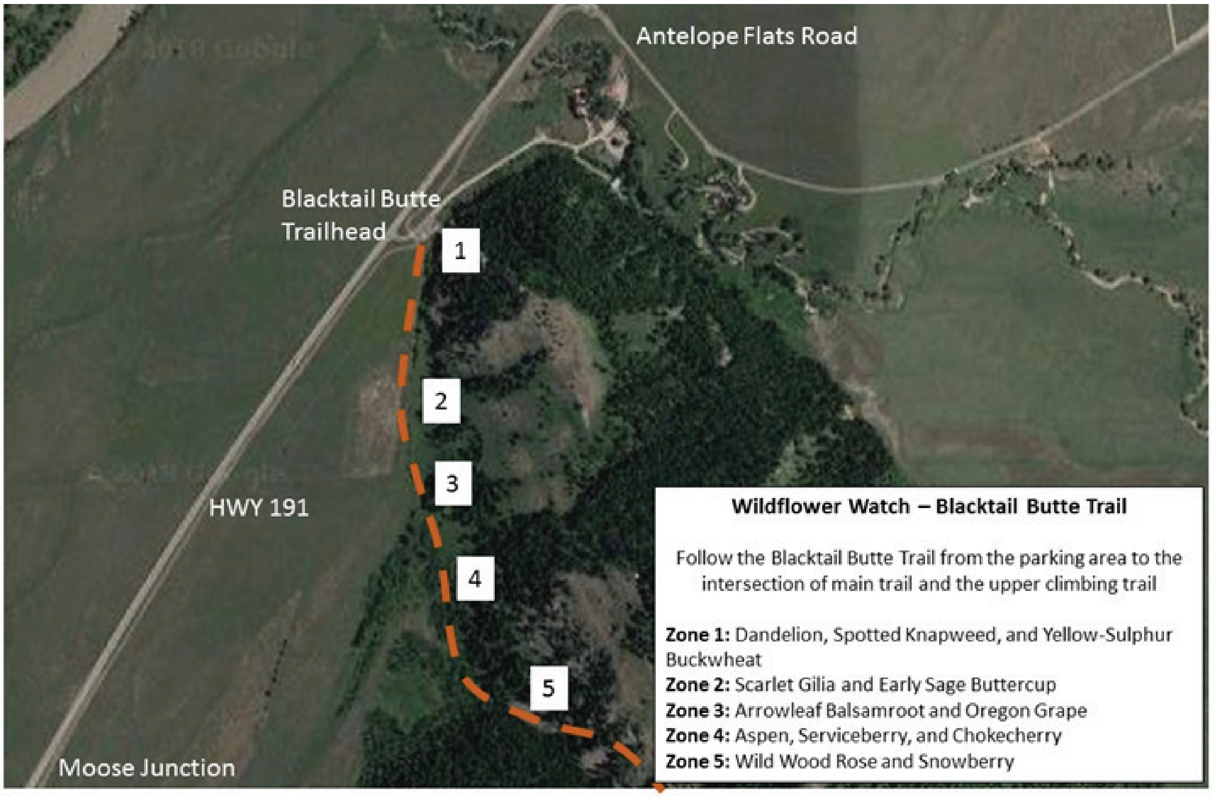
We are asking for your help, as citizen scientists, to learn the flowers and their fruit, to observe, and to collect valuable data that will be used to better understand and conserve the greater Teton community of plants, wildlife, and ourselves. Thank you for taking the time to be part of the solution!

MAP OF THE STUDY REGION



Blacktail Butte Trail, Grand Teton National Park

Blacktail Butte is one of the most accessible hiking trails in Grand Teton National Park. It boasts spectacular views of the Tetons and a big variety of wildflowers. The trailhead is just north of Moose Junction. Follow this mellow trail through wildflower meadows, sagebrush, golden aspens, and into a rich forest. 3 miles round-trip, moderate hike.



Zone 1: Dandelion, Spotted Knapweed, and Sulphur-flower Buckwheat
Begin at the Blacktail Butte Trailhead and monitor dandelion, spotted knapweed, and sulphur-flower buckwheat within 10 feet of the trailhead sign.

Zone 2: Scarlet Gilia and Early Sage Buttercup
Follow the Blacktail Butte trail for a few minutes south. From trailhead until you enter a mature aspen forest, keep your eyes out for early sage buttercup (until the end of May) and scarlet gilia along the trail.

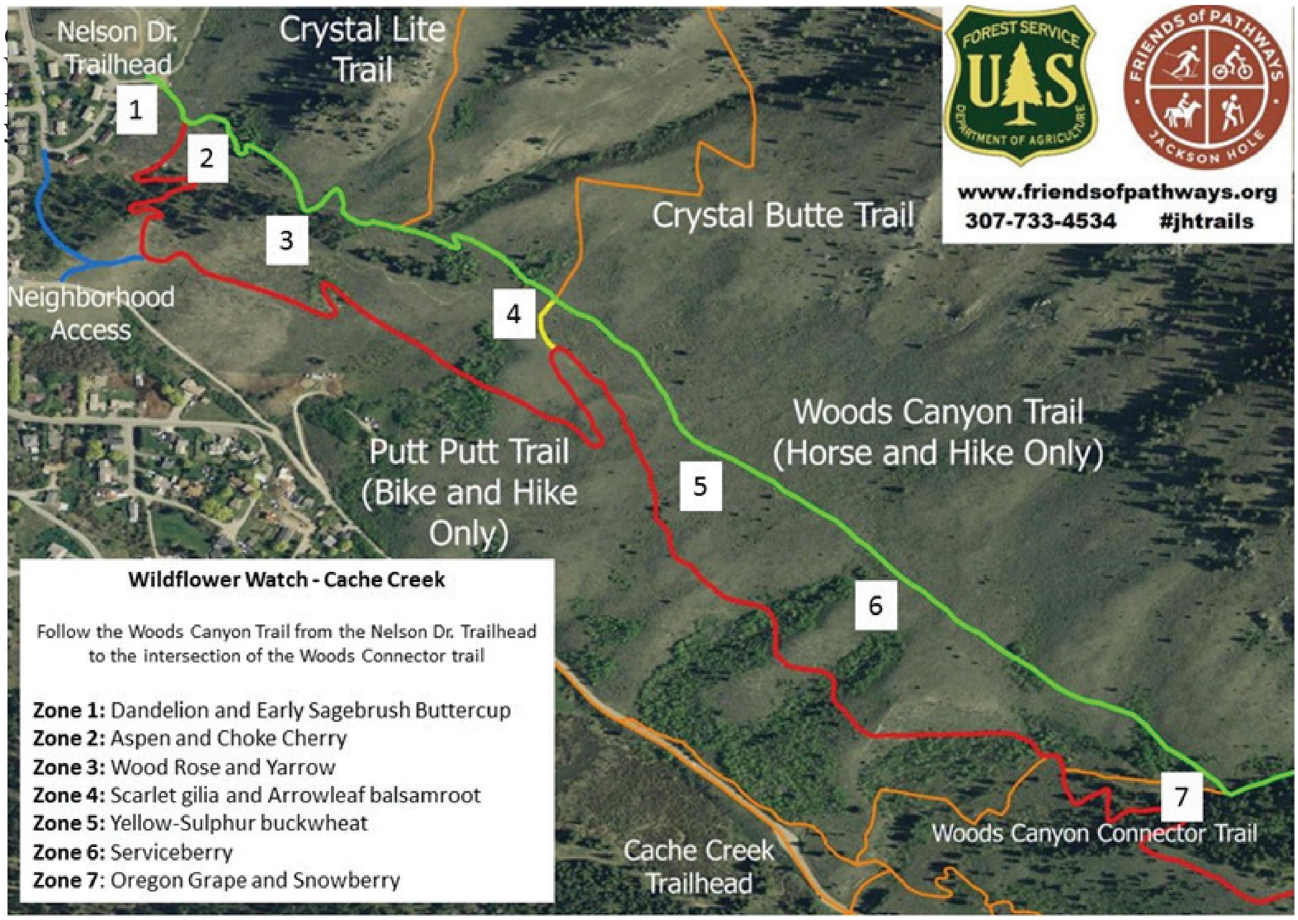
Zone 3: Arrowleaf Balsamroot and Oregon Grape
Follow the trail until it turns slightly and begins to gradually climb a west facing slope. On this hillside keep your eye out for arrowleaf balsamroot and Oregon grape.

Zone 4: Aspen, Chokecherry, and Service Berry
Zone 4 begins in the mature stand of aspens that shade both sides of the trail and ends in a large green wet meadow before the trail veers upwards into the mixed conifer forest. In this zone, monitor aspen, serviceberry, and chokecherry.

Zone 5: Wild Wood Rose and Snowberry
After the aspen grove, the trail opens into a lush green grass meadow with a small ephemeral stream running through it. This was the site of the old Smith homestead. From here the trail veers east and upwards into a dense mixed conifer forest along the stream. Zone 5 begins as soon as you enter the shade of this forest and ends at the intersection with the climber's trail beyond the second stream crossing. Monitor wild wood rose and snowberry here. If you are up for a larger hike, feel free to continue upwards towards the top of Blacktail Butte.

Cache Creek Trail, Bridger-Teton National Forest

Cache Creek is the most popular hiking area in the Bridger-Teton National Forest. For Wildflower Watch we utilize the "horse and hike only" Woods Canyon Trail accessed via the Nelson Drive trailhead, minutes from downtown Jackson. Please stay on the trail and do not trample the vegetation. Also, if you use any other trails in the area, be mindful of mountain bikers. 2 miles round-trip from the Nelson Dr. trailhead via the Woods Canyon Trail to the intersection of the Woods Canyon Connector Trail and back, easy hike.



Zone 1: Dandelions and Early Sagebrush Buttercup
Start at the Nelson Dr. trailhead and begin on the Woods Canyon Trail. Within the first 100 feet of the start of the trail, keep your eyes out for dandelions, and if you are there before the end of May, early sagebrush buttercup.

Zone 2: Aspen and Choke Cherry
Within about a ¼ mile of the trailhead you will enter a nice, shady aspen forest. Here monitor the aspen trees. Remember that they will flower as early as late March and April before the leaves begin to emerge. Also monitor the choke cherry shrubs, which will produce buds at the same time as they leaf out.

Zone 3: Wood Rose and Yarrow
After the first aspen patch, you enter a drier hillside ecosystem briefly before ascending a series of switchbacks through a second aspen grove. In this forest, keep an eye out for the feathery leaves of yarrow and the thorny wild wood rose.

Zone 4: Scarlet Gilia and Arrowleaf Balsamroot
After you exit the aspens, meander through a dry open hillside dominated by Wyoming big sage and antelope bitterbrush. From here until the signed intersection with the Crystal Butte Trail (not to be confused with the Crystal Lite Trail) look for arrowleaf balsamroot with silver-tinted, arrow-shaped leaves, and scarlet gilia, which may be more inconspicuous until it produces its brilliant red flowers.

Zone 5: Sulphur-Flower Buckwheat
From the intersection of the Crystal Butte Trail, continue through dry sagebrush steppe vegetation past the Wilderness Boundary signs. In this stretch, keep your eyes out for the low-lying perennial leaves of the sulphur-flower buckwheat. Later in the summer, look for its showy yellow flowers, which are butterfly magnets!

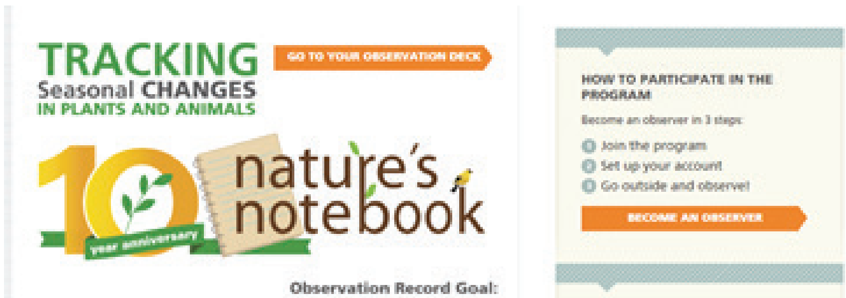
Zone 6: Serviceberry
After a rather long stretch of wandering slightly uphill through a sagebrush dominated landscape, you will enter another shady grove of aspens before cresting this hill and descending towards the trail junction. Here in this aspen grove, monitor service berry – an important late summer/fall food for bears and birds.

Zone 7: Oregon Grape and Snowberry
Within 100 feet or so of the junction of the Woods Canyon Trail and the Woods Canyon Connector Trail, keep your eyes out for the leathery, spiny leaves of Oregon grape and snowberry shrubs. There is a large snowberry shrub located directly at the intersection – be aware that the white berries are poisonous. Here you have reached the end of the Wildflower Watch trail, so great job! Feel free to return the same way you came or continue on a nice day hike on other trails. Be mindful if you hike anything other than the Woods Canyon Trail-- you must be vigilant for mountain bikers!

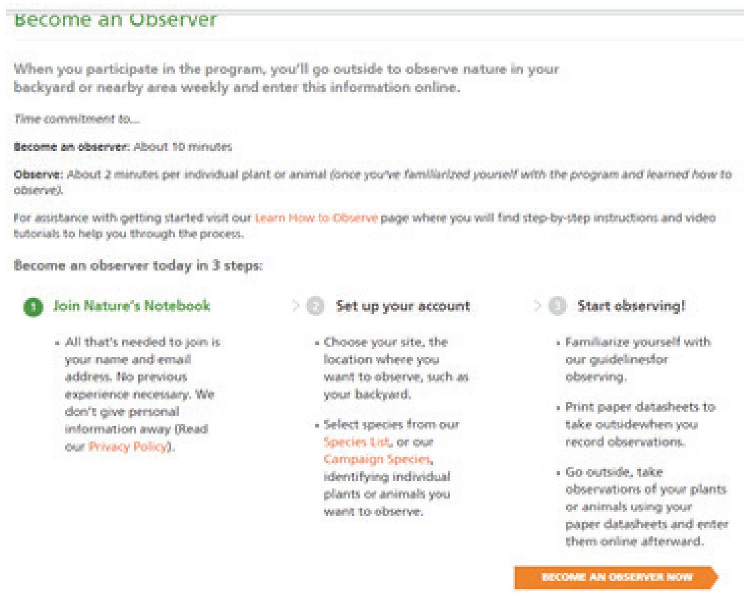
Photo: Julia Huggins

How to get started on Nature's Notebook and join TNC's Wildflower Watch

1) Go to https://www.usanpn.org/natures_notebook
2) Click "Become an Observer"



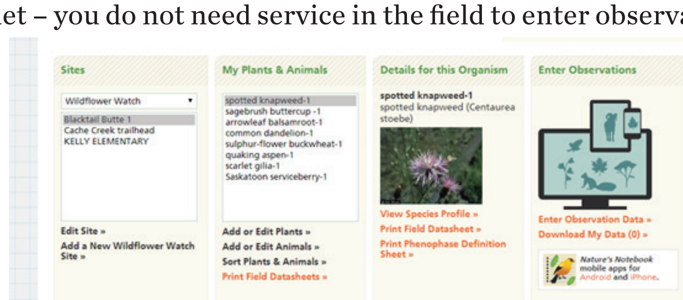
3) Follow steps 1-3



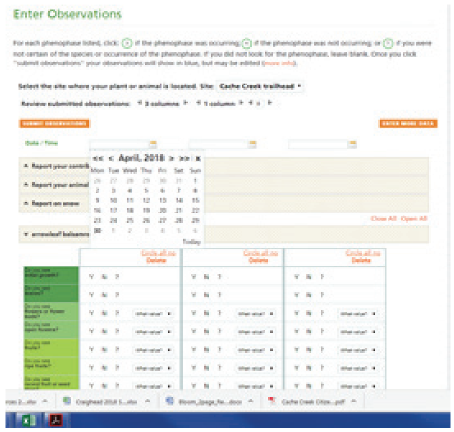
Enter email address and choose a password

Under "Partner Groups", scroll down and select "Wildflower Watch"

4) Now you are ready to make observations! You will be directed to your observation deck, here you can select the site for which you would like to make an observation, print a datasheet, or track your observations over time. To make an observation via the Nature's Notebook website, click Enter Observations. Better yet, download the Nature's Notebook Application on your smart phone or tablet – you do not need service in the field to enter observations using the app.



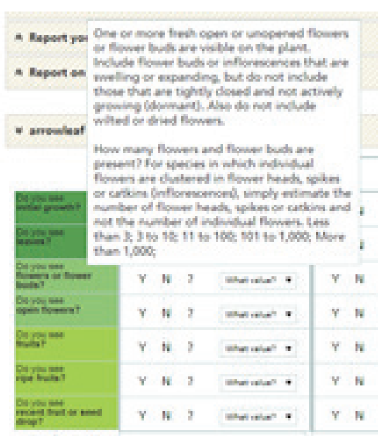
5) Three ways to record data
   - Download Nature's Notebook app from your app store on your phone/tablet – Preferred method
   - Print datasheets from Observation Deck, and later input the data in the app or website
   - Or enter data on the Nature's Notebook website - from your Observation Deck, select Enter Observation Data, then select the date (or up to 3 dates) and enter data

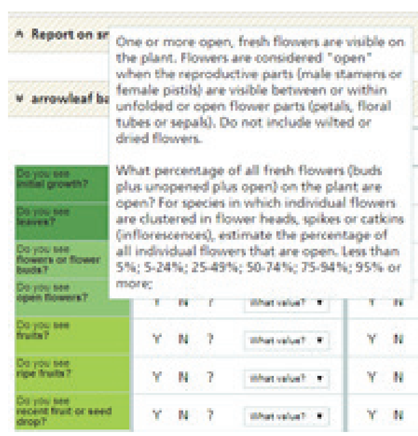


6) For all methods, be sure to record the correct date, and the correct data. For each species on the list you will be asked a series of Yes/No/Don't Know questions, for example for arrowleaf balsamroot "Do you see initial growth," "Do you see leaves," "Do you see flowers or flower buds," "Do you see open flowers," etc. Answer each question carefully and if you are unsure, mark it with a "?"

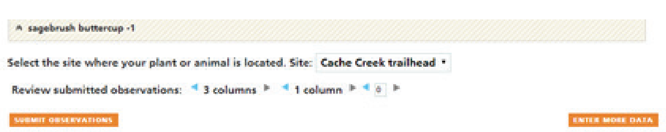
   For "Do you see flowers or flower buds," you may be asked "What Value" – for example, fewer than 3, 3-10, 11-100, 101-1000, or more than 1000. These numbers refer to how many buds or flowers you have seen along the trail.

   - For "Do you see open flowers", you will be asked "What Value." This is asking what percentage of all the buds (open and unopened) you see are open. Possble answers are: Less than 5%, 5-24%, etc. If you are unsure, you can leave this "What Value" blank (but be sure to answer the "Do you see open flowers" question with a yes or no or ?).

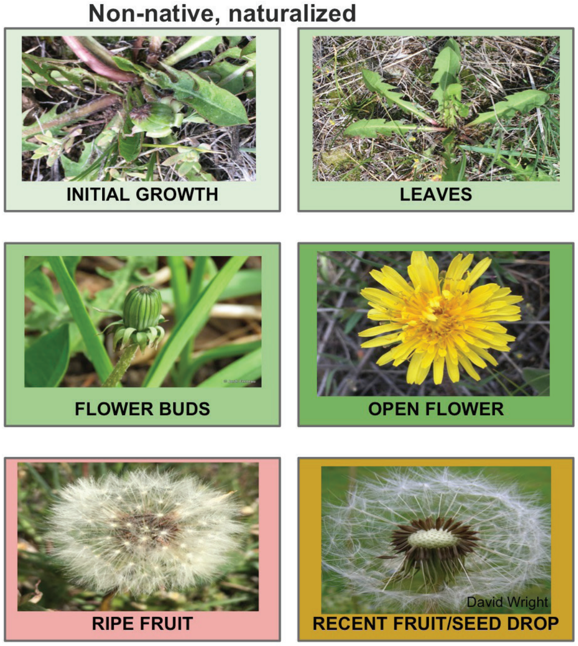




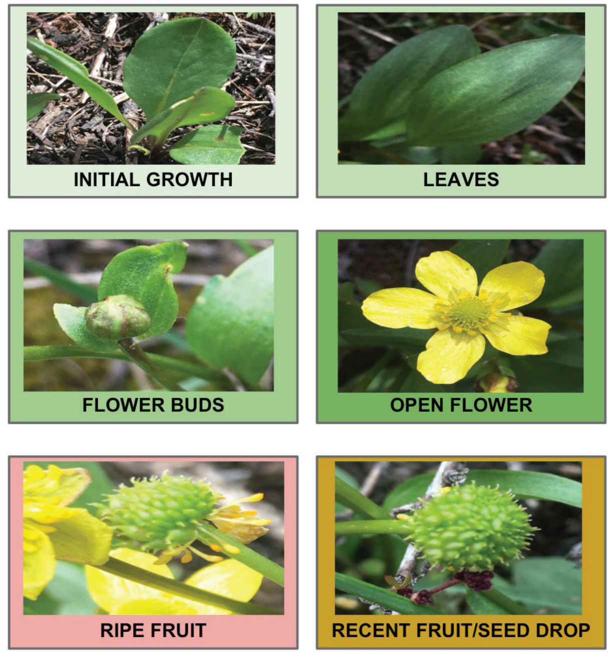
7) Once you have entered all the wildflower data for that date, you can enter "Submit Observation," or if you want to add another site or more data, hit "Enter More Data"



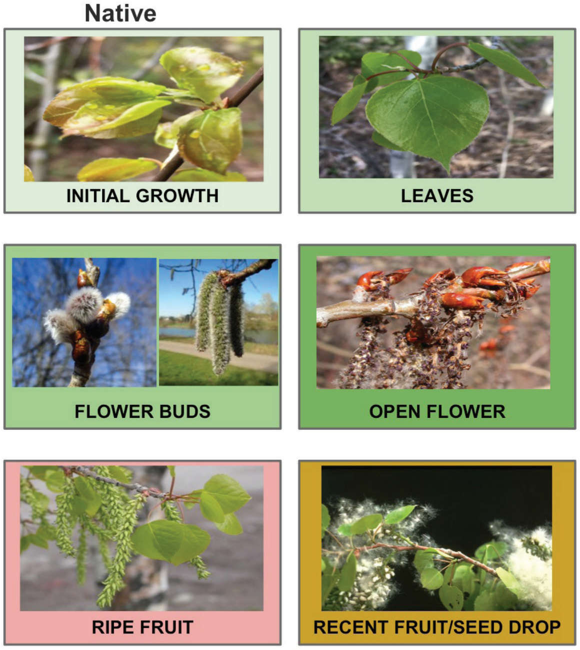
Common Dandelion
Taraxacum officinale
Non-native, naturalized



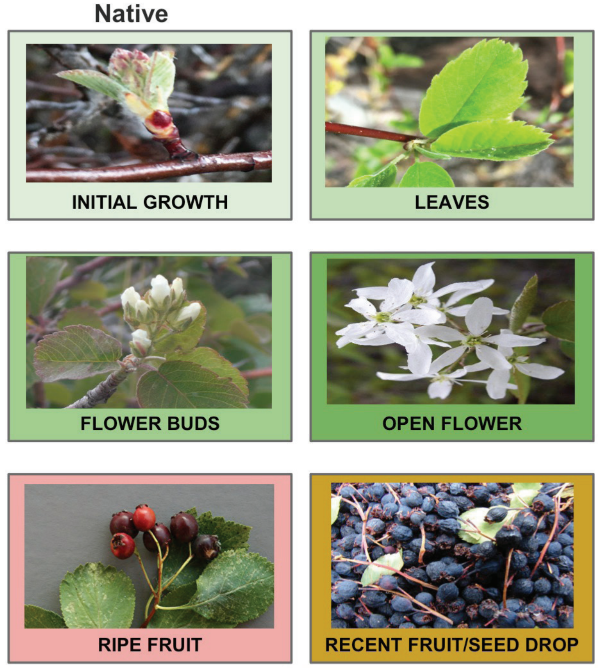
Sagebrush Buttercup
Ranunculus glaberrimus
Native



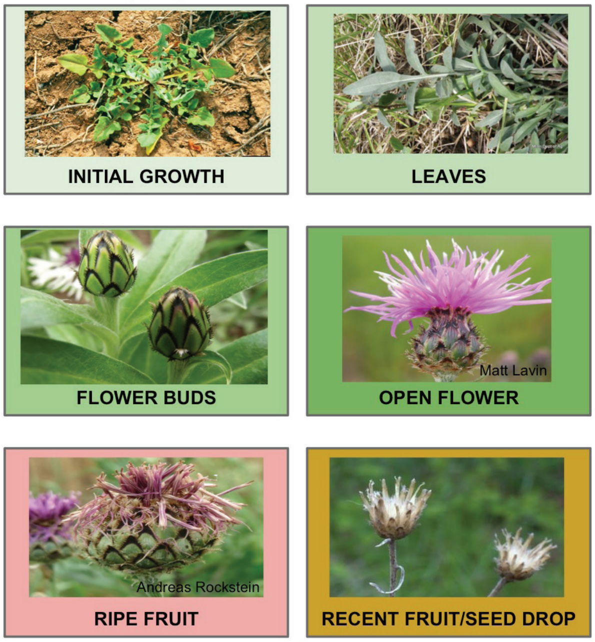
Quaking Aspen
Populus tremuloides
Native



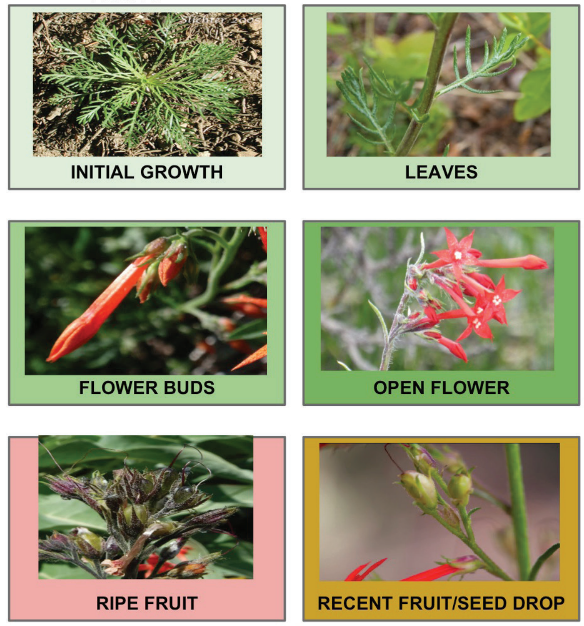
Saskatoon Serviceberry
Amelanchier alnifolia
Native



Spotted Knapweed
Centaurea maculosa
Invasive

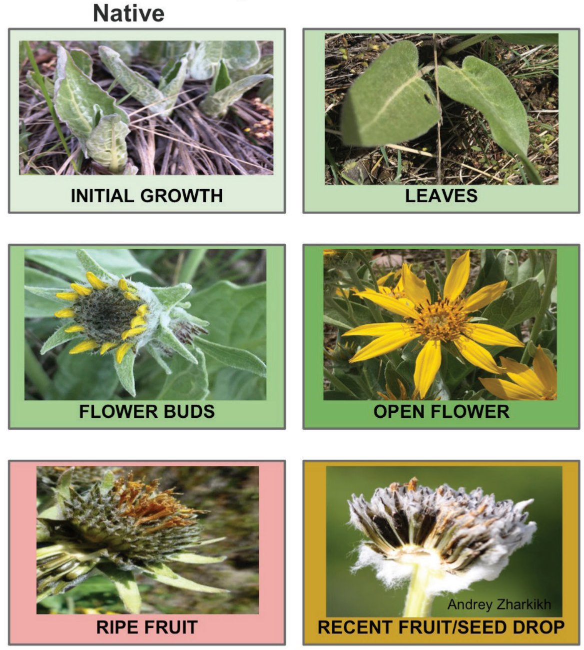


Scarlet Gilia
Ipomopsis aggregata
Native



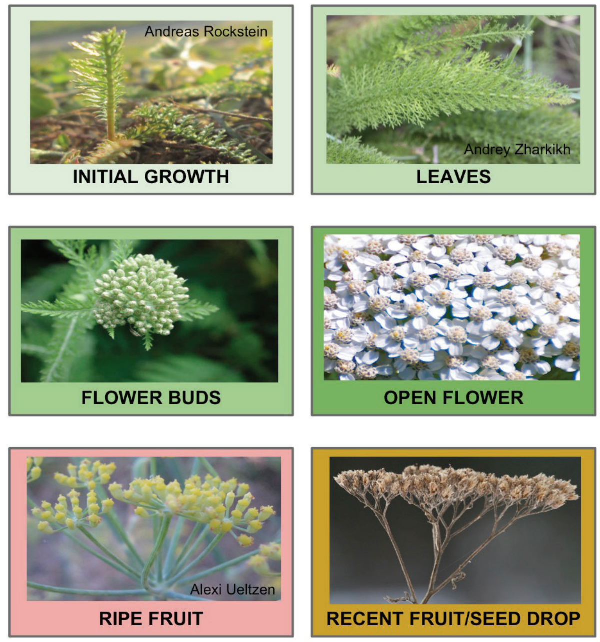
Sulphur-flower Buckwheat
Eriogonum umbellatum
Native

Arrowleaf Balsamroot
Balsamorhiza sagittata
Native

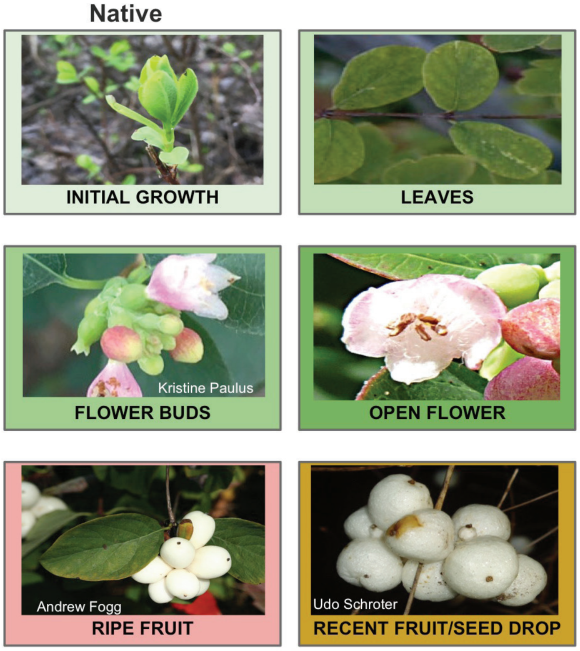


Wild Wood Rose
Rosa woodsii
Native

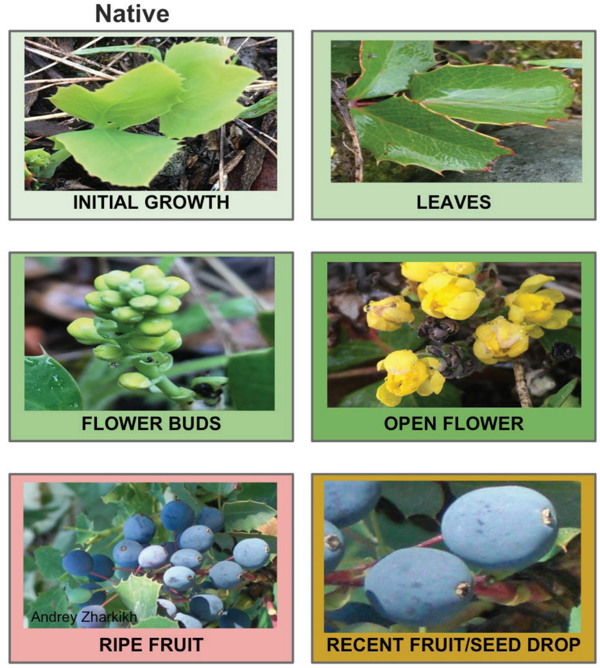
Yarrow
Achillea millefolium
Native

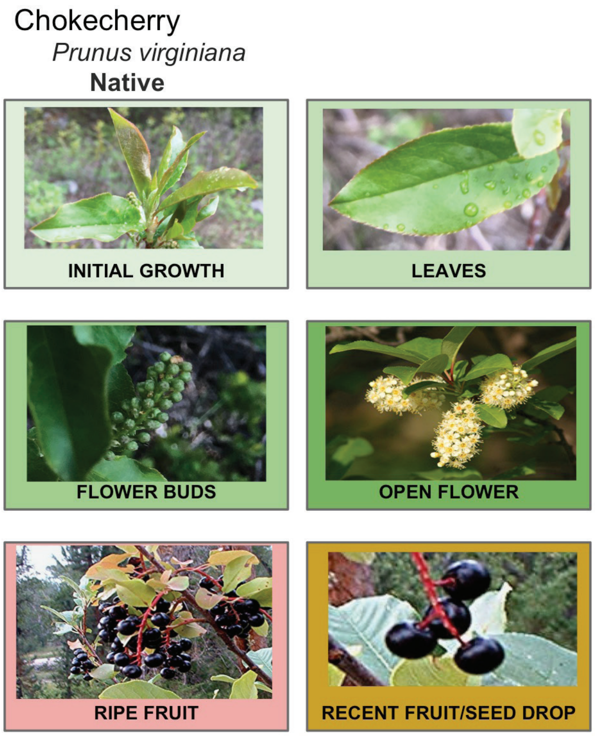


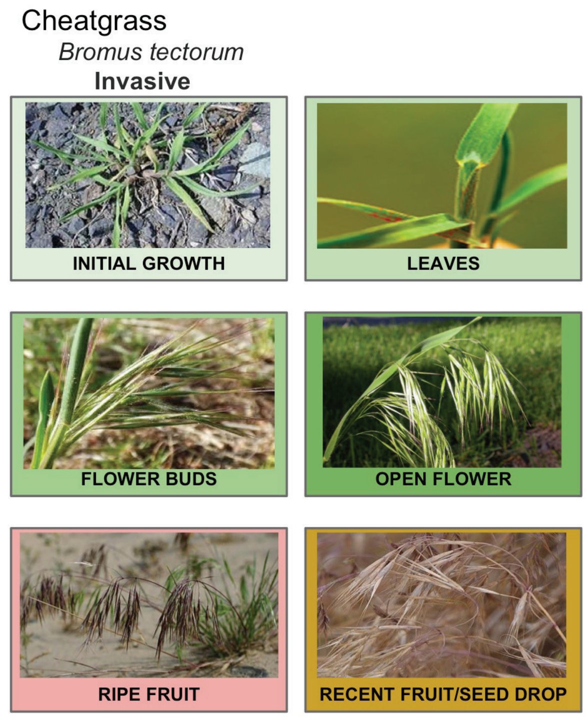
Snowberry
Symphoricarpos albus
Native



Oregon Grape
Mahonia repens
Native







What to Bring on the Walks

- Water
- Hiking shoes
- Snacks
- Small notebook (optional)
- Camera (optional)
- Hand lens (optional)
- Bear spray (recommended)

Great job!
Now get out there and watch those wildflowers!

Email Trevor with any questions or comments at trevor@nrccooperative.org