Society for Range Management

Plant Phenology: Taking the Pulse of Rangelands

By Dawn M. Browning, Keirith A. Snyder, and Jeffrey E. Herrick

On the Ground

- Plant phenology–timing of seasonal life cycle events–is a primary control on ecosystem productivity.
- Phenology data can be used to design better management systems by adjusting the timing of grazing or managed burns relative to growth stages of key species and planning restoration activities, such as targeted grazing.
- Tower-mounted digital cameras (phenocams) provide a cost-effective way to collect data to capture phenology metrics for vegetation greenness.
- Phenocam greenness values can provide canopy-level metrics in real time for a fraction of the cost of field observations and link field and satellite observations to reveal species contributions to greenness.

Keywords: plant phenology, management tools, phenocams, monitoring, invasive species, grasslands.

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Rangeland managers require timely, reliable, and easily interpretable information about their land to inform decisions. One of the biggest challenges managers face is the high temporal variability in plant establishment, growth, and reproduction. A better understanding of this variability can help decide when, where, and how to adjust management to optimize livestock production and the other services provided by rangelands.

Phenology—the timing of seasonal life cycle events in plants and animals—is the term used to describe this variability. Phenology is an integrative indicator of species' responses to environmental conditions.[1] Research on phenology generally focuses on the timing of plant and animal seasonal cycles and the role of environmental factors, such as temperature and precipitation, on changes in those cycles.[2] Plant phenology influences many critical factors in production systems such as crop yields, forage condition, and wildlife habitat suitability.[3]

How can phenology inform range management? Reliable long- and short-term forecasts of grassland productivity are important components for resource planning with clear links to phenology. Two recent developments designed to improve our ability to forecast grassland productivity are based on phenology-based models using satellite imagery inputs. The "phenograss" model developed by Hufkens et al.[4] incorporates soil parameters, fractional cover estimated from phenology cameras, and the normalized difference vegetation index (NDVI) from the MODIS satellite to predict how climate will influence grassland productivity. Shorter-term (or growing season) forecasts for grassland productivity have been developed for the Northern Great Plains with the "Grass-Cast" forecasting tool.[*] Grass-Cast combines NDVI values representing vegetation greenness and weather data to forecast growing season grass productivity.

In addition to these two applications that rely on satellite imagery, phenological data can also inform the development of management plans to curtail the spread of undesirable species and/or promote conditions that support desirable species. Differential phenology patterns for invasive species relative to native or desirable ones have important implications for how managers might curtail the spread or eradicate invasive species.[5]

For example, targeted livestock grazing of cheatgrass (*Bromus tectorum*) in the Great Basin during fall and early winter months can be used to reduce standing litter and decrease fire risk.[6] This grazing strategy is based on the phenological profiles of cheatgrass and native coexisting bunch grasses. It reduces cheatgrass standing crop during months when coexisting perennial grasses are dormant.[7] Another way that plant phenology can inform range management is via the use of online tools that depict grass production in real time at the scale of 7,500 m^2 (phenocam field of view) to guide movement of grazing livestock in order to achieve improved livestock production and potentially minimize the need for supplementation.[8] This phenocam

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[*] http://grasscast.agsci.colostate.edu; accessed 18 September 2018.

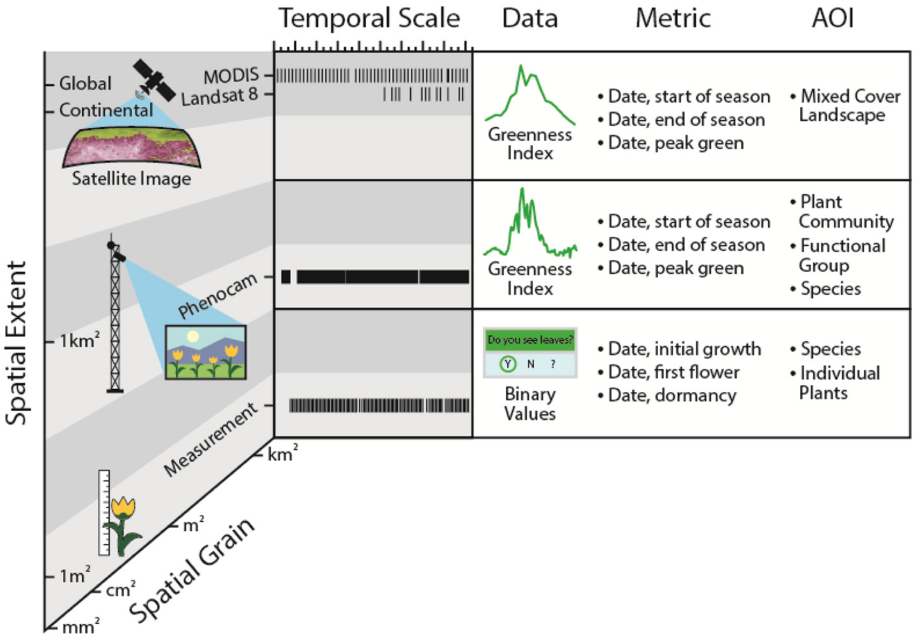

Figure 1. Phenology observations span many areas of interest (AOIs), such as plants, plant communities, and landscapes, and can be collected using standardized protocols such as those developed by the USA-National Phenology Network[20] for monitoring individual plants. Additionally, the Phenocam Network[†] has guidelines for collecting data with digital cameras. Satellite image time series are freely available through NASA. Phenocams offer flexibility in defining the AOI and share AOIs across field and satellite platforms.

perspective is more finely resolved than the complementary county-level forecasts provided by Grass-Cast.

Even with these recent advances, there remain gaps in understanding and appreciating the value and utility of seasonal (i.e., phenological) information that can enhance management decision-making.[9] We aim to change this. Here we describe phenological data, direct readers to more information about common techniques used to translate these data into informative metrics, and highlight two applications that integrate field and satellite data to generate actionable information.

Phenological data are collected at a wide variety of spatial scales and temporal frequencies (Fig. 1), with repeat observations as a core asset of these data. The spatial scale can range from individual plants to communities up to landscape-level greenness. At each of these scales the data can often be resolved to characterize different functional groups of species. Data collection frequency can be as high as multiple observations per hour to just a few observations per year with implications for uncertainty on the dates of seasonal transition (Fig. 1).

The spatial scale and temporal frequency determine which metrics can be calculated. The phenological metrics that are most informative for management depend on management objectives and can include: 1) timing of initial growth (at species level) or start of season (functional group or landscape level) based on changes in greenness; 2) timing of flowering (at species level) for pollinators or seed set for native seed collection; 3) timing of peak greenness or production for grazing; and 4) timing of brown-down into end of season for grazing to reduce standing crop, litter, or fuel loads.

How Do Phenocams Work?

In between the levels of field and satellite observations, near-surface digital cameras mounted on towers (phenocams) provide images that fill the gaps in time and space (Fig. 1). In addition to bridging the spatial extent between field and satellite, the user can define the area of interest (AOI) for phenocam seasonal metrics to represent individual plant canopies, groups of plants in a single functional group (e.g., perennial grasses vs. shrubs), or the entire plant community.

Phenocams collect multiple images daily and use user-defined AOIs on the image. Digital numbers from the red, green, and blue image bands are combined to create vegetation greenness index values.[10] Daily greenness values are then used to calculate growing season metrics using fitted values to identify inflection points (i.e., increase or decrease in greenness) in the time series that correspond to start of season or end of season and peak growing season greenness (Fig. 1). Phenocam growing season metrics identified from the greenness index time series can be calculated with online tools such as those available through the Phenocam Network for real-time online data. Data can also be processed locally using one of several programs, such as the Phenopix Package in the R environment.[11] One benefit of online processing of phenocam data is the live link to field conditions in cases where daily images are transmitted wirelessly to the online repository.[†]

In the examples that follow, authors use the green chromatic coordinate greenness metric, GCC, which is the green digital

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[†] https://phenocam.sr.unh.edu/webcam/gallery; accessed 13 September 2018.

number (DN) divided by the sum of the red, green, and blue digital numbers (DNg/(DNr + DNg + DNb).[12] Higher values indicate greener plants. The phenocam greenness time series offers daily details on plant growth patterns important to forage production, invasive species, or wildlife habitat. Phenocam greenness values and seasonal metrics have been shown to correlate well with field estimates of greenness for mesquite (*Prosopis glandulosa*) and the C_4 black grama grass (*Bouteloua eriopoda*) on a sandy ecological site in the Chihuahuan Desert.[13] At this same site, seasonal metrics for start of season and end of season from landscape phenocam greenness values were positively and significantly correlated with those from NDVI from the MODIS satellite ($R^2 = 0.83$).[13] Data and metrics from phenocams provide an opportunity to gauge their strengths and limitations for rangeland monitoring.

Phenological Data Support Land Management Needs

Phenological metrics from remotely sensed imagery can be especially valuable in semiarid and arid rangelands of the western United States with vast, rugged, and remote terrain. These metrics can also be used to distinguish contrasting phenological patterns for herbaceous grasses and woody vegetation. Two additional benefits of phenological metrics for rangelands with high year-to-year variability in weather and plant productivity are 1) the ability to put indicators of landscape condition in the context of variability within and between years to inform both short- and longer-term management decisions, and 2) the ability to assess outcomes of management and restoration.[14] However, the high reflectance of exposed soil[15] and the aggregated phenological signals resulting from grass and woody plant species[16] can make data interpretation challenging. Scientists around the world are continuing to develop new strategies for addressing these challenges, including integration of field data from long-term monitoring plots as well as fine-scale phenocam observations as illustrated by the two case studies below.

Two Case Studies

Shift in Species Composition in a Great Basin Mountain Meadow

Groundwater dependent ecosystems, such as meadows and riparian areas, have been successfully monitored using NDVI from 30-m Landsat imagery.[17] Using a 30-year record of Landsat satellite NDVI for six groundwater-dependent sites in Nevada, Huntington et al.[17] showed increased plant greenness in two sites where restoration efforts were implemented. Examination of NDVI time series for two sites where management intervention occurred indicated that restoration efforts yielded more resilient systems with higher NDVI even during dry years because of improved groundwater levels that reduced drought stress in riparian plants.[18] Decision-makers and managers often need to know what species are responding to management interventions. In this way, phenocams can provide a visual record of species responses over the course of a growing season. In addition, for landscapes that have a limited spatial extent or complex arrangement of meadows or riparian areas that are not easily monitored by coarser scale satellite imagery, phenocams provide an alternative scale of measurement.

We calculated greenness using phenocam and Landsat satellite image time series for a mesic meadow in the central Great Basin, NV (Fig. 2A). During the 4-year drought (2012–2015) the mesic meadow experienced a change in species composition. The characteristic sedges, field sedge (*Carex praegracilis*) and Douglas sedge (*Carex douglasii*; Fig. 2C), declined and the less desirable poverty weed (*Iva axillaris*) expanded to dominate in 2015 (Fig. 2D). By 2017, with a slightly above average precipitation year in 2016 and an extremely wet winter in 2017, groundwater levels recovered in the mesic meadow, and the area was dominated by field sedge and Douglas sedge.

The camera GCC and Landsat NDVI were correlated through time (Spearman rank correlation, $r_s = 0.77$). This correlation with Landsat allows the record for this meadow to be extended back to 1984 using the freely available Landsat archive, which can be useful for assessing the effect of past management on restoration efforts. Contemporary phenocam images provide additional detail not obtainable from the satellite NDVI that changes in greenness were not only because of more plant available water, but also because of a change in species composition. If phenocam or Landsat patterns are relatively stable through time across variable weather conditions, this can indicate a stable groundwater level and more resilient ecosystem.[17]

Phenology: An Untold Story in Shrub Encroachment

Many studies addressing shrub encroachment have examined the role of soils, land use, and landscape configuration on rates and long-term patterns on changes in grass and shrub cover, but few have compared patterns in phenology between coexisting deep-rooted C_3 shrubs and more shallow-rooted grasses. Browning et al.[13] compared phenological metrics for C_4 black grama (*Bouteloua eriopoda*) and C_3 mesquite shrub (*Prosopis glandulosa*) in a Chihuahuan desert grassland using standardized field protocols, phenocam, and satellite time series. Field observations of percent green canopy were highly correlated with phenocam greenness index values for black grama (Spearman rank correlation, $r_s = 0.609$) and mesquite ($r_s = 0.735$) indicating good agreement. Dates for start of season from field observations and phenocam corresponded more closely for mesquite (11 days average across thresholds), but less so for black grama. Browning et al.[13] found a difference of approximately 60 days between field-observed unfolded basal leaves and a discernable change in foliar greenness detected by the phenocam—approximately 25% foliar greenness.

The other notable finding with management implications was the contrast in phenological profiles for black grama and mesquite AOIs. Black grama grass AOIs showed a rapid increase in greenness in response to summer monsoon rains, the timing of which is different every year. In contrast, there is

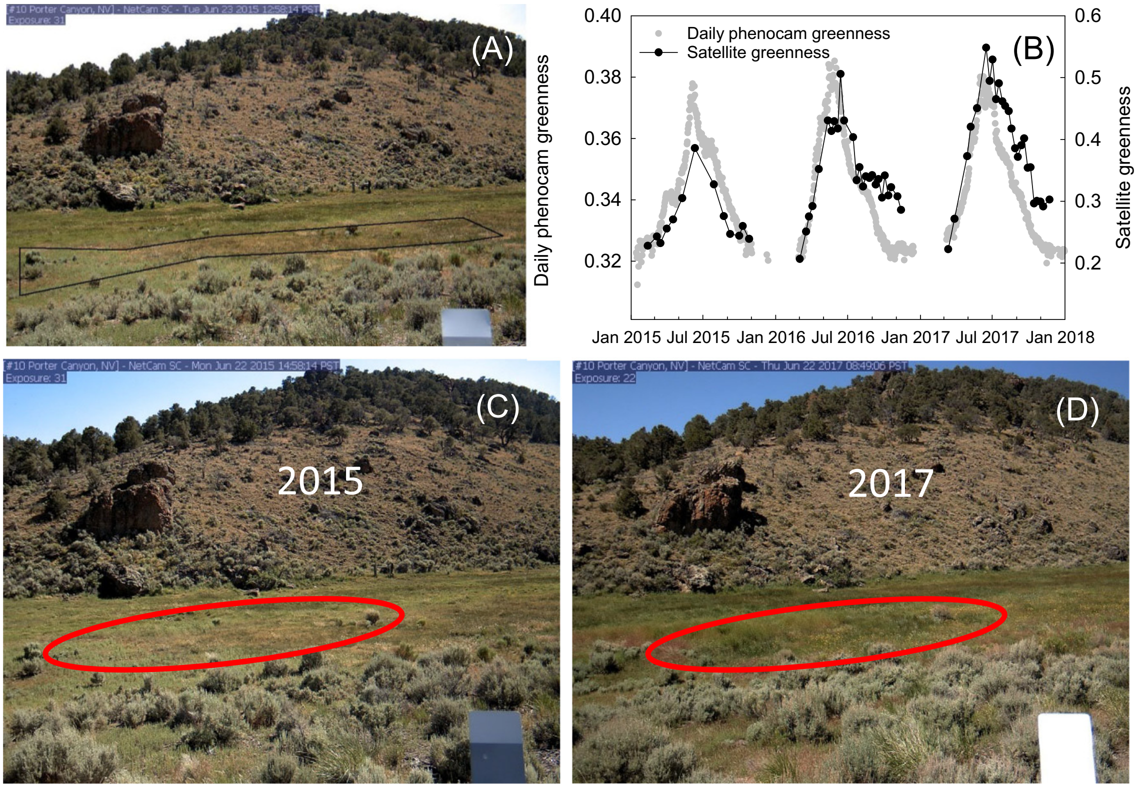

Figure 2. A Great Basin meadow in Porter Canyon Experimental Watershed, Desatoya Mountains, Nevada. **A,** The black outline is the mesic meadow area of interest (AOI). **B,** Phenocam-derived greenness and normalized difference vegetation index derived from the Landsat satellite platform for the mesic meadow AOI. **C,** The meadow after 4 dry years in 2015. Red circle is where species composition shifted to *Iva axillaris* (poverty weed). **D,** The meadow after the 2016 average precipitation year followed by an extremely wet winter in 2017. Red circle is where *Carex praegracilis* (field sedge) and *Carex douglasii* (Douglas sedge) were dominant in 2017.

a more consistent spring emergence date for deeper-rooted mesquite shrub AOIs (consistently in late March) regardless of rainfall (Fig. 3). Understanding the distinguishing characteristics of phenological profiles for dominant plant species or functional groups can augment interpretations of land surface phenology derived from satellite remote sensing. Browning et al.[13] also found in this Chihuahuan desert grassland landscape that the MODIS NDVI signal is driven by the perennial grass response. C_4 grass and C_3 shrub species exhibit markedly different phenological patterns that were consistent between both field and phenocam observations. If landscape indicators for management are based on mesquite, the sampling window is more predictable and longer than if the indicators are based on perennial grass abundance or reproductive phenology. We demonstrated that fine-scale estimates of canopy greenness can be achieved as effectively with phenocams as they are with costlier regular (e.g., weekly) measurements by field crews.

Summary and Conclusions

Our goal is to promote the understanding and application of phenological data to enhance management decision-making and expand capabilities to meet resource management needs. We highlight how data from phenocams can bridge field and satellite observations of landscape condition and provide informative ancillary data for grassland monitoring and ecosystem modeling. Greenness indices from phenocams can increase the frequency of monitoring "snapshots" and expand understanding of how different plant functional groups (e.g., grasses vs. shrubs) contribute to greenness signals from moderate resolution satellite images.

Grasses have a different phenology profile than shrubs, particularly in warm deserts characterized by growing-season summer rainfall and with predominantly grasses with C_4 photosynthetic pathway. Timing of peak greenness can be identified in real time, and both short- and long-term records of peak greenness can assist with several management decisions. For example, timing of peak greenness can guide plans for managing grazing-herd movements to utilize or avoid particular forage types to optimize livestock production and species conservation.[8] Both short- and long-term records of timing of peak greenness can be used to help determine when to measure peak biomass to estimate primary production. Even in sagebrush-dominated landscapes, a mainly evergreen species, these cameras can detect seasonality in greenness and how it varies with soil water availability across years.[19]

Phenological data provide an incredibly powerful and under-used opportunity to increase management effectiveness

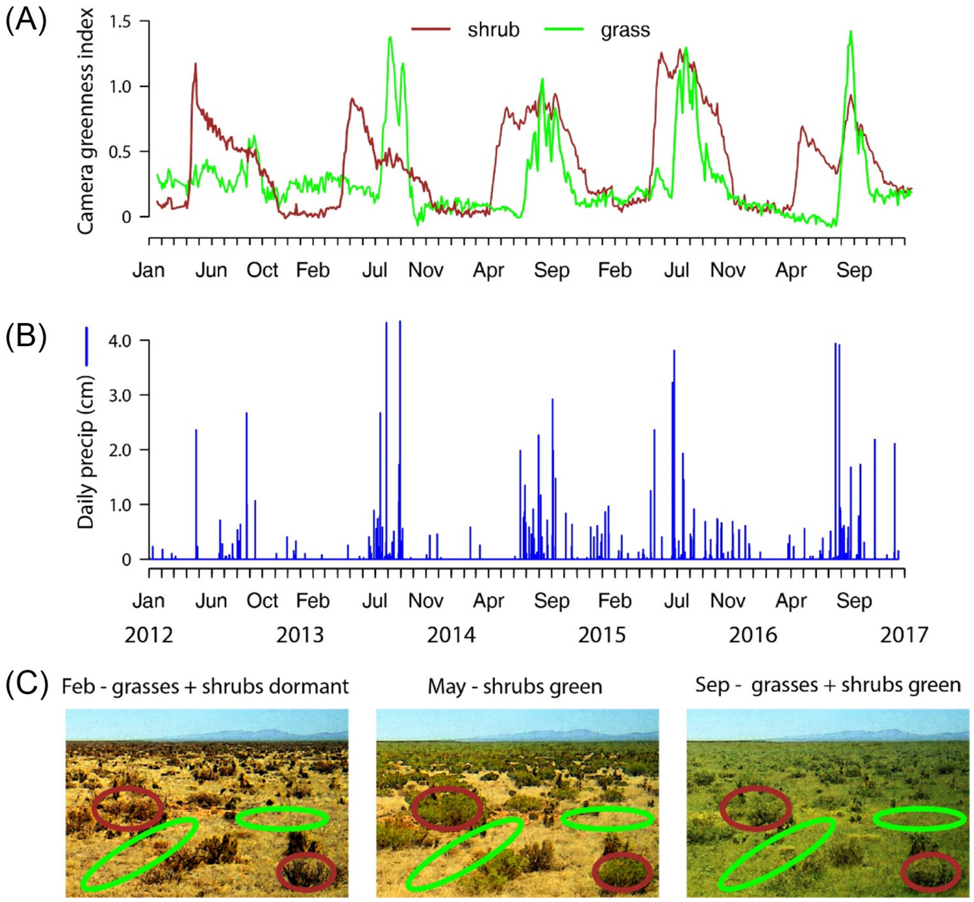

Figure 3. Phenological profiles for *Prosopis glandulosa* mesquite shrub areas of interest (AOIs) (**C,** brown outlines) and *Bouteloua eriopoda* black grama grass AOIs (**C,** green outlines) on an ungrazed sandy ecological site on the Jornada Experimental Range in southern New Mexico from 2012 through 2016. Black grama greenness responded rapidly to summer rains while mesquite green-up occurred more consistently (**A,** late March to early April) prior to summer monsoon rains in **B,** both wet (2015) and dry (2012-2013) years.

through precision timing. The data are easier to collect than ever using field observations, phenocams, and satellite imagery. Online tools make metric calculation simple, while increasingly sophisticated algorithms are facilitating the integration of different sources of phenological data. The results of these integrated analyses will increasingly allow managers to target management interventions, including grazing, herbicide applications, and prescribed fire, with pinpoint accuracy in both space and time.

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Authors are Research Ecologist, U.S. Department of Agriculture – Agricultural Research Service, Jornada Experimental Range, New Mexico State University, Las Cruces, NM 88003, USA (dawn.browning@ars.usda.gov, Browning); Research Ecologist, U.S. Department of Agriculture – Agricultural Research Service, Great Basin Rangelands Research Unit, Reno, NV 89512, USA (Snyder); Research Soil Scientist U.S. Department of Agriculture – Agricultural Research Service, Jornada Experimental Range, New Mexico State University, Las Cruces, NM, 88003, USA (Herrick).