CHARACTERIZING THE PHENOLOGY OF SOUTHWEST LANDSCAPES

U.S.A. National Phenology Network (NPN) & Southwest U.S. Region, American Society of Photogrammetry & Remote Sensing (ASPRS)

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ABSTRACTS OF PRESENTED PAPERS (LISTED ALPHABETICALLY BY FIRST AUTHOR)

25 YEARS ON A MOUNTAIN TRAIL: A FLORISTIC STUDY OF AN ARIZONA CANYON
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Since 1984 I have recorded all flowering plant taxa along a five-mile trail that climbs 4158 ft into the Santa Catalina Mountains. With a primary focus on an area 30 ft on either side of the trail, a “transect” of about 1.6 million ft², I amassed 111,012 records along five trail segments during 1024 hikes in the first 20 years. I also compiled a flora of 596 specific and infraspecific taxa. The flora and its phenology are extremely variable, both temporally and spatially. Although taxa were added each year, decreasing annual rainfall and increasing average annual temperature have been accompanied by a decreasing proportion of know taxa seen in bloom. Annually, a strongly bimodal distribution, with spring and summer peaks, was seen for the flora as a whole. With increase in elevation, the spring peak became progressively smaller, and the summer peak greater. Most growth forms showed strongly bimodal distributions within a given year, but succulents, annual vines, and trees had essentially unimodal distributions.

CLIMATE CHANGE AND PHENOLOGY IN THE WEST
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This keynote address will include Reevaluation of the Spring Onset/Fire Association in the Western U.S. using Phenological vs. Hydrological Models by Julio Betancourt, Anthony Westerling, and Mark Schwartz of the following abstract: An important aspect of climate variability and change is the exact timing of the transition from winter to spring, generally defined here as spring onset. Spring onset can have important hydrological and ecological consequences, including changes in the timing of snowmelt and snowmelt runoff, in timing of plant and animal phenologies and their interactions, in ecosystem fluxes, and in the probabilities of ecological disturbances such as fire and insect outbreaks. Spring onset can be variably defined, which can affect its use as a predictor. To evaluate changing fire probabilities in the western U.S., Westerling et al. (2006) used center of mass of annual streamflow (CT, after Stewart et al 2005) for snowmelt-dominated gauge records as a proxy for spring onset, and compared it with the number of forest wildfires greater than 400 ha annually around the western U.S. This study indicated a strong association between large wildfire occurrence across the West and CT, and a particular sensitivity to the timing of snowmelt in the Northern Rockies. Though the timing of snowmelt can affect fire occurrence in several ways, the use of CT as a proxy for spring onset biased the analysis towards higher elevations and latitudes. To skirt this bias, we undertook a similar analysis using Spring Indices (SI) developed from cloned lilac and honeysuckle phenological data and representing seasonally integrated changes in temperature (Schwartz et al. 2006). The SI models can be generated at any location that has daily maximum-minimum temperature time series, and allowed comparison of large fire occurrence in defined regions with a network of select weather stations across the West for which we computed SI. The SI/fire comparison showed strong associations between SI at weather stations, particularly those in
the Central Rockies/Colorado Plateau and large fire frequency in the northern, central and southern Rockies, as well as in the Sierra Nevada, but less so in southern California and the Black Hills. Given large differences in fire seasonality, vegetation type, and the importance of snowpack, explanations for the spring onset/fire association could be inherently complex. Though they also have biases and shortcomings, phenological models such as SI may be particularly useful in predicting climate change impacts on fire and other phenomena, and could offer more precision and better lead time in fire forecasting.

Schwartz, M.D., R. Ahas, A. Aasa 2006: "Onset of spring starting earlier across the Northern Hemisphere" Global Change Biology, 12: 343-351.


**TIMING MATTERS: EFFECTS OF PLANT SIZE AND WEATHER ON THE FLOWERING PHENOLOGY OF THE ORGAN PIPE CACTUS (STENOCEREUS THURBERI)**

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Flowering phenology is a critical life-history trait that influences reproductive success. It has been shown that genetic, climatic, and factors such as plant size, affect the timing of flowering and its duration. We studied the spatial and temporal variation in the reproductive phenology of the columnar cactus *Stenocereus thurberi*, and its association with plant size and environmental cues. Flowering was monitored during three years in three populations of *S. thurberi* along a latitudinal gradient. Plant size was related to phenological parameters. The actual, as well as past weather, was used for each site and year to investigate the environmental correlates of flowering. There was significant variation in the timing of flowering within and among populations. Flowering lasted four months in the southern population and only two months in the northern one. A single flowering peak was evident in each population, but occurred at different times. Large plants produced more flowers, and bloomed earlier and for a longer period than small plants. Population synchrony increased as the mean duration of flowering per individual decreased. The onset of flowering is primarily related to the variance in winter minimum temperatures and the duration with the autumn-winter mean maximum temperature, whereas spring mean maximum temperature is best correlated with synchrony. Plant size affects individual plant fecundity as well as flowering time. Thus, population structure strongly affects flowering phenology. Indications of clinal variation in the timing of flowering and reproductive effort suggest selection pressures related to the arrival of migrating pollinators, climate, and resource economy in a desert environment. These pressures are likely to be relaxed in populations where individual plants can attain large sizes.

**FLOWERING RANGE CHANGES AND WARMING SUMMER TEMPERATURES IN THE CATALINA MOUNTAINS**

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Mountain gradients are ideal laboratories for studying species range changes. In this study of 363 plant species in bloom collected in five segments across the 1,200 m (4158') Finger Rock elevation gradient in the Santa Catalina Mountains north of Tucson, AZ, we look for changes in species flowering ranges over a 20-year period. Ninety-three species (25.6%) exhibited a significant change in the elevation at which they flowered from the first half to the second half of the record, with the majority of these changes occurring at higher elevations. Most of the species exhibiting the changes were perennial plants. Interestingly, changes in flowering range were not specific to certain elevations or biomes; rather, range changes occurred all across the gradient. The changes reported in this study are concurrent with significant increases in summer temperatures across the region and are consistent with observed changes around the globe.

**DAILY BLOOM PRODUCTION OF THE SAGUARO CACTUS (CARNEGIEA GIGANTEA)**
The bloom production of a population of the columnar saguaro cactus (*Carnegiea gigantea*) has been studied since 1997 in the Rincon Valley of the Tucson Basin located in eastern Pima County, Arizona. The Red Hills survey site is an eight by twelve array of contiguous 10 meter by 10 meter plots (0.96 hectare) that drapes the southern aspect of a hill situated at an elevation of 1,073 meters (3,250 feet). The local saguaros grow within the Arizona Upland subdivision of the Sonoran Desert scrub biome that is mixed with floristic elements from the Chihuahuan Desert to the east southeast. A net gain in the number of reproducing saguaros over the past twelve blooming seasons has caused a change from N=122 to N=145. Data of the bloom were acquired for each reproducing saguaro by tallying and recording the flowers open daily on each stem throughout the bloom season each consecutive year. Rigorous collection of the data has recorded the temporal characteristics of the sites saguaro bloom – the date of first bloom, the average bloom date, the date of peak bloom, the opening of the first fruit, and the date of the last bloom. Contrary to previous anecdotal observations the data illustrate remarkable variability in the total number of blooms from year to year and day to day within a given bloom season for a saguaro population.

As phenology becomes a more central research theme for both biologists and remote sensing scientists, bridging phenologic information across varying temporal and spatial scales of analysis becomes increasingly important. Field observations of phenology taken coincidently with digital photography and reflectance spectra for representative and focus vegetation types/species can provide a clear link to remotely sensed imagery. Here we present a preliminary phenologic spectral reference library for four vegetation species occurring in an invaded grassland in coastal California. Physical measurements, digital photographs, and reflectance spectra from an ASD spectroradiometer were collected on a bi-weekly basis for *Foeniculum vulgare* (wild fennel), *Baccharis pilularis* (coyote brush), *Carduus pycnocephalus* (Italian thistle) and *Brachypodium distachyon* (false brome) at the University of California Coal Oil Point Reserve from October, 2007 to September, 2008. These data capture phenologic events including onset of greenness, maximum greenness, flowering, and onset of senescence. Ancillary environmental data including temperature, soil moisture, precipitation, and incoming and outgoing radiation, were also collected at the site. The applications of this dataset and phenologic spectral libraries in general, including more accurate sub-pixel mapping of vegetation type/species with remotely sensed imagery and enhanced scheduling of image acquisition, are discussed.

The Arizona landscape is undergoing changes in vegetation growth patterns that are due to disturbances related to wildfire, extreme drought and precipitation events, and human interactions. Some vegetation communities might be affected by invasive species, variation in species ranges, connectivity and patchiness, which will in turn affect biodiversity. One vital sign that is of interest to the National Park Monitoring Network is vegetation phenology. Time series of spectral vegetation indices are used to examine the vegetation growth trajectories in response to climate and human interactions. Vegetation phenology of the Arizona landscape is characterized with a focus on National Parks and surrounding areas. Long term Moderate resolution Imaging Spectroradiometer (MODIS; 250m; 16-day interval; 2000-2007) and Landsat (30m; ~1 per year) time series vegetation index data are used to characterize phenological metrics. These metrics include time of the start, peak, and end of the growing season with corresponding vegetation index values and time integrated metrics related to seasonal biomass production. It is shown that the MODIS time series data provide a temporal reference for annual Landsat data, resulting in more...
informed land surface change assessments. Inter- and intra-annual spatio-temporal phenological characterization and patterns not only provide a tool to monitor and manage natural resources in Arizona and the National Parks, but also offer a means to support conservation and management practices by illuminating landscape responses to climate variability and human activities.

INTEGRATING PHENOLOGY INTO SATELLITE IMAGE-BASED CLASSIFICATIONS FOR LANDSCAPE DYNAMICS MONITORING

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The National Park Service Sonoran Desert Inventory and Monitoring (I&M) network recently identified 25 ecological “vital signs” to monitor at 11 park units throughout Arizona and New Mexico. Two vital signs ranked as high-priority by park management were landscape fragmentation and land use patterns around parks. Effective protocols for Landscape Dynamics monitoring require a Remote Sensing and Geographic Information Systems (GIS) approach to model broad scale patterns and temporal changes occurring in and around National Parks. Using Tumacácori National Historical Site and the surrounding Upper Santa Cruz River watershed as a case study, we developed landcover classifications that exploit phenological cycles of vegetation types through the use of multi-season satellite imagery. We derived various spectral vegetation indices and image transformations (e.g. tasseled cap, texture) from pre-and post-monsoon Landsat Thematic Mapper imagery and combined these with topographic data (e.g. aspect, slope), and consequently classified these variables into land cover classes using both Maximum Likelihood and non-parametric Classification and Regression Tree (CART) models. Classification accuracies were assessed against field and air-photo data and the results indicate higher accuracies for the CART classification. Results suggest that seasonal phenological information captured with multi-temporal satellite data improves landscape classification and landscape dynamics monitoring efforts.

THE CHANGING CHARACTER OF PHENOLOGY, DROUGHT, AND THE SEASONS IN THE SOUTHWESTERN U.S.A.

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The growing importance of phenological monitoring and modeling in the face of climate change is manifest in ongoing implementation of a U.S.A.-National Phenology Network (NPN) with regional branches. Subtropical and semi-arid regions like the southwestern U.S.A. (Southwest), where phenophases may be triggered by both temperature and precipitation, arguably present some of the biggest challenges. Not only is the Southwest characterized by high spatiotemporal variability of plant phenology due to a highly seasonal climate and complex terrain, but it is also projected to be a hotspot of future change in climate means and variability. Climate constraints on plant phenology are anticipated to change both seasonally and topographically. We examine this hypothesis by comparing seasonal phenological constraints based on observed surface climates during the pronounced Southwest droughts of the 1950s and 2000s, the latter influenced by warmer winters and longer, hotter growing seasons now attributed mostly to the buildup of greenhouse gases. Compared to the 1950s drought, plant phenology during the 2000s drought in the Southwest was: (i) less constrained by minimum temperatures in mid-winter at lower elevations, and from mid-spring through mid-autumn at higher elevations throughout much of the region; (ii) more constrained by the atmospheric demand for evapotranspiration from mid-spring through late summer at lower elevations, particularly across Arizona, Utah, and the western periphery of the region; iii) less constrained by overall growing season conditions at higher elevations and, in contrast, more constrained at lower elevations from mid-spring through late summer, and less constrained in mid- to late autumn and mid-winter at lower elevations. Apart from these significant differences, seasonal phenological constraints during the 1950s and 2000s droughts were similar. Results thus support the hypothesis in that during the 2000s drought, the Southwest has seen significant changes in seasonal phenological constraints corresponding to warmer winters, longer and hotter growing seasons, and topography. Our demonstration of high spatiotemporal variability in phenological constraints can inform regional strategic phenological monitoring and forecasting based on lagged relationships with ENSO or other climate indices, and long-term climate projections from downscaled climate models.

TOWARD A SOUTHWEST REGIONAL PHENOLOGY NETWORK
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The predictive potential of phenology requires a new data resource—a national network of integrated phenological observations and the tools to access and analyze them at multiple scales. The USA National Phenology Network (USA-NPN) is an emerging and exciting partnership between federal agencies, the academic community, and the general public to monitor and understand the influence of seasonal cycles on the Nation’s resources. The USA-NPN (www.usanpn.org) will establish a wall-to-wall science and monitoring initiative focused on phenology, the seasonal pulse of the biosphere and thus the gateway to climatic effects on ecosystems and ecosystem services. Key to this national network is the regional phenology network (RPN). The RPN is a consortium of local and regional individuals, researchers, scientists, community groups and all others interested in tracking current and future climate change through the integrative measure of phenology. The regional focus captures elements not necessarily detectable at the national level, yet important on the local level, and for the potential to become nationally important. The USA-NPN promotes the development of RPN’s through resource sharing and acting as a clearing house for scientific, educational, and outreach tools, contacts, and communications. For example, the USA-NPN will provide a regional web page template; plant and animal observational protocols, data entry, visualization, and download tools; and educational handbooks and “How-to” manuals. The RPN’ are newly emerging, with the NE-RPN (http://www.nerpn.org/) active, and the Mid-Atlantic RPN and the Southeast RPN in stages of development. The Southwest is ripe for an RPN, with many potential and enthusiastic organizations and individuals, waiting for a SW-RPN coordinator.

EXPLORING THE NEXUS BETWEEN PHENOLOGY AND INFECTIOUS DISEASE

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Phenology is typically coupled tightly to interannual variations in soil moisture. Soil moisture has been linked, in turn, to a variety of infectious diseases (e.g., hantavirus). Time series data from the Advanced Very High Resolution Radiometer (AVHRR) produce phenology maps. Such maps are linked in this study to incidence of Coccidioidomycosis (Valley Fever) in southern Arizona. Valley Fever results from inhalation of fungal spores that thrive in desert soils of the Southwest United States, northern Mexico, Central and South America. Humans and other mammals (e.g., dogs and cattle) are susceptible. There are 6,000-8,000 severe human cases per year in the United States. Interannual variations in soil moisture, proxied using the AVHRR Normalized Difference Vegetation Index (NDVI), mediate the reproductive success of Coccidioides spp, the soil-dwelling fungi causing Valley Fever. Results suggest increases in soil moistures during a preceding spring produce increases in human Valley Fever incidence in Pima, Pinal and Maricopa counties, Arizona. Phenological monitoring using the AVHRR NDVI provides information on soil-moisture-mediated vegetation emergence leading to increased fungal growth. Such phenological information may be associated with disease incidence. Phenology thus provides a biophysical ‘portal’ that offers spatially explicit insights into this complex infectious disease.

ABSTRACTS OF PRESENTED POSTERS (LISTED ALPHABETICALLY BY FIRST AUTHOR)

NORTHERN HEMISPHERE MODES OF VARIABILITY AND THE TIMING OF SPRING

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Spring Indices (SI), based on seasonally integrated changes in temperature and calibrated with continental-scale, first bloom and first leaf lilac data, have been used to document ecological impacts of northern hemisphere warming (e.g., Schwartz et al., 2006). The SI models can be generated at any location that has daily maximum-minimum temperature time series. In this analysis, we perform principal component analysis (PCA) on an SI dataset from western North America to identify large-scale patterns of variability in the onset of spring. We then use observational climate data to assess the physical mechanisms and dynamics associated with those patterns. Our results show that at least two significant and independent modes of climate variability control the timing of spring throughout much of the West. The first shows a regional trend towards earlier springs and is associated
most strongly with warm March temperatures. In addition to the long-term trend, there is a strong correspondence between early springs in this mode and the positive phase of the Pacific North American (PNA) pattern. The second mode of spring variability exhibits a north-south dipole and correlates strongly with conditions in the tropical Pacific. It likely reflects teleconnections between the El Niño/Southern Oscillation (ENSO) and western North American temperatures. Our analyses also suggest that knowledge of large-scale patterns during the antecedent winter could help forecast the onset of spring. Finally, a continuing challenge for climate change detection and attribution studies, including advances in the onset of spring, is the ability to discriminate decadal-scale variations in synoptic and hemispheric-scale circulation patterns from directional trends associated with the buildup in greenhouse gases.

ANALYZING DIGITAL IMAGES AS A MEANS TO IDENTIFY CLIMATIC INFLUENCES ON PLANT-LEVEL PHENOLOGY

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The U.S. Desert Southwest is expected to experience warmer, drier conditions as a result of climate change in the coming decades. Research has shown that plant phenophases are particularly sensitive to temperature and have been occurring earlier as time progresses due to recent warming trends. Additionally, decreased water availability is a dominant factor associated with delayed flowering and decreased flower production. The creosotebush (Larrea tridentata) is the most dominant and widespread plant species in these warm desert regions of North America. Consequently, this species exerts a strong influence on the structure, functioning, and flow of resources (i.e., carbon, water, and energy) in these southwest landscapes, and when in bloom serves as an abundant and reliable food source for hundreds of pollinating insects that synchronize their emergence with flowering time. The objectives of this study are to unravel the climatic factors (i.e., temperature and available moisture) that trigger blooming events in the creosotebush. We hypothesize that frequency, duration, and abundance of flowers in creosotebush are regulated by (1) temperature during the spring and (2) soil moisture below the depth of atmospheric demand in the summer. We make use of daily digital images from one site at the Arizona-Sonora Desert Museum and three monitoring cameras at the Santa Rita Experimental Range that are located within the footprint of an eddy covariance tower where continuous records of precipitation, air temperature, soil temperature, soil moisture at various depths, and net radiation are also being collected. Unlike more discrete methods used to observe seasonal changes in vegetation, use of daily images results in a continuous record that can be directly compared to micrometeorological data, allowing us to evaluate the bloom-up response of creosotebush alongside (1) air temperature, (2) soil temperature, and (3) soil water content fluctuations across time. We show that this technique increases data collection efficiency, enables better quantification of phenological events, and provides a continuous record of phenological activity that can be linked to climate records across time.

REMTELY SENSED VEGETATION DYNAMICS ALONG SKY ISLAND WOODY PLANT GRADIENTS: BAROMETERS OF CLIMATE CHANGE AND VARIABILITY

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Global increases in greenhouse gases are predicted to result in a warmer climate with more severe storms and more variable weather patterns. Changes in weather regimes directly affect terrestrial systems through interaction with vegetation growth cycles, as plants, especially long-lived woody plants, provide ecosystem structure, function, and habitat for other organisms. Insight into such bioclimatic interactions can be gained with remote sensing of vegetation dynamics that provides a synoptic view of plant communities’ responses and feedbacks to the atmosphere. In particular, assessment of vegetation phenology and productivity across gradients such as the water-limited Sky Island mountain ranges of the southwestern USA, where many communities are represented within a small area and sensitivity to environmental change is high, could be very useful for understanding not only the gradients as conservation priorities but the vegetation communities that are represented therein. We used remotely sensed data quantifying vegetation greenness from 2000 through 2007 to identify spatial and temporal patterns in vegetation dynamics across the Santa Rita Mountains, a Sky Island in southeastern Arizona. We then compared these patterns to climate and other environmental parameters. The spatial and temporal patterns in the phenology of the Santa Rita Mountains were related to those of seasonal precipitation and temperature, showing shifts in the timing and magnitude of greenness as might be expected in this water-limited environment. These
patterns across the gradient further related to soils and to the type and distribution of woody plants, suggesting interactive effects with climate. Our developing approach contributes potential insights into the productivity and phenology of steep, sensitive elevation gradients that may serve as important barometers of vegetation responses to climate and other drivers.

EXPLORING NDVI-CLIMATE RELATIONSHIPS IN SUPPORT OF DROUGHT MONITORING IN ARIZONA

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The normalized difference vegetation index (NDVI), derived from multispectral remote sensing data, has widely been used as a means to monitor vegetated areas and to detect live, green plant canopies. A sufficient time-series of NDVI data, collected by the Advanced Very High Resolution Radiometer (AVHRR) sensor on the NOAA’s spacecraft, is now available to evaluate long-term variability in vegetation greenness. This study explores the use of NDVI as a drought monitoring tool for the state of Arizona in support of the Operational State Drought Plan. Time series NDVI data were analyzed to establish a baseline for normal vegetation productivity for several regions throughout the state. Inter-annual increases or decreases relative to this baseline can serve as an indicator for drought intensity based on how vegetation responds to changes in climate (e.g. precipitation and temperature). The 1-km AVHRR NDVI time series data, from 1989-2007, were correlated with climate data from 17 National Weather Service Cooperative Observer sites throughout Arizona and with Standardized Precipitation Index (SPI) values derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset. Sites were chosen based on representative and dominant land cover types within a 2-km radius surrounding the weather gage. Relationships found between site-specific precipitation and NDVI indicate that vegetation response is dependent on site location and dominant land cover types surrounding the gage. Strongest precipitation correlations occur in the spring and summer due to concurrent and lagged seasonal precipitation. SPI-NDVI regression analysis shows that most of the significant correlations are with SPI-6, occurring in the April/May/June season. This indicates that fall/winter precipitation has an important impact on spring green-up. The 12-month SPI correlated best with NDVI variability in any season. These preliminary results suggest that remotely-sensed vegetation and climate records can be an important tool for drought monitoring, natural resource management, and decision making.

ECOHYDROLOGICAL CONSEQUENCES OF VEGETATION COVER AND SEASONALITY: TRENDS IN SOIL EVAPORATION FROM A MESQUITE-DOMINATED GRADIENT AT SANTA RITA EXPERIMENTAL RANGE

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Evapotranspiration drives the majority of the water budget in semiarid ecosystems. The partitioning of Evapotranspiration into soil evaporation and transpiration fluxes has important ecohydrological implications. The presence of vegetation has implications for the partitioning of evapotranspiration, and in particular for the dynamics of soil evaporation, as previously demonstrated for evergreen systems. However, the interactive effects of vegetation presence and seasonality of deciduous vegetation on soil microclimate and soil evaporation remains elusive and need to be tested systematically. We used a gradient of vegetation cover spanning 6 transects with canopy cover of the deciduous woody plant Prosopis velutina (mesquite) ranging from 2% to 73% at the Santa Rita Experimental Range close to the University of Arizona cell. At each transect we selected 5 canopy and 5 intercanopy locations and deployed 2 microlysimeters at each: one containing bare soil and the other with soil covered at the surface with a litter layer. The microlysimeters were built using a well mixed soil from the study site. During each of the main phenological stages, a pulse of moisture equivalent to 20 mm was added to each microlysimeter. Soil evaporation rates were calculated from changes in gravimetric soil moisture content, intensively measured through the duration of the experiments. In addition, we estimated incoming solar radiation using hemispherical photography. Our results quantify the seasonal dynamics of soil evaporation rates as a function of woody plant cover. Overall, increases in woody plant cover produce decreases in soil evaporation rates. However, our results illustrate how the seasonal dynamics of vegetation and their influence on soil microclimate, wind dynamics and presence of a litter layer in the soil modify the dynamics of soil evaporation.