

Phenology and Trend Indicators Derived From Spatially Dynamic Bi-Weekly Satellite Imagery to Support Ecosystem Monitoring

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Abstract—Ground-based ecosystem monitoring presents some practical challenges to natural resource managers and ecologists tasked with assessing vegetation dynamics across large areas through time. RangeView (<http://rangeview.arizona.edu>) provides online access to spatially and temporally explicit biweekly vegetation indices derived from satellite data. It also permits side-by-side comparisons of different periods and relative greenness products (e.g., difference from average). Qualitative visualization of vegetation dynamics could be enhanced with quantitative assessment of phenology for specific locations and time periods. Case studies of the Santa Catalina Mountains and the Mogollon Rim suggest phenological indicators of greenness onset, peak greenness, and length of growing season show promise for quantitative assessment of vegetation trends.

Introduction

Of the 2.26 billion acres that comprise the land area of the United States, 590 million were considered pasture/rangeland and 740 million were considered forest land in 1992 (Daugherty 1995; NRCS 2000). Vegetation change on these lands has been significant over the past century, with 62 million acres undergoing afforestation and another 70 million undergoing deforestation (Birdsey and Lewis 2003). The periodic ground-based measurement of the status of vegetation resources or associated indicators is essential to assess the health of rangelands and forests (National Research Council 1994). Nevertheless, the monitoring of vegetation dynamics over large areas is a major challenge identified by natural resource managers. Ground-based methods could be enhanced if regularly captured satellite images are made operationally available in a spatially and temporally explicit manner. Natural resource managers have been making requests for value-added, easy-to-use, and spatially explicit products derived from remote sensing data since the launch of the first civilian satellite in 1972. Government officials (ARSC 2001) and natural resource managers (Marsh and others 2001) in the agriculture sector (Moran and others 1997) have echoed the constraints to adoption of such products. From the end user's standpoint, the adoption of geospatial technology is predicated on the regular availability of timely, quantitative, validated, operational, and site-specific information products.

Though a variety of satellite sensor options are now available, practical considerations (i.e., data and processing costs, the inherent tradeoff between spatial and temporal resolution, and the influence of cloud cover) favor platforms that provide frequent images that are systematically processed into products useful for the assessment of vegetation. Two sensors

among those that currently meet these criteria are the NOAA Advanced Very High Resolution Radiometer (AVHRR) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). Both capture spectral information in the requisite wavelengths which, when ratioed or otherwise transformed, enhance the vegetation signal. Among the products that can be derived from these images are vegetation indices (VI) that allow us to reliably monitor seasonal and inter-annual variations in photosynthetic activity (often termed vegetation "greenness") associated with biophysical, structural, and phenologic vegetation canopy parameters (Huete and others 2002). The most widely used VI is the normalized difference vegetation index (NDVI), which is a normalized ratio of reflectance (ρ) in the near infrared (NIR) and red bands (equation 1). NDVI has served as an intermediary for the assessment of other biophysical parameters such as green canopy cover, biomass, and leaf area index. The USGS creates biweekly NDVI composites derived from AVHRR (14 days) and MODIS (16 days) imagery that may be ordered through the EROS Data Center (USGS 2004). To produce composite images for AVHRR, daily NDVI data are compiled such that the highest NDVI value over the composite period is selected for each pixel in the resultant

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

Equation 1. Normalized Difference Vegetation Index.

image. MODIS composites balance the highest NDVI value method with the optimal view angle for each pixel. For both sensors this technique minimizes cloud contamination.

These derived products are of great value, but are delivered in a form that requires expertise and software, limiting their operational potential. To address this need, the University of Arizona (UA) partnered with natural resource managers to make these data operationally accessible online via the RangeView (<http://rangeview.arizona.edu>) Web site (University of Arizona 2004). This web-based information system allows users to assimilate disparate spatial datasets and visualize time-varying spatial relationships. RangeView is used primarily by vegetation scientists and natural resource managers who are now requesting the tools necessary to analyze spatially and temporal explicit vegetation trends. Through case studies in the Santa Catalina Mountains and the Mogollon Rim, we are evaluating methods to assess greenness onset, peak greenness and length of growing season in a spatially and temporally explicit manner (e.g. Reed and others 1994; Zhang et al 2003). This paper describes the dynamic visualization tool, associated analytical products, and the development of phenological indicators which, when automated, should help natural resource managers quantitatively assess vegetation dynamics.

Visualization

RangeView is a NASA/Raytheon-sponsored initiative that seeks to make NASA Earth Observation System (EOS) data accessible and useful to natural resource managers. The system serves to enhance users' understanding of and ability to manage natural resources as they vary across the landscape and change through time. The underlying application has flexibility to handle raster, vector, and tabular data at varying spatial and temporal resolutions. It provides the user with the spatial dynamic of an Internet map server, the temporal dynamic of time-series animation, and the analytical capability of graphing software. RangeView currently provides near-real time (~3-7 days lag time) access to time-series data, including:

- NOAA's Advanced Very High Resolution Radiometer (AVHRR) (1989 to present)
 - NDVI (1 km spatial and 14 day temporal resolution)
 - Coverage over the conterminous United States, Southern Canada and Northern Mexico
- NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) (2000 to present)
 - NDVI and the Enhanced Vegetation Index (EVI) (250 m and 1 km spatial and 16 day temporal resolution)
 - Leaf Area Index (1 km and 8-day)
 - Coverage of Western United States, Southern Canada, and most of Mexico at 1 km spatial resolution
 - Coverage of Southwestern United States at 250 m spatial resolution

Spatially and temporally explicit visualization is made possible through a series of automated data conversion steps that transform AVHRR and MODIS data from their native format into bitmapped graphic images compressed for Web-based viewing. The data are displayed interactively through the use

of an internet map server (ESRI ArcIMS 4.01 with the Java Connector to serve maps and ESRI ArcSDE 8.3 for MS SQL Server 2000 to store spatial data). RangeView permits the overlay of ancillary data layers (such as roads or boundaries to facilitate geo-location), zooming and panning capabilities as well as capacity to run time-series animations. Figure 1 provides the example of the Aspen Fire, which, in the summer of 2003, burned 84,750 acres and destroyed 333 structures on Mount Lemmon in the Santa Catalina Mountains sky island just north of Tucson, Arizona.

Interpretation

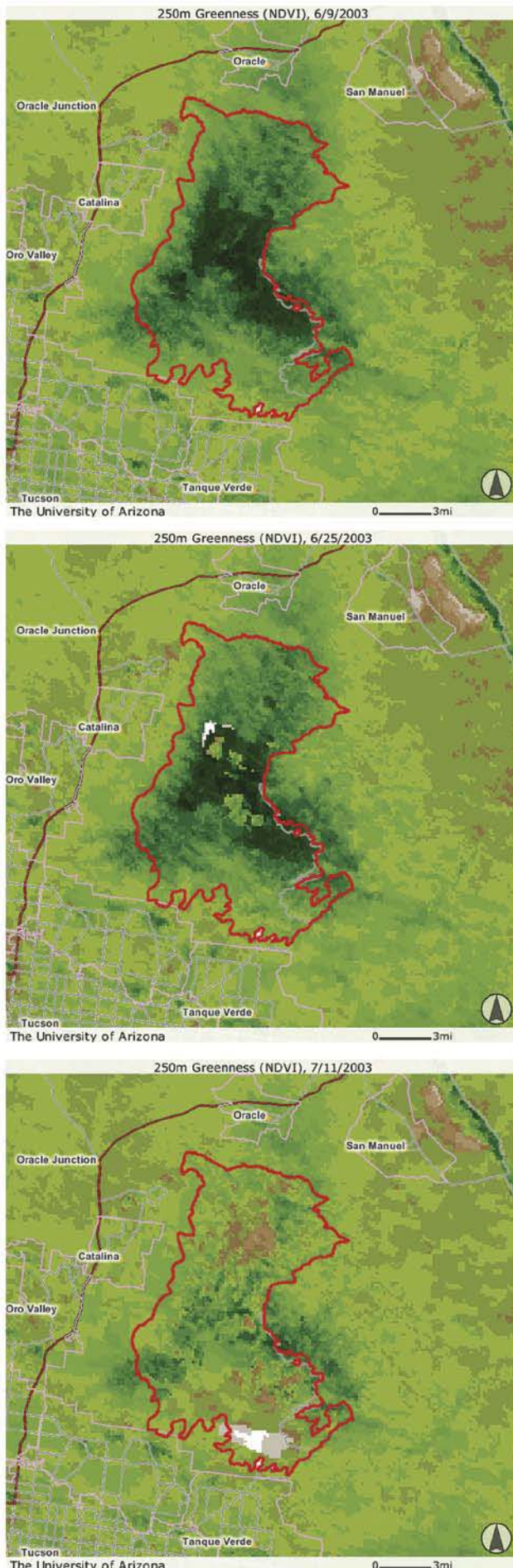
Visualizing vegetation greenness on a biweekly basis provides insight into vegetation dynamics through time. However, in order to answer questions like, "Is it greener than it usually is for this time period in this location?" it was necessary to develop a suite of interpretive tools. The RangeView application allows users to view several map windows at once to compare vegetation greenness between different years. Using the longer-term AVHRR data set (1989 to date), users can also assess departures in vegetation greenness from a 14-year average. Figure 2 depicts the period ending May 4, 2004, during which much of the Madrean sky islands and desert seas exhibited vegetation greenness levels less than the average greenness recorded for early May (averages are calculated pixel-by-pixel on NDVI data from 1989 through 2003). Notice the pronounced impact of the 2003 Aspen Fire (north of Tucson) and the 2002 Rodeo-Chediski Fire (top of image). Options to visualize differences in vegetation greenness from the previous year or the previous bi-weekly period are also available.

Indicators of Phenology

Spatially and temporally dynamic access to visualizations of VIs greatly enhances the capacity of non-specialists to use MODIS and AVHRR imagery for understanding vegetation dynamics. However, further assessment of trends and temporal transitions in vegetation greenness require quantitative analysis of the underlying VI data. Discussions with RangeView lead users (Orr and others 2003) suggest that identification of trends in the start, peak, end, and duration of the growing season would greatly assist in management decision making. Ultimately users would like to visualize these indicators graphically for selected areas on the images such as for specific vegetation types or pastures (user-defined) in conjunction with the time-series animations.

In order to begin addressing this challenge, we set up a methodological case study on an elevation gradient across Mt. Lemmon to capture eight of the Arizona gap analysis vegetation types (Halvorson and others 2001) represented by Madrean sky islands and their environs in the Sonoran Desert (figure 3). This also permitted the assessment of phenological changes associated with the recent Bullock (2002) and Aspen (2003) fires.

We began by automating a method to extract NDVI data for pixels residing within individual polygons. Using scripting



language associated with a geographic information system (GIS) software (ESRI ArcINFO's Arc Macro Language [AML]), we calculated the mean NDVI for pixels within each polygon for each time period and stored these in a spreadsheet. A number of different methods have been developed to determine the timing of green-up and senescence (Zhang and others 2003), the simplest being a characterization of phenology through multitemporal profiles (NDVI plotted against time). The multitemporal profiles depicted in figure 4 are based on the mean NDVI values extracted from the gap analysis (Halvorson et al. 2001) vegetation type polygons (figure 3). The profile shows the high variability within phenologic trends, particularly at higher elevations where snow and cloud cover can impact the vegetation signal.

This variability must be addressed in any system that automates the identification of the start, peak, and end of the growing season. An operationally simple, yet intuitive method for curve characterization involves calculating moving averages (Reed and others 1994). In the Mt. Lemmon case study we applied a three-period (a) forward-looking, (b) backward-looking, and (c) centered moving average. The convergence of these curves can be used to identify the timing of the beginning, peak, and end of the growing season in the NDVI temporal profile (figure 5). Changes in phenological patterns exhibited in satellite data have been linked to short-term impacts like wildfire as well as to the longer term impacts of drought (e.g., Kogan 1995). Analysis of the sum of NDVI values over the length of the growing season for the Mt. Lemmon vegetation cover types highlights the impact of drought, particularly in lower elevation vegetation (figure 6).

The greater relative difference between maximum and minimum cumulative NDVI for upper elevation woodland vegetation types indicates that these types are not as immediately responsive to changes in precipitation as are lower elevation vegetation types. At higher elevations these values may be impacted by the presences of snow or clouds; however, this contamination is generally limited to a couple of periods, so the impact should be slight. The cumulative NDVI of upper elevation woodland also shows the impacts of the Bullock Fire of 2002. Ultimately, providing natural resource managers direct access to these information products should significantly enhance their ability to monitor and understand changes in vegetation associated with climatic or anthropogenic impacts.

Conclusions and Future Directions

RangeView currently provides interactive access to current and historical vegetation products derived from AVHRR and MODIS satellite data. The ability to zoom in on any area of interest and run a time-series animation of absolute greenness

Figure 1—From left, MODIS 250m NDVI composites before (period ending June 9) and during (periods ending June 25 and July 11) the Aspen Fire of 2003 (outlined in red) north of Tucson, Arizona.

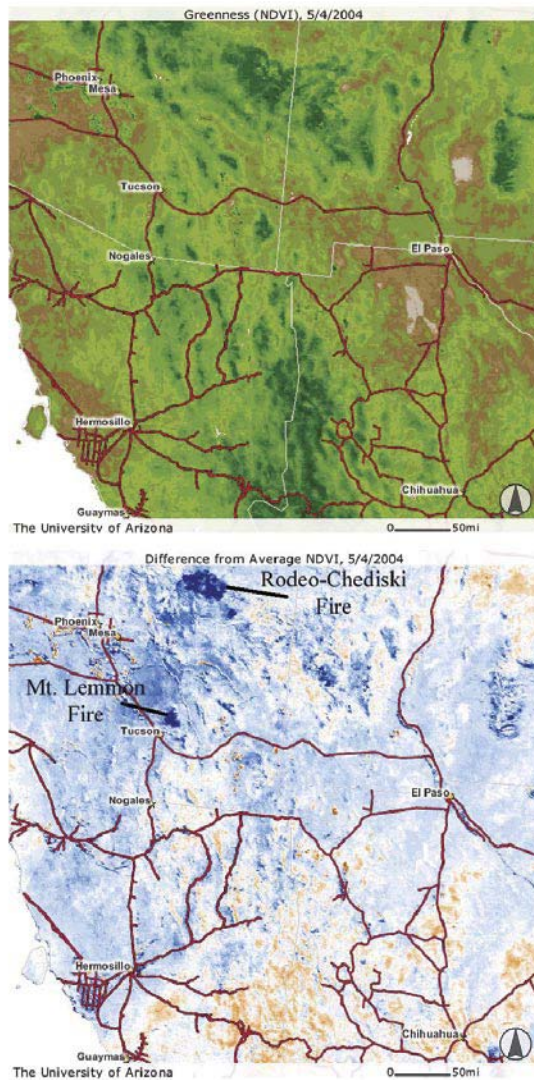


Figure 2—Example of viewing vegetation greenness (AVHRR NDVI) on the left and difference from average on the right (white = average greenness, blue = below average greenness, orange = greener than average).

as well as create departure-from-average maps can aid in ecosystem monitoring efforts and associated decision making. The RangeView team has begun to explore methods that will take the application beyond data visualization into the realm of data analysis. This paper documents our first steps in this transition as we develop methods to automate the site-specific identification of phenological indicators and their temporal trends. This case study of the evaluation of multitemporal greenness profiles across a range of vegetation types utilizing moving averages has demonstrated the potential of quantitative monitoring techniques and the automation of trend indicators. We will continue to explore additional techniques such as the Vegetation Condition Index (VCI), which is a ratio of the NDVI collected in a given period compared to its historical range (Kogan 1995), piecewise logistic regressions fit to

NDVI data (Zhang and others 2004), and waveform polynomial curve fitting. Ultimately, we will implement the most effective methods that will both map and analyze trend indicators to help natural resource managers meet the considerable challenge of ecological monitoring.

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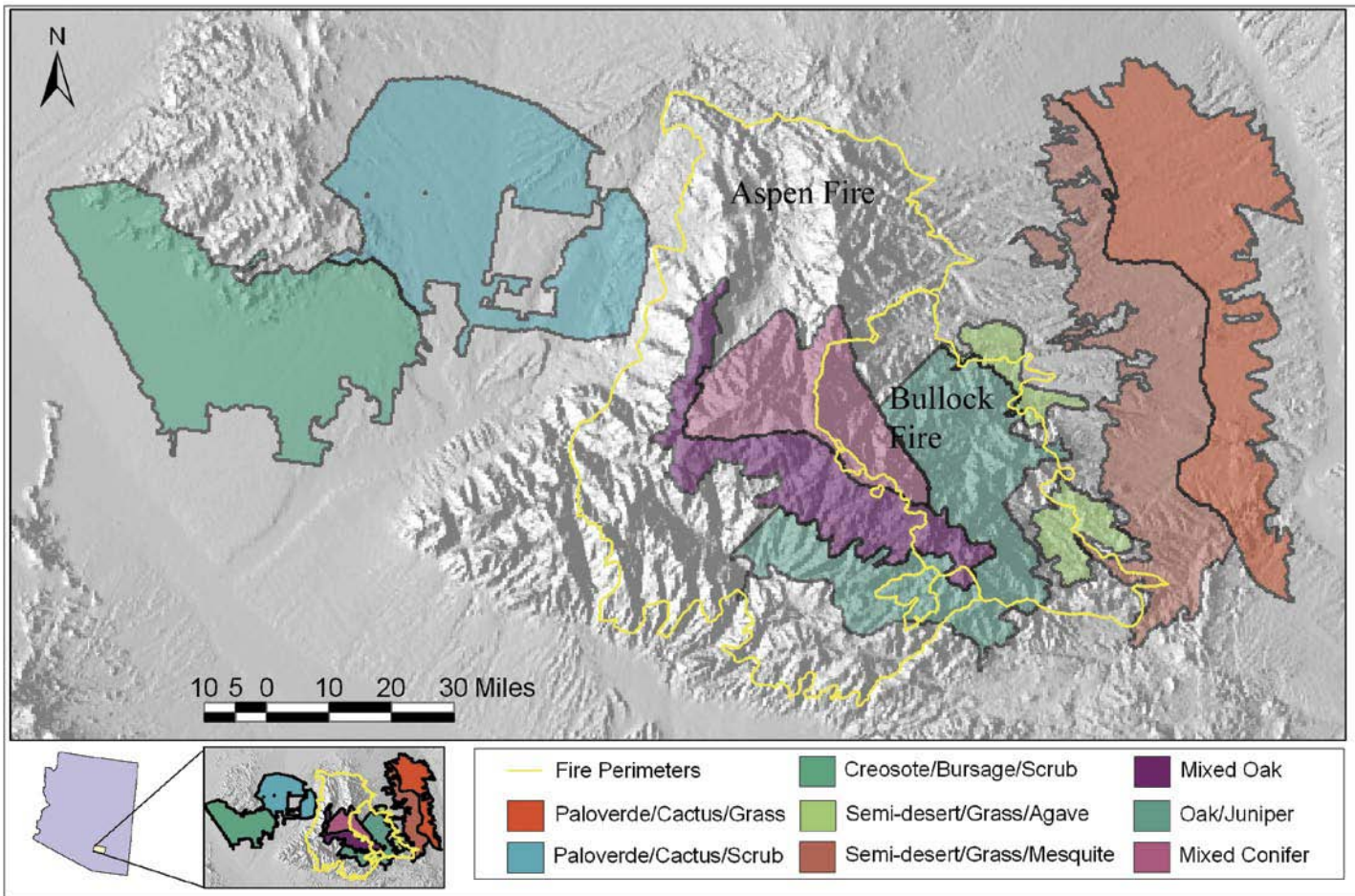


Figure 3—Arizona gap analysis vegetation polygons used to extract NDVI data.

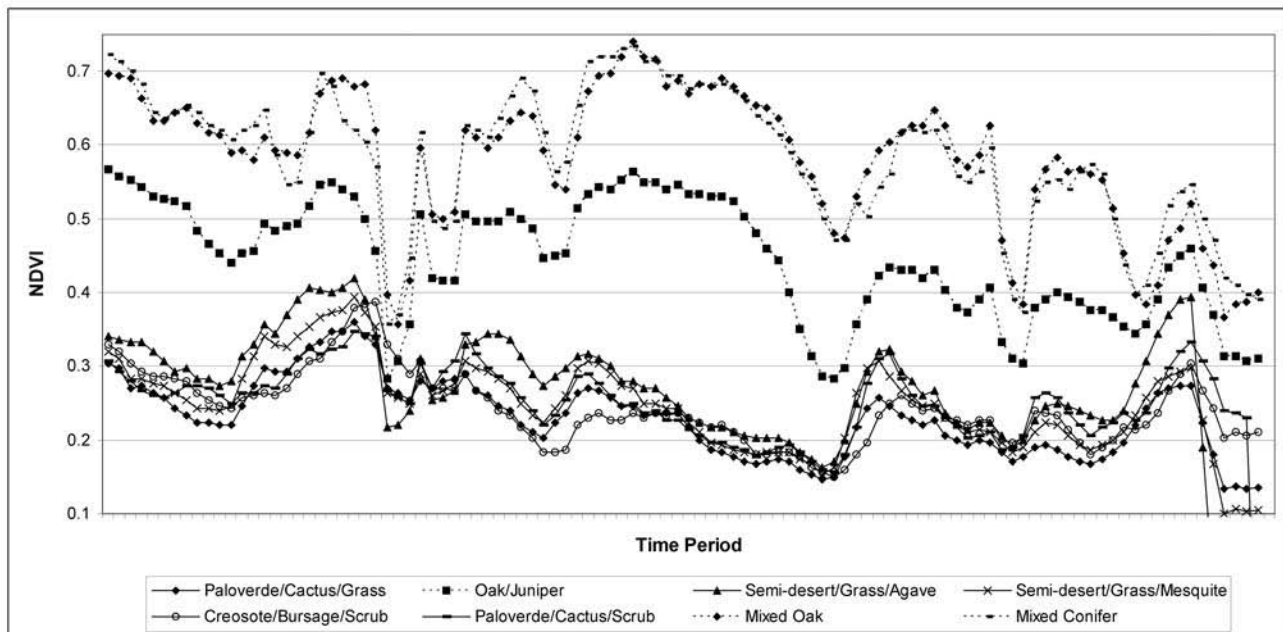


Figure 4—Multi-temporal NDVI profiles of 8 sky island gap analysis vegetation types.

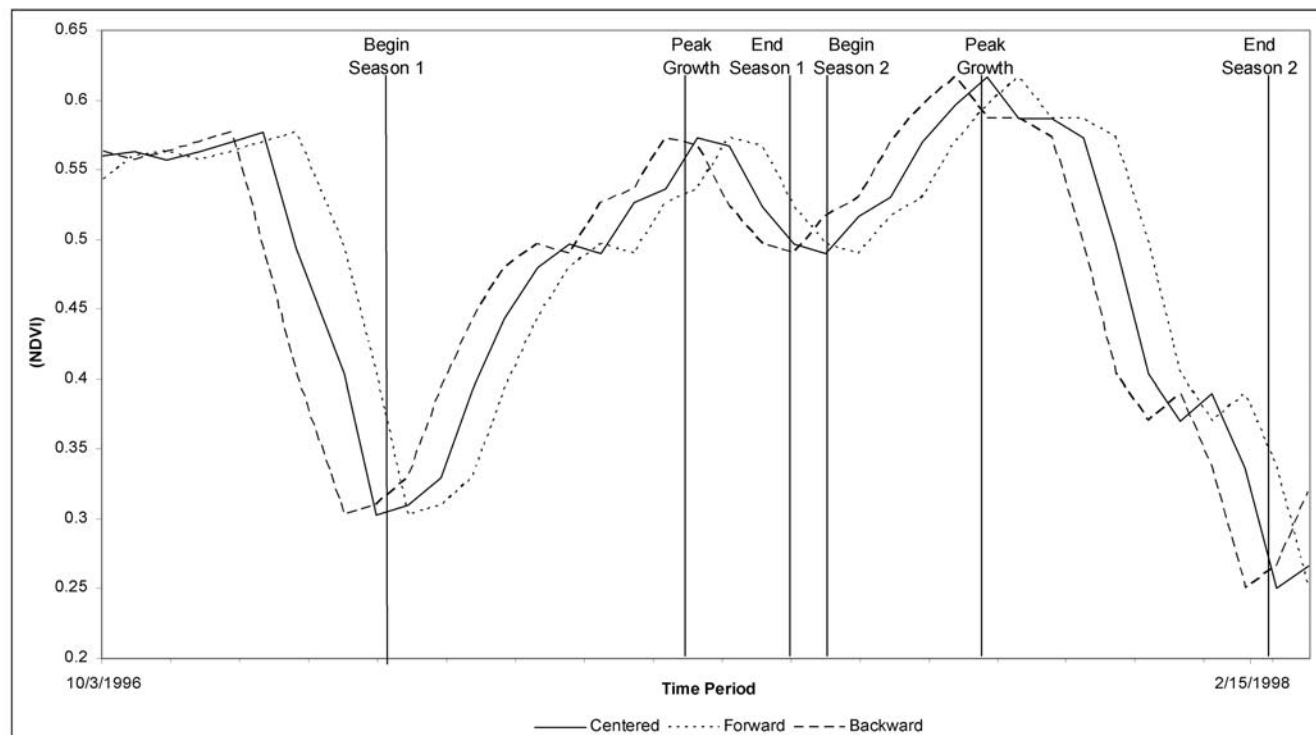


Figure 5—The convergence of forward, backward, and centered moving averages can be used to identify phenological indicators in the NDVI temporal profile.

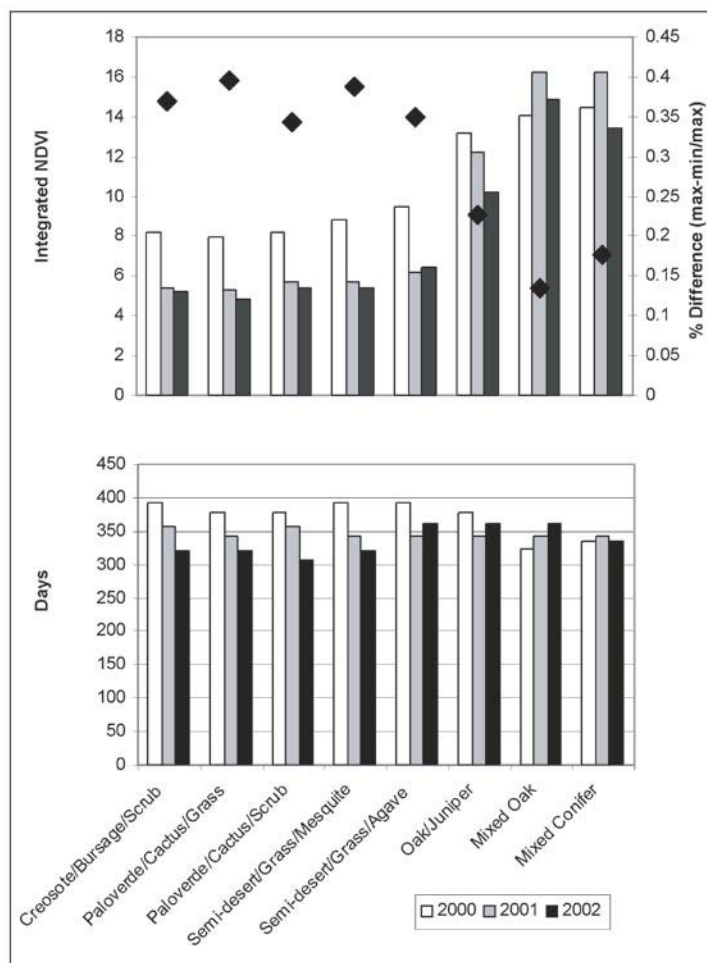


Figure 6—Cumulative NDVI and length of growing season for Mt. Lemmon vegetation types between 2000 and 2002. Average elevation for vegetation types increases from left to right.