

PALMS Standard Operation Procedure

Estimating Landscape Indicators of Phenology from Satellite Observations: Start of Season

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Introduction

Vegetation phenology is the timing of seasonal patterns in vegetation growth, and provides an integrative measure of seasonal and long term climate patterns and their impact on vegetation growth. Key phenological indicators include the date of initiation of vegetation growth or 'start of season' (SOS), the date of secession of vegetation growth or 'end of season' (EOS), and the dates of minimum and maximum greenness. Interannual variation in climate patterns can directly affect these indicators, resulting in interannual shifts of forty-five days or more. Variations in vegetation phenology can affect the timing of animal movements across a landscape, carbon uptake rates by ecosystems, and soil water depletion rates which, in turn, can affect vegetation growth and wildfire risk. One potential impact of climate change is a sustained shift in phenological indicators resulting from warmer spring temperatures and a longer and potentially drier growing season, especially in the western U.S. As such, routine monitoring of phenology provides a useful indicator that has applications not only for fire management (Westerling et al., 2006) and visitor management (e.g., timing of wildflower blooms), but which may also provide a useful early warning indicator of vegetation response to climate change.

There are a number of techniques for monitoring vegetation phenology including: 1) *in situ* networks for observing specific species of plants or particular plant communities; 2) phenology modeling; 3) eddy covariance flux towers; 4) global change experiments; and 5) remote sensing and digital cameras (Cleland et al., 2007). While *in situ* monitoring networks offer clear advantages for parks (e.g., localized information that can be tied to particular species of ecological significance or interest to park visitors), the cost of implementing a monitoring network over a large area can be significant. Remote sensing observations provide an alternative method for monitoring phenology within parks, and can also be used to supplement *in situ* monitoring networks to facilitate evaluation of conditions across park landscapes.

There are also a number of published methods for estimating phenological indicators through the use of remote sensing. Friedl et al. (2006) provide an accessible and detailed description of the uses of remote-sensed phenological data and issues in current approaches to the analysis of remotely sensed phenological data. Satellite-based measures of vegetation greenness (e.g., NDVI/EVI) and photosynthetic activity (e.g., FPAR) in particular can provide useful measures of vegetation state. By tracking patterns in vegetation condition over time, these measures can provide a standardized method for estimating phenological state at the landscape scale. There are, however, limitations to satellite-based monitoring of phenology, particularly in high-altitude ecosystems that experience snow cover much of the year, and ecosystems dominated by evergreen vegetation. In these ecosystems, satellite-based monitoring may detect seasonal differences in the background reflectance due to emergence of understory vegetation but the signal may be very faint, particularly in closed canopy evergreen forests. Furthermore, in all ecosystem types, satellite-based monitoring will only provide an average or integrative measure at a spatial resolution of ~1km, and in most cases will not be able to detect the phenological signal for specific plant species.

While the remote sensing community has yet to reach consensus on the best method or methods for deriving phenological indicators from satellite observations, White et al. (2009) reported results of a comparison of ten different satellite-based methods for estimating SOS and identified the methods that provided the best agreement with ground-based indicators. Ongoing analyses are currently evaluating the accuracy of different satellite-based methods for estimating other phenological studies such as seed maturation and senescence, and additional

SOPs for phenological monitoring may be prepared upon completion and publication of these analyses.

This SOP describes a method for use of remote sensing data to monitor phenological indicators using the best performing methods as identified by White et al. (2009). The SOP describes the input data sets used, location of the source data, and analysis steps used to compute the phenological indicators. The NASA Terrestrial Observation and Prediction System has been applied to automate much of the data processing, and the SOP also describes these processing steps and options for retrieving the final phenological indicators and maps.

This SOP focuses on SOS as defined by White et al. (2009): a rapid and sustained increase in remotely sensed greenness after the longest annual period of photosynthetic senescence. The indicators described in this SOP are focused on measures of land surface phenology (the spatio-temporal development of the land surface as measured by satellite remote sensing), and incorporate factors inherent in remote sensing, including atmospheric interference, cloud cover, snow cover, and soil wetness. As such, the SOS indicator for land surface phenology should be considered to be related to plant phenology, but not a direct measure of plant phenology. Ideally, any satellite-based measure of phenology should be supported with a coordinated ground-based observation network. The National Phenological Network (NPN) is currently working to establish such a network, and as the NPN network evolves separate SOPs may be developed to describe methods for integrating satellite-based indicators with available ground-based observations.

Key monitoring objectives of the SOP include:

1. Monitor the date of SOS for different regions with a resolution that can detect a 1-week change in date over a 5-year period.
2. Provide a standardized measure of the annual SOS date for multiple phenological regions within a park from March, 2000 to present.
3. Identify emerging long-term trends and patterns in SOS.
4. Identify sustained shifts in SOS.

Data Acquisition and Preprocessing

Normalized difference vegetation index (NDVI) data from the NASA MODerate resolution Imaging Spectroradiometer (MODIS) instrument onboard the Terra satellite were used as the source data for calculations described in this SOP. MODIS MOD13A2 16-day NDVI composites were retrieved from the NASA Land Process Distributed Active Archive Center (LPDAAC). Additional information about the MODIS NDVI data products is contained in the MODIS MOD13 User Guide (Solano et al., 2010, <http://tbrs.arizona.edu/project/MODIS/MOD13.C5-UsersGuide-HTML-v1.00/index.html>) and the MODIS MOD13 Algorithm Theoretical Basis Document (Huete et al., 1999, http://modis.gsfc.nasa.gov/data/atbd/atbd_mod13.pdf). MODIS NDVI data were retrieved, reprojected, and composited for each region of interest using TOPS. As such, retrieval of the source data sets is not required as part of the SOP, but methods for retrieval of the source data are included for completeness.

Option 1: LPDAAC MRTWeb Tool

Data can be subset and downloaded for a particular park or region directly from the LPDAAC using the MRTWeb Tool (<http://mrtweb.cr.usgs.gov/>). The user should select the MODIS MOD13A2 data product, and provide the desired date range, spatial domain, and format prior to submitting the request. The MRTWeb tool will queue the processing request and notify the user via email when the request is ready for download.

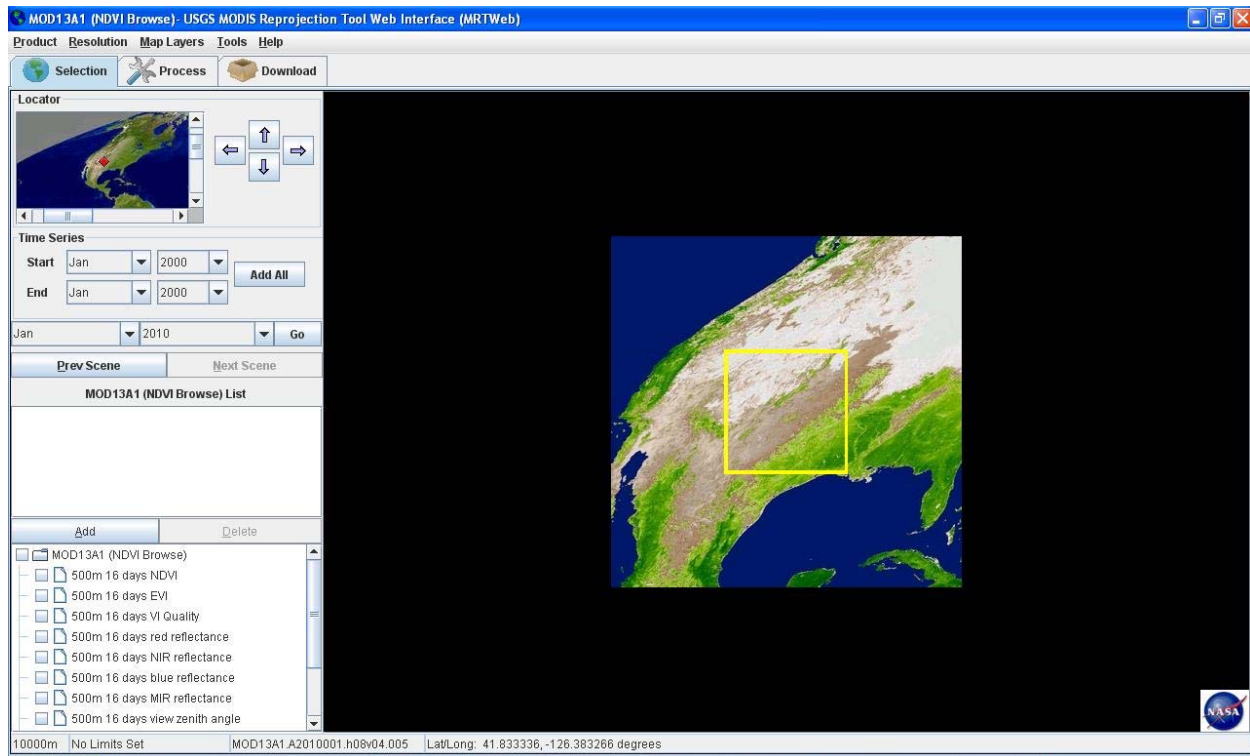


Figure 1: The MRTWeb interface available at <http://mrtweb.cr.usgs.gov/>

Option 2: TOPS OPeNDAP Server

National grids are currently being developed for the U.S. using TOPS and will be available via an OPeNDAP server in late summer 2010. Once complete, data will be available for download from the TOPS OPeNDAP server at: <http://ecocast.arc.nasa.gov/opensdap>

As with the MRTWeb tool, the user should select the MODIS MOD13A2 data layer, specify the preferred data format, and enter the latitude range of interest, longitude range of interest, and date range of interest. The TOPS OPeNDAP server will process the request on-the-fly and return the requested data immediately upon processing the request, which can take 5-10 minutes or more for larger data requests.

OPeNDAP Server Dataset Query Form - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://ecocast.arc.nasa.gov/opendap/for/nw_ca/tos_O1_2001-2002.nc.html

OPeNDAP Server Dataset Access Form

Action:

Data URL:

Global Attributes:

NC_GLOBAL.title: IPSL model output prepared for IPCC Fourth Assessment SRES A2 experiment
 NC_GLOBAL.institution: IPSL (Institut Pierre Simon Laplace, Paris, France)
 NC_GLOBAL.source: IPSL-CM4_v1 (2003) : atmosphere : LMDZ (IPSL-CM4_IPCC, 96x71x19) ; ocean ORCA2 (ipsl_cm4_v1_8, 2x2L31); sea ice

Variables:

☐ **lon:** Array of 64 bit Reals [lon = 0..179]
 lon:
 standard_name: longitude
 long_name: longitude
 units: degrees_east
 axis: X
 bounds: lon_bnds
 original_units: degrees_east

☐ **lon_bnds:** Array of 64 bit Reals [lon = 0..179][bnds = 0..1]
 lon: bnds:

☐ **lat:** Array of 64 bit Reals [lat = 0..169]
 lat:

Figure 2: The TOPS OPeNDAP interface available at <http://ecocast.arc.nasa.gov/opendap>

Option 3: TOPS Data Gateway

Smaller data requests can also be handled via the TOPS Data Gateway (<http://ecocast.arc.nasa.gov/kamap>). The TOPS Data Gateway provides a browser-based web interface for browsing and query TOPS data products. Individual data files can be downloaded from the Ecocast ftp server by clicking the [i](#) (info) link, and then clicking the link labeled 'Data File', which will open a direct ftp link for download of the data file.

Option 4: ArcGIS Server

In the near future, an ArcGIS Server interface will also be added to the TOPS framework to facilitate direct retrieval of TOPS datasets from ArcGIS desktop tools. For more information or to inquire about the status of this interface, please contact Forrest.S.Melton@nasa.gov.

Data Preprocessing

Within TOPS, MODIS data is reprojected from the MODIS sinusoidal projection to other more commonly used projections using the MODIS reprojection tool (MRT, https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool), composited from multiple tiles into a single grid, and reformatted. Data retrieved by the user directly from the LPDAAC MRTWeb interface, the TOPS OPeNDAP server, or the TOPS Data Gateway may also have been reprojected using the MRT, composited, and reformatted per the users specifications. Additional processing may be required using ArcGIS or other tools familiar to the user.

SOS Calculation

Once the timeseries of NDVI data has been produced for a region, the next step is to calculate the SOS date for each pixel for each year. White et al. (2009) identified the Midpoint_{Pixel} (White et al., 2009) and the HANTS-FFT (Roerink et al., 2000) as the two algorithms for calculating SOS that provided the best agreement with multiple surface observations of phenology. For this SOP, a modified version of the Midpoint_{Pixel} algorithm was selected since it is computationally more elegant, and thus easier to implement. Modifications to the Midpoint_{Pixel} algorithm are described below, and were added to improve filtering to remove barren and evergreen land cover classes, and to find local NDVI minima, instead of assuming minimum values occur at January 1 of each year.

At this time, the code for calculating SOS using the Midpoint_{Pixel} algorithm has been implemented within TOPS, and is included in Appendix A. While it was beyond the scope of the PALMS project, at a future date the Midpoint_{Pixel} code could be adapted for compatibility with ArcGIS tools. In addition, if a park or I&M network has selected an alternate algorithm or method for calculating SOS from satellite data, this algorithm can be implemented within TOPS to provide phenological indicators tailored to each park or I&M network. For more information on implementation of an alternate algorithm, please contact Forrest.S.Melton@nasa.gov.

Midpoint_{Pixel} SOS Calculation Steps

1. For each pixel, extract the full timeseries of MODIS MOD13A2 NDVI values. The Midpoint_{Pixel} algorithm by default screens all records missing more than 10% of the observations in the annual record. Due to the inherent gaps due to snow cover in many parks, we removed this filter.
2. To account for cloud cover, high aerosol loads, and other factors that can result in poor data quality, the MODIS MOD13A2 algorithm uses a 16-day compositing interval that screens out poor quality observations. This 16-day compositing window is too coarse for phenological monitoring, so data are interpolated to a 0.5 day timestep using a 7-day moving average. The Midpoint_{Pixel} algorithm uses a cubic spline interpolation by default, but the linear interpolation provided comparable performance and is easier to implement computationally.
3. The Midpoint_{Pixel} algorithm assumes that the annual minimum occurs on or about January 1. However, because grassland and savannah ecosystem can begin to green-up in some regions before January 1 (e.g., Mediterranean ecosystems), the algorithm used in this SOP identified the local maximum and minimum NDVI values and the dates on which these values occurred.
4. The threshold value, $NDVI_{Threshold}$, was calculated as the midpoint (average) between the $NDVI_{Max}$ and $NDVI_{Min}$ values for each year in the timeseries extracted from each pixel.
5. The SOS date was calculated as the date on which the interpolated NDVI curve passed the $NDVI_{Threshold}$ value.
6. Multiple factors can affect phenological signals for an individual pixel, including disturbance events and cloud cover during periods where NDVI maxima are expected.

For the purpose of calculating summary indicators, pixels were aggregated into phenoregions to minimize bias introduced by the signal at any single pixel. Phenoregions can be defined based on multiple biological and physical characteristics, including land cover, monthly temperature and precipitation, and elevation (White et al., 2005). Since the park boundaries and ecologically relevant adjacent lands for most I&M networks are relatively small geographic areas compared to national scale analyses, for the purpose of this SOP, we aggregated the pixels based on the land cover class using the MODIS MOD12 land cover map. The SOS date for all pixels associated with each land cover class within the PACE were averaged to produce the summary metrics.

Phenology Summary Metrics

Direct interpretation of SOS maps can be challenging, and summary metrics can be useful in tracking the emergence of trends and patterns. To facilitate evaluation of spatial and temporal patterns, the SOP includes four summary metrics that are produced from the annual SOS data, including: 1) a map of the phenological anomalies for the most recent year; 2) graphs of the NDVI timeseries for each land cover type showing the current SOS date and the historical average SOS date for reference; 3) a table showing the SOS dates and anomalies for recent years summarized by land cover type and elevation; and 4) a plot of the SOS dates from 2000 to present with a linear trendline fitted for reference. The relatively short length of the satellite data record prevents use of rigorous timeseries analysis methods for identifying phenological trends. However, the data can be used to evaluate local and regional patterns and identify early evidence that long-term patterns related to climate and land cover change impacts may be emerging. As the length of the data record increases, these summary metrics may be replaced with alternate measures designed to rigorously quantify phenological trends. Calculation and update of the summary metrics has been automated, and results are accessible for each network via the Ecocast NPS data gateway (Figure 3).

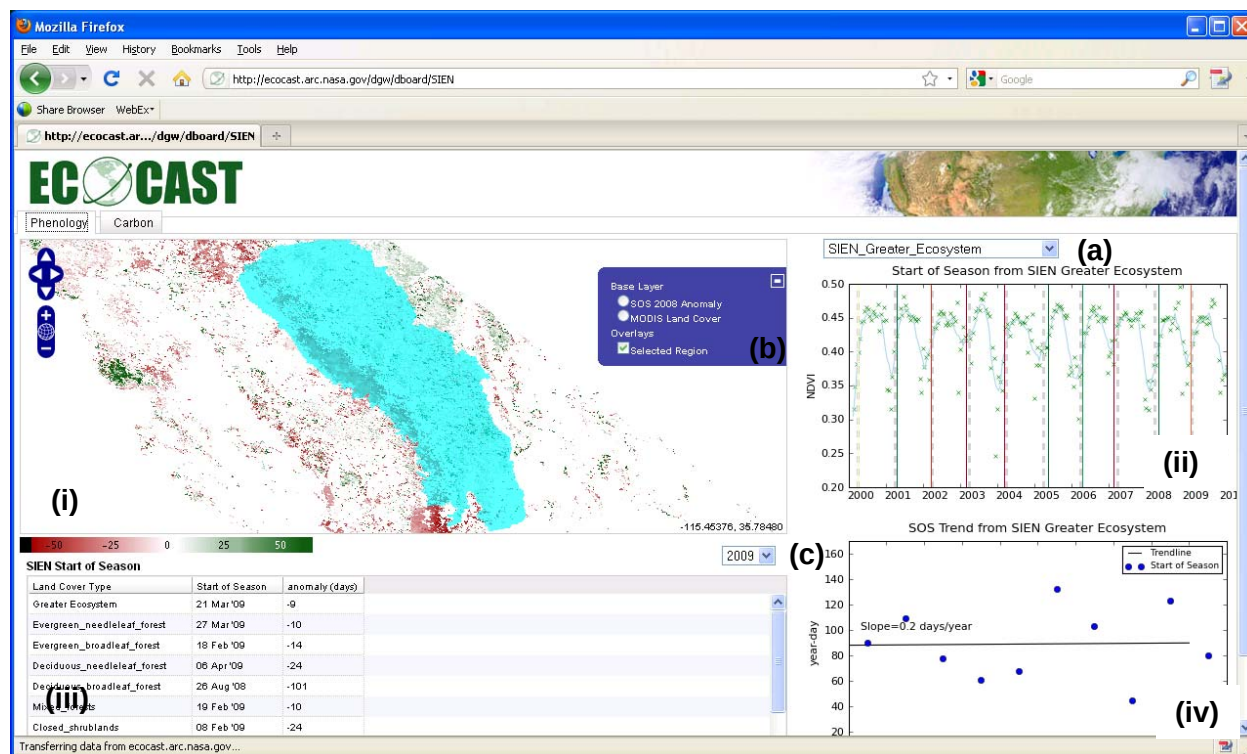


Figure 3, the Ecocast NPS Data Gateway: Example of the Ecocast NPS Data Gateway for the SIEN I&M Network, showing the (i) Annual Anomaly Map, (ii) NDVI graph, (iii) SOS Summary Table, and (iv) SOS Summary Graph. Different regions of interest can be selected using the 'Region' pulldown menu (a), and the pixels associated with the selected region are highlighted in blue on the Annual Anomaly Map. The highlighting can be controlled in the layer tab (b). Different years may be viewed for the summary table using the Year pulldown menu (c).

Annual Anomaly Maps

The anomaly maps show the average anomaly, measured in days, for each pixel within the park and the protected area centered ecosystem (PACE) for each park or network. Positive values are shown in green, and indicate a later than average SOS date. Negative values are shown in red, and indicate an earlier than average SOS date. To generate the anomaly maps, the average SOS date for the nine year period spanning 2001 – 2009 was calculated for each pixel. At the completion of 2010, the baseline average will be updated and the anomaly maps will be recalculated to provide a 10-year average to serve as the baseline for future analyses. The value for each pixel in the anomaly maps was calculated by subtracting the average SOS date from the SOS map for each year. The blue shading indicates pixels associated with the region of interest (PACE, park boundary, land cover type) selected using the pull down menu at the upper right of the screen (Figure 3a), and can be controlled using the Layer tab (Figure 3b).

The anomaly maps provide a measure of the spatial patterns in landscape phenology relative to the average SOS date for 2001 to present. Consistent positive or negative annual anomalies across all land cover types throughout a park or PACE are indicative of a strong climate driver (e.g., warmer than average temperatures, higher precipitation, earlier snowmelt) or significant

disturbance event (e.g., major wildfire, freeze, or insect infestation). Mixed patterns of positive and negative anomalies may be indicative of weaker climate forcings, or seasonal weather patterns that only affect certain ecosystems or plant species at certain elevations (e.g., earlier snowmelt, low precipitation). Figure 4 provides an example of an anomaly map from 2008 for the central California and SIEN network showing a mixed SOS pattern for the region.

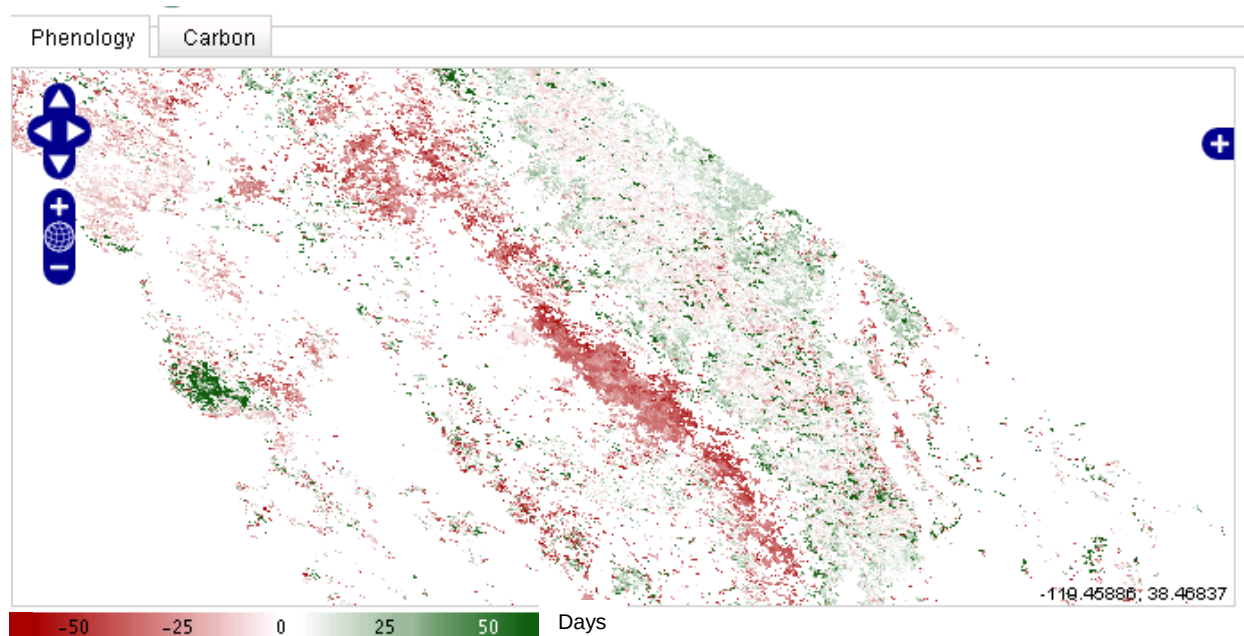


Figure 4: SOS Anomaly Map for Central California and the SIEN I&M Network for 2008.

NDVI Timeseries

The NDVI timeseries graphs show the average NDVI values for all pixels associated with the selected region of interest plotted on the same grid as the smoothed and interpolated timeseries. The average SOS date is indicated with a grey dashed line, and the SOS dates for each year are indicated with dashed and solid vertical lines, with green lines used to indicate an earlier than average SOS date, and red lines used to indicate a later than average SOS date. Graphs for each land cover type within the park boundary or PACE can be selected using the pull down menu above the graph (Figure 3a).

Since the SOS calculations are designed to be automated, the NDVI graphs are provided to allow for visual inspection of the timeseries data and evaluation of the fit provided by the interpolation algorithm. In cases where there are a significant number of outliers and the line clearly does not fit the plotted NDVI values for particular years or land cover types, the anomaly maps should be used with caution. Please contact Forrest.S.Melton@nasa.gov to request that data for a particular year or location be removed from the database and replaced with 'No Data' values.

Figure 5a provides an example from the GRYN network showing the NDVI graph for grasslands and demonstrates a reasonable fit between the NDVI observations and the interpolated timeseries. Figure 5b provides an example from the SIEN network showing the NDVI graph for mixed forests. The interpolated curve closely fits the observed NDVI values with the exception of outlier values of 0.5 and below. Since these points all occur in December and January, it can

be assumed that they are due to snow cover and can be safely ignored. If this pattern was observed in a region without winter snow cover, they should be flagged and reported.

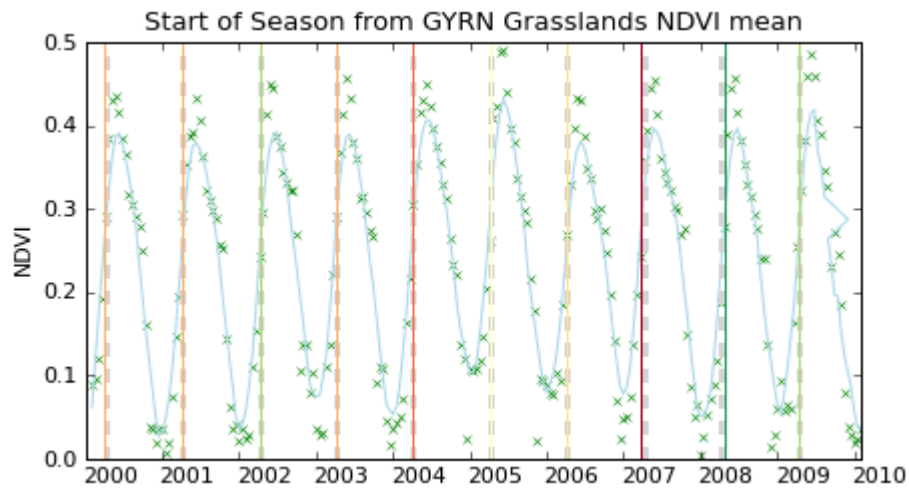


Figure 5a: NDVI graph for grasslands within the GRYN PACE boundary

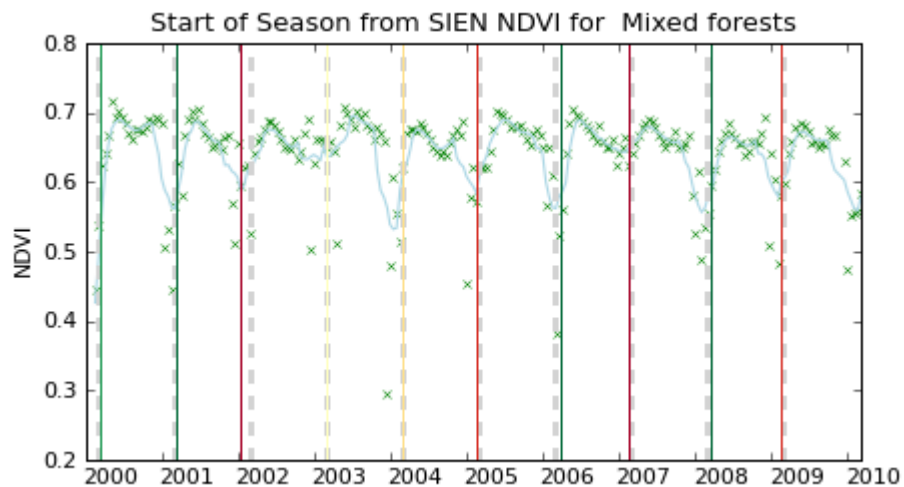


Figure 5b: NDVI graph for mixed forests within the SIEN PACE boundary

SOS Summary Table

This table provides a summary of recent patterns in SOS dates and SOS anomalies for all pixels within a park, PACE, land cover type, or elevation band. Positive values indicate later than average SOS dates, and negative values indicate earlier than average SOS dates. The summary table provides a quick reference for evaluating the consistency of landscape response to weather patterns in each year. Figures 6a and 6b compare the phenological response for different elevation bands in the SIEN PACE in 2004 (a warm, dry year), and 2005 (a cooler year with a later than average melt of the winter snowpack). These patterns are also reflected in the summaries by land cover type, and indicate an early SOS date for most land cover types and

elevation bands in 2004, and much later SOS dates in 2005, with the exception of the 1000-1500m elevation band.

SIEN Start of Season

2004 ▼

Land Cover Type	Start of Season	anomaly (days)	
NDVI from 0m to 500m	10 Nov '04	-24	
NDVI from 500m to 1000m	23 Aug '04	-98	
NDVI from 1000m to 1500m	11 Jan '04	0	
NDVI from 1500m to 2000m	01 Mar '04	-17	
NDVI from 2000m to 2500m	27 Mar '04	-25	
NDVI from 2500m to 3000m	01 May '04	-14	
NDVI from 3000m to 3500m	02 Jun '04	-6	
NDVI from 3500m to 4000m	23 Jun '04	-7	
NDVI from 4000m to 4500m	23 Jul '04	-10	

Figure 6a: Summary table for 2004 for different elevation bands within the SIEN PACE

SIEN Start of Season

2005 ▼

Land Cover Type	Start of Season	anomaly (days)	
NDVI from 0m to 500m	28 Dec '05	23	
NDVI from 500m to 1000m	31 Jan '06	62	
NDVI from 1000m to 1500m	28 Aug '04	-136	
NDVI from 1500m to 2000m	27 Apr '05	39	
NDVI from 2000m to 2500m	17 May '05	25	
NDVI from 2500m to 3000m	05 Jun '05	20	
NDVI from 3000m to 3500m	01 Jul '05	22	
NDVI from 3500m to 4000m	22 Jul '05	21	
NDVI from 4000m to 4500m	31 Aug '05	28	

Figure 6b: Summary table for 2005 for different elevation bands within the SIEN PACE

SOS Summary Graph

The average SOS date for all pixels within a PACE, park, or land cover type is plotted for each year on the graph. The relatively short timeseries of SOS dates available from MODIS precludes detailed timeseries analysis. A linear trend line fitted with least squares regression is shown as a point of reference, and the slope is provided in days per year. This metric provides an indication of the recent interannual variability in SOS dates, which may be significant for some regions, and is intended for use in establishing baseline conditions and monitoring for emerging trends. The trend line provides an initial reference for evaluating emerging trends, and sustained, consistent shifts in SOS dates over multiple years may indicate a need to perform a more detailed analysis. Figure 7a and 7b show the recent patterns for mixed forests in the SIEN and GRYN PACE respectively, indicating significant recent interannual variability in SOS dates with no clear trend.

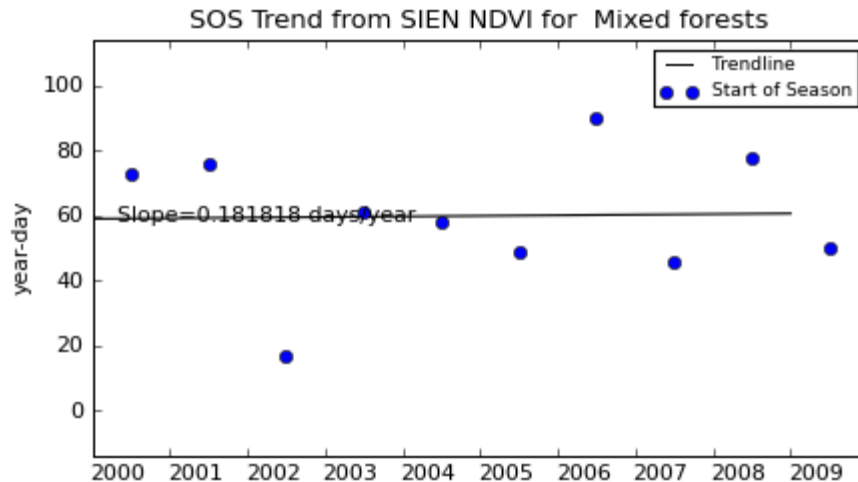


Figure 7a: Summary table for the mixed forest land cover class for the SIEN PACE

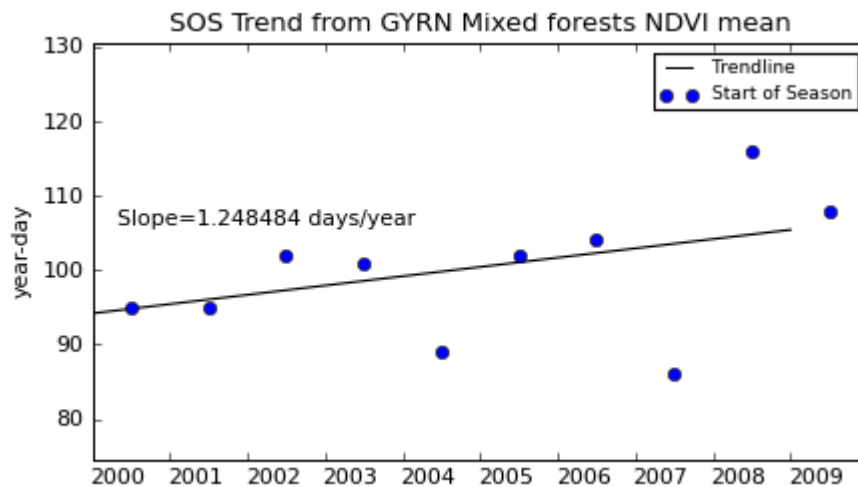


Figure 7b: Summary table for the mixed forest land cover class for the GRYN PACE

Use of ground observations of phenology in evaluating patterns derived from satellite observations

Ideally, monitoring of phenological patterns would incorporate both ground and satellite observations, with satellite-derived indicators used to evaluate the extent to which patterns observed at ground monitoring stations vary across the landscape. Unfortunately, phenological stations and conventional phenological data are comparatively scarce for many regions throughout the U.S., and use of phenological observations for evaluation of long-term trends requires a sustained timeseries of observations. Efforts such as the National Phenology Network (NPN) are working to establish long-term monitoring sites, and NPS may play a key role in expansion of the NPN monitoring network, but at present there remain a limited number of NPN sites, especially in the western U.S. In anticipation of the future growth of NPN sites, current analyses are evaluating different strategies for comparing satellite and ground-based measures of phenology. Upon completion of these analyses, an additional SOP may be

developed describing integrated use of satellite and surface observation networks for phenological monitoring. For additional details on methods for ground-based phenology monitoring, please refer to the USA NPN website at <http://www.usanpn.org>.

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Appendix A – Python Code for Phenology Calculations

To be added.