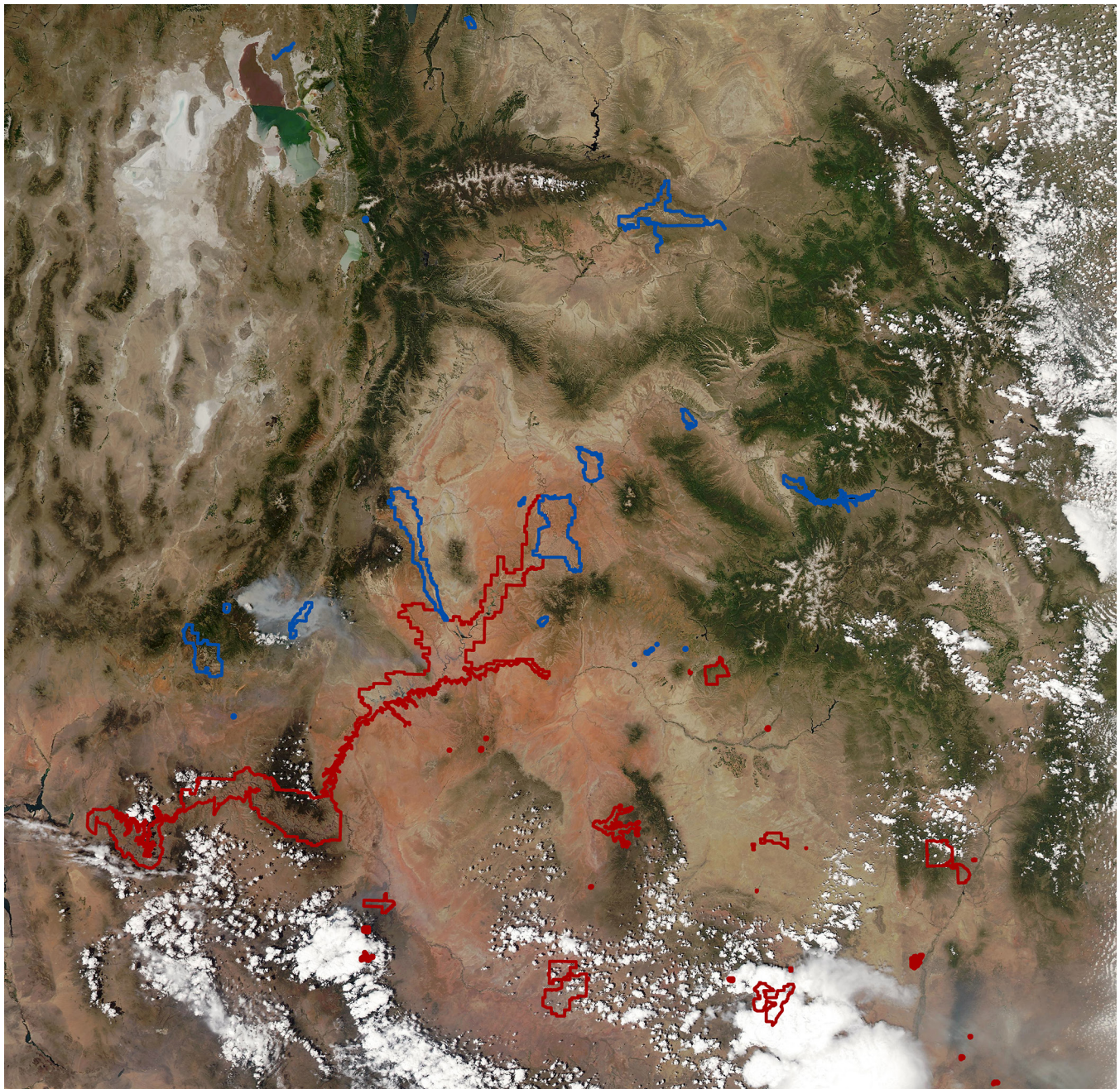




Satellite-based Vegetation Phenology and Condition, and Snow Cover Extent Monitoring Protocol for the Northern and Southern Colorado Plateau Networks

Natural Resource Report NPS/SCPN/NRR—2017/1533



ON THE COVER

This composite MODIS image from June, 2017 shows how strongly elevation controls vegetation on the Colorado Plateau. Higher elevation mountains and mesas receive more moisture and have cooler temperatures, and so are often covered by forests or woodlands, which seen here in shades of green. At lower elevations vegetation is sparse, and the patterns of the underlying rock formations often dominate the view. This faint vegetation signal seen in many of the low elevation parks complicates our use of satellite imagery to track phenology in the NCPN and SCPN (park boundaries shown in red and blue, respectively). Also visible are clouds over the southern and eastern parts of the image, as well as smoke from the 2017 Brian Head fire near Cedar Breaks National Monument (center left) and covering much of Bryce Canyon National Park. Snow can be seen in the high mountains on the east and north side of the image.

Satellite-based Vegetation Phenology and Condition, and Snow Cover Extent Monitoring Protocol for the Northern and Southern Colorado Plateau Networks

Natural Resource Report NPS/SCPN/NRR—2017/1533

David Thoma¹

Jodi Norris²

Paul Lauck²

¹National Park Service
Northern Colorado Plateau Network,
2327 University Way, Suite 2
Bozeman, MT 59715

²National Park Service
Southern Colorado Plateau Network,
PO Box 5663
Northern Arizona University
Flagstaff, AZ 86011

Editing and design

Jean Palumbo
Southern Colorado Plateau Network

November 2017

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available from the [Southern Colorado Plateau Network website](#) and the [Natural Resource Publications Management website](#). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

Thoma, D., J. Norris, and P. Lauck. 2017. Satellite-based Vegetation Condition and Phenology, and Snow Cover Extent Monitoring Protocol for the Northern and Southern Colorado Plateau Networks. Natural Resource Report NPS/SCPN/NRR—2017/1533. National Park Service, Fort Collins, Colorado.

Contents

Figures v

Tables vi

Executive Summary vii

Acknowledgments viii

About the Standard Operating Procedures ix

1 Introduction 1

2 Climate as a Driver of Vegetation Phenology and Snow Cover in the Southwest 5

 2.1 Factors affecting vegetation phenology 5

 2.2 Factors affecting snow cover 5

 2.3 Effects of climate change on ecosystems 6

3 Monitoring Phenology 9

 3.1 Using remote sensing to monitor phenology 9

4 Monitoring Objectives 11

 4.1 Monitoring questions 11

5 Monitoring Land Surface Phenology Using MODIS 13

 5.1 MODIS data properties 13

 5.2 Quality assurance/quality control and validation 13

 5.3 Compositing and temporal resolution 14

 5.4 MODIS data sources 16

 5.5 Measuring vegetation greenness 16

 5.6 Snow extent change 17

6 Pixel-based Processing 19

7 Target Area Processing 19

 7.1 Ecological site approach to target area processing 20

 7.2 Vegetation phenology metrics at landscape scales 22

 7.3 Associated climate data 26

 7.4 Evolving technology and integrative uses 27

8 Data Management 29

 8.1 Operational data management 29

 8.2 Archival data management 29

 8.3 Documentation 30

9 Analysis 31

Contents *(continued)*

9.1 Overview of analysis methods 31

9.2 Temporal analysis 33

10 Report Types and Schedule 37

11 Personnel Requirements and Training 37

12 Operational Requirements 39

12.1 Workload/acquisition schedule 39

12.2 Hardware capability 39

12.3 Software requirements 39

13 Literature Cited 41

Figures

Figure 1. Location of Colorado Plateau Networks park units, and approximate northern boundary of the warm moist summer air mass associated with what is now called the North American Monsoon (From Mitchell 1976, see also NOAA 2004). 1

Figure 2. a) An example of the typical annual greenness cycle on the Colorado Plateau, b) common forms of interannual variability on the Colorado Plateau, and c) hypothesized effects of projected climate change on land surface phenology. 3

Figure 3. Examples of growing season changes in the western United States.. . . . 6

Figure 4. Optimizing spatial and radiometric resolution: An example of nested analysis scales 23

Figure 5. Some of the seasonality parameters generated in TIMESAT: (a) beginning of season, (b) end of season, (c) length of season, (d) base value, (e) time of middle of season, (f) maximum value, (g) amplitude, (h) small integrated value, (h+i) large integrated value. 26

Figure 6. A “dashboard” view of charts created from custom Excel scripts. These data are from a forested area affected by disease. 32

Figure 7. (top) Example snow depletion and accumulation curves created from custom Excel scripts for recent year and long-term average, and (bottom) snow persistence curves on a calendar-year basis. 35

Tables

Table 1. Data acquisition process and the spatial, temporal and spectral characteristics of some MODIS products and derived metrics used by Colorado Plateau Networks.	15
Table 2. Examples of some MODIS data sources and characteristics.	16
Table 3. Comparison of the advantages of pixel-based and target area-based analysis.	20
Table 4. Example of Excel script output for NDVI summary statistics from the forested area used in the Figure 6 example.	33
Table 5. Example of Excel script output for NDVI phenology metrics derived from Timesat.	33
Table 6. Example of Excel script output for snow metrics and statistics.	34
Table 7. Potential metrics to report for landscape processes vital signs.	37
Table 8. Tasks and responsible personnel for phenology and snow cover monitoring.	38
Table 9. Initial personnel qualifications for monitoring of landscape processes.	38
Table 10. Approximate timing of when remotely sensed data become available after collection.	39

Executive Summary

This document describes the rationale and methods for monitoring land surface phenology and snow cover extent in the park units of the Northern and Southern Colorado Plateau Inventory and Monitoring Networks of the National Park Service.

Phenology refers to the timing of annual biological events and is an indicator of vegetation response to a suite of environmental variables, most notably climate. Vegetation condition also changes in response to environmental variables, such as land management, disturbance, invasive species and vegetation assemblage. Individual plant responses cumulatively scale-up resulting in spatial and temporal landscape patterns that are detectable using satellite remote sensing techniques. Vegetation phenology and condition have been identified as core vital signs for long term monitoring in the Northern and Southern Colorado Plateau Networks (CPNs). Because vegetation condition and phenological responses are often interrelated, it can be beneficial to measure the two simultaneously.

The CPNs have chosen to monitor phenology and vegetation condition by using remote sensing to measure vegetation greenness, as expressed by the Normalized Difference Vegetation Index (NDVI). Vegetation provides the foundation for ecosystems, and remote sensing methods have been developed to measure greenness using satellites with sensors designed for this purpose. In addition to measuring seasonal pulses of vegetation greenup, the same satellite sensors provide measurements of the intensity of greenness. The timing, intensity and duration of greenness provide important information about changes in vegetation condition and shifts in phenology.

Snow cover can be used to understand the relationship between climate and the associated timing and intensity of spring greenup. The same satellite sensors that measure vegetation greenness can also measure the presence or absence of snow cover. Monitoring the variability and trends in the timing and intensity of vegetation phenology, as well as snow cover extent may provide early indicators of climate change impacts that represent increased stress or vulnerability for plants and animals, or may presage gradual or sudden vegetation community shifts.

The process described in this protocol not only provides information on vegetation phenology and the link with climate and snow cover extent, it also links climate with landscape vegetation condition, and other NPS vital signs. Many of the changes we anticipate in other NPS vital signs, such as upland bird populations, upland vegetation condition, aquatic macroinvertebrates, and riparian systems, are likely to be associated with changes in the timing, intensity, and duration of greenness and the timing, extent, and duration of snow cover.

This protocol is divided into a narrative and a series of Standard Operating Procedures (SOPs). The narrative describes the history, advantages, and limitations of using remote sensing and specifically MODIS data to measure phenology. It then outlines the approaches that the CPNs will use to monitor phenology. Because of changing technology and data availability, we anticipate that the networks' methods will change as well.

Acknowledgments

This project stemmed from pilot protocol development work by Bradley Reed, which was funded through the National Park Service, Inventory and Monitoring Program via Inter-agency Agreement S2121060016 with USGS. The information gained from that study was instrumental in shaping the scope and methods that are described within this protocol. The protocol also benefited from review comments made by William Hargrove (National Forest Service) and Kevin James (National Park Service).

About the Standard Operating Procedures

Land surface phenology will be an enduring concept over the coming decades; however, as time passes there will be changes in satellite data sources, data distributors, processing software, analysis, and communication techniques. As a result, Standard Operating Procedures (SOPs) for the *Satellite-based Vegetation Phenology and Condition, and Snow Cover Extent Monitoring Protocol for the Northern and Southern Colorado Plateau Networks* may change significantly over time, and SOP's that are necessary at one time may be unnecessary and so removed, while new SOPs may be added.

Furthermore, because the two networks have selected different methods (although the underlying processes remain the same), the SOPs for the Northern Colorado Plateau Network (NCPN) and the Southern Colorado Plateau Network (SCPN) will be different, and will be provided separately. Broadly, though, the SOPs will cover (1) selecting target ecosystems, (2) acquiring the data, (3) processing the data, and (4) examples of basic analyses.

To accommodate the fluid nature of the SOPs, they will be self-published to Integrated Resource Management Applications (IRMA) by SCPN and NCPN in locations different from the narrative for this protocol. However, there will be links to the SOPs on the protocol's IRMA record site (<https://irma.nps.gov/Portal>). As methods described in the SOPs change, SCPN will document those changes in different versions of SOPs. All versions of the SOPs will be available from the IRMA record for that SOP.

1 Introduction

This document describes the rationale and methods for monitoring vegetation phenology and snow cover extent in the park units of the Northern and Southern Colorado Plateau Inventory and Monitoring Networks (NCPN and SCPN, or CPNs collectively). The CPNs include all the NPS units in the area that encompasses northern Arizona,

northwestern New Mexico, western Colorado, nearly all of Utah, and southwestern Wyoming (Figure 1). The park units within the CPNs are dominated by arid and semi-arid ecosystems, but also include higher elevation forests and grasslands. Most of the CPN area is characterized by erratic moisture availability; annual precipitation that is

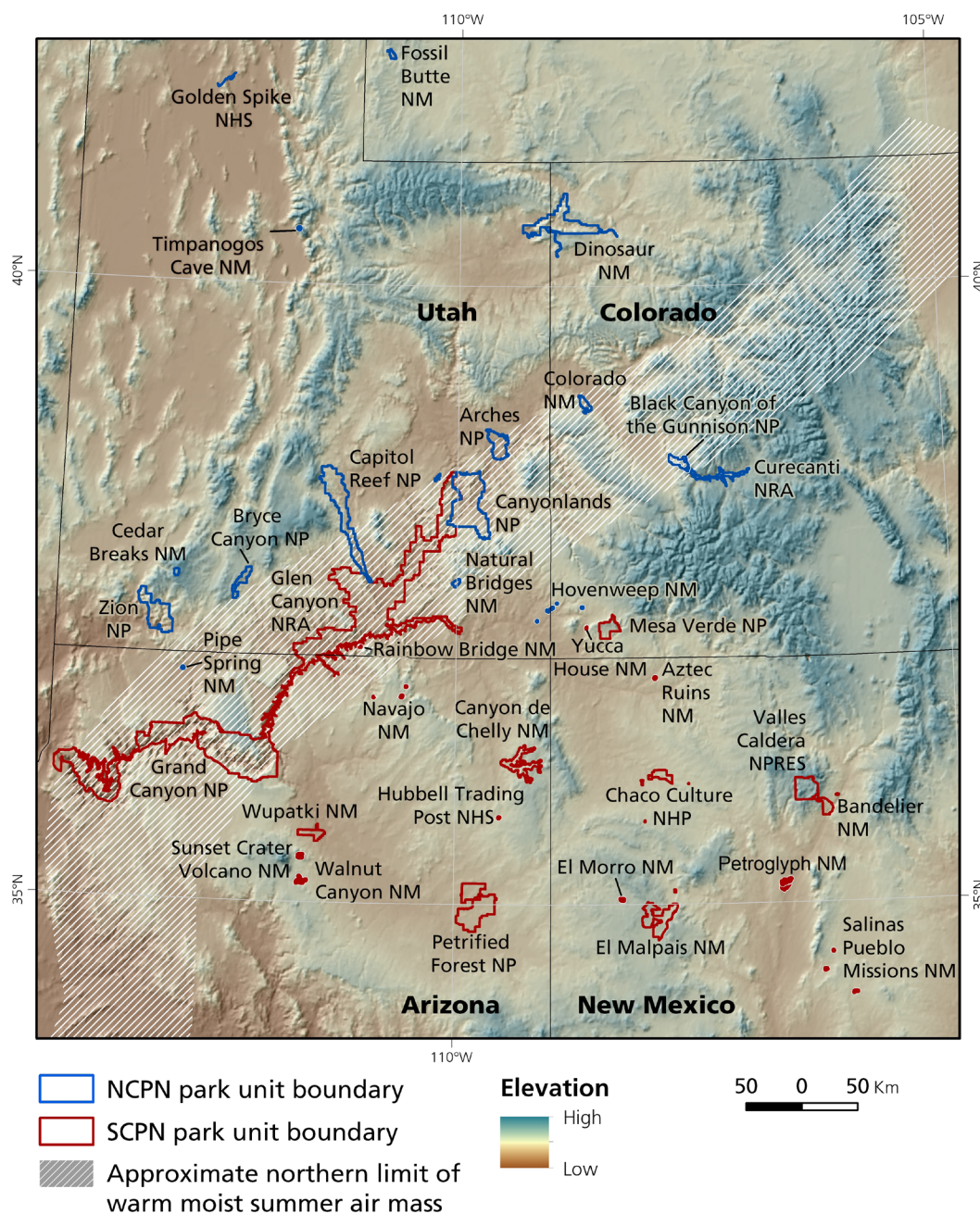


Figure 1. Location of Colorado Plateau Networks park units, and approximate northern boundary of the warm moist summer air mass associated with what is now called the North American Monsoon (From Mitchell 1976, see also NOAA 2004).

characterized by a bimodal distribution, primarily in winter and late summer; warm to hot growing seasons; and winters with sustained periods of freezing temperatures. Broad scale patterns in vegetation type and condition reflect recent and past climates and their interactions with geologic substrate, slope, aspect, elevation, and disturbance agents.

In order to describe long-term trends in ecosystem properties and to understand their condition and dynamic nature, the CPNs monitor “vital signs”. Vital signs are selected physical, chemical, and biological elements or processes of park ecosystems that represent the overall health or condition of the park, known or hypothesized effects of stressors, or elements that have important human values (Thomas et al. 2006). The CPNs have identified several physical and biological processes as vital signs to monitor across all park units. Among these are vegetation phenology and condition, as well as snow cover extent.

Phenology refers to the timing of annual biological events, such as spring greenup, flowering, and fall senescence. Within this protocol we use a broader working defini-

tion of phenology that includes the related measures of the intensity and amplitude of annual phenological events. Phenology is an indicator of an ecosystem’s response to a suite of environmental variables, most notably climate (Hudson and de Beurs 2011, White et al. 2009, Jolly et al. 2005, Jenerette et al. 2010). We include the annual cycle of snow accumulation and melt in our analysis of phenology because (1) it is inherently tied to the seasonal cycles that drive change in vegetation phenology, (2) it responds to some of the same drivers, and (3) it directly impacts vegetation phenology by covering vegetation (at times deeply) and providing moisture during spring melt (Peng et al. 2010). Phenological monitoring of vegetation provides a means to examine relationships between climatic drivers and the integrated vegetation response to interannual climate variability and climate trends. Phenology reflects vegetation response to gradual or abrupt disturbance, such as die-offs or fires and community shifts caused by invasive species or climate change. Figure 2 illustrates the typical annual cycles, current interannual variability, and projected phenological changes that may affect CPN ecosystems.

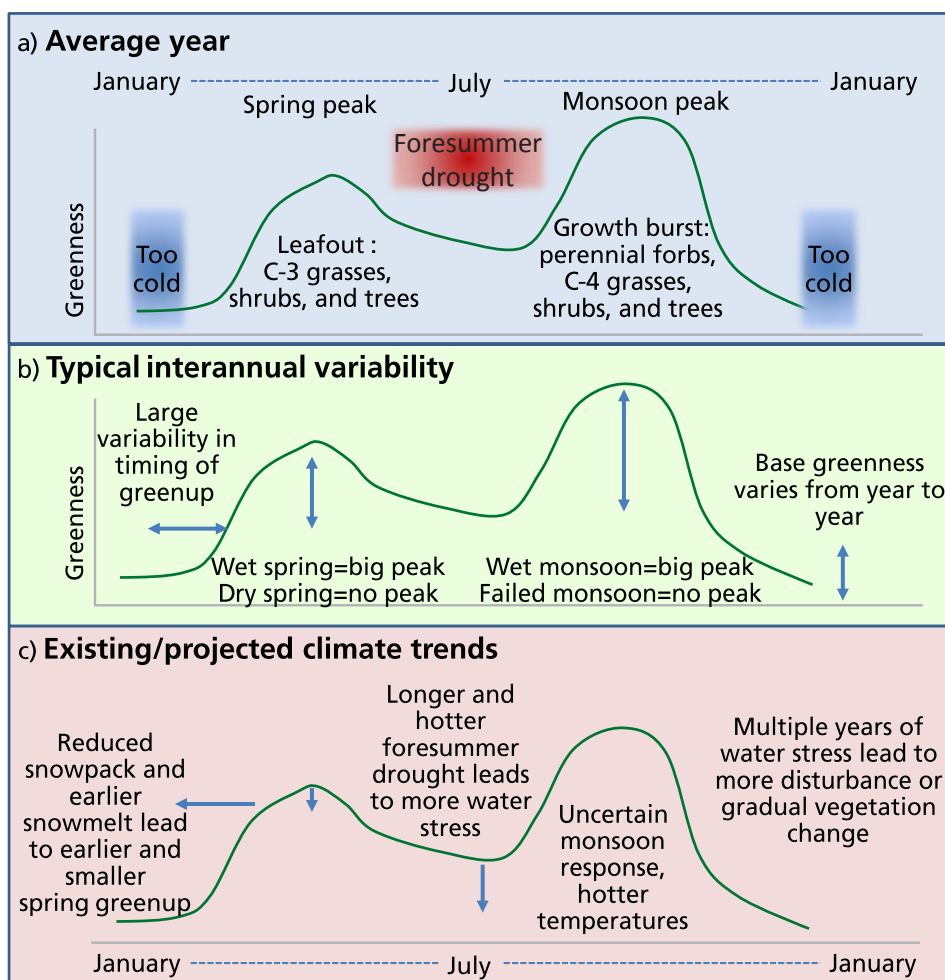


Figure 2. a) An example of the typical annual greenness cycle on the Colorado Plateau, b) common forms of interannual variability on the Colorado Plateau, and c) hypothesized effects of projected climate change on land surface phenology.

2 Climate as a Driver of Vegetation Phenology and Snow Cover in the Southwest

Ecosystems develop and are maintained by landscape processes related to climate, geology, and hydrology that operate over a range of scales and influence the distribution, abundance and productivity of plants and animals (Alcaraz-Segura et al. 2009; Stephenson 1998).

2.1 Factors affecting vegetation phenology

On a global scale, vegetation productivity is limited by four primary abiotic factors: temperature, light, water, and nutrients. While nutrient availability varies locally, broader patterns in the effects of water, temperature, and light on vegetation productivity can be discerned on a landscape scale. Churkina and Running (1998) have described and mapped these broader patterns. They found that across much of the western United States, water stress is the primary limiting factor, though in some high elevation mixed conifer forests of the CPNs (BAND, GRCA, CEBR), low temperatures may be the primary limiting factor.

In arid areas, water availability controls more than gross primary productivity; it also determines the timing (phenology) of that productivity (Jolly et al. 2005, Jenerette et al. 2010). Perennially moist riparian areas are an exception as they are relatively insensitive to water limitations, thus making them good candidates to study phenologic response to temperature. The erratic availability of water in arid regions results in a phenologic response quite different from most light- and temperature-limited ecosystems across most of the rest of the United States. It introduces complications to phenological monitoring that make it difficult to determine what factor caused a change in phenology from one year to the next. For instance, “warm” or “cool” droughts, as well as cold snaps, at times of adequate moisture may have different effects on phenology.

An additional consideration for monitoring vegetation phenology is that the current vegetation may have established under a different range of ‘average’ climate conditions than those being experienced today, or those that will be experienced in the coming decades. Although water availability is a limiting factor for most CPN ecosystems, at any specific location, vegetation and phenology will also be affected by nutrient availability, the history of land management practices, and natural or anthropogenic disturbance agents, such as fire, forest disease and invasive exotics.

2.2 Factors affecting snow cover

Two abiotic factors affecting vegetation phenology—precipitation and temperature—also affect snow cover extent and duration. Precipitation determines the potential for snowfall, while air and ground temperatures determine whether the precipitation falls as rain or snow, and whether the snow is maintained as snowpack or melts.

Snow cover extent, timing, and duration are important factors that respond to climate and are related to other ecosystem processes and functions, such as quantity and timing of soil moisture recharge, runoff, and stream flow. Over half of the water supply in the western U.S. is derived from snowmelt (Lundquist and Roche 2009). Storage and release of snowpack is pivotal in regulating higher elevation terrestrial and lower elevation aquatic systems in the region (Liu et al. 2008). Changes in snow depth and duration at higher elevations may lead to significant shifts in the timing and amount of runoff, and may also influence growing season dynamics and net primary productivity (Lundquist and Roche 2009, Pederson et al. 2011).

2.3 Effects of climate change on ecosystems

That climate change is occurring in the southwestern United States is evident in numerous ways—warmer temperatures, longer frost free periods and more frequent periods with increased high temperatures (Figure 3). Climate predictions for the Southwest have consistently forecast warmer temperatures, lower winter precipitation, and an extension of the growing season with associated early summer water stress (Weiss et al. 2009, McAfee and Russell 2008). Predictions of the strength of the North American Monsoon are much less consistent (Liang et al. 2008, Geil et al. 2013), and high interannual precipitation variability may make it difficult to detect short-term and mid-term trends (Arriaga-Ramírez and Cavazos 2010).

Changes in water and temperature translate into a variety of observed and predicted ecological drivers: more precipitation falling as rain than snow, earlier snowmelt and decreased runoff (Garfin et al. 2010, Lundquist and Roche 2009), and altered stream flow regimes affecting aquatic systems (Lundquist and Loheide 2011, Muhlfield et al. 2011). Upland ecosystems of the southwest are experiencing earlier starts to the growing season, lower soil moisture during the summer, and greater water vapor pressure deficits for water-limited ecosystems during the growing season (Kunkel et al. 2004, Booth et al. 2012, Williams et al. 2012). The consequences of changes in moisture availability driven by climate change may be severe in the semi-arid western United States, as evidenced by recent drought (Rosenberg and Edmonds 2005, Williams et al. 2010, Gonzalez et al.

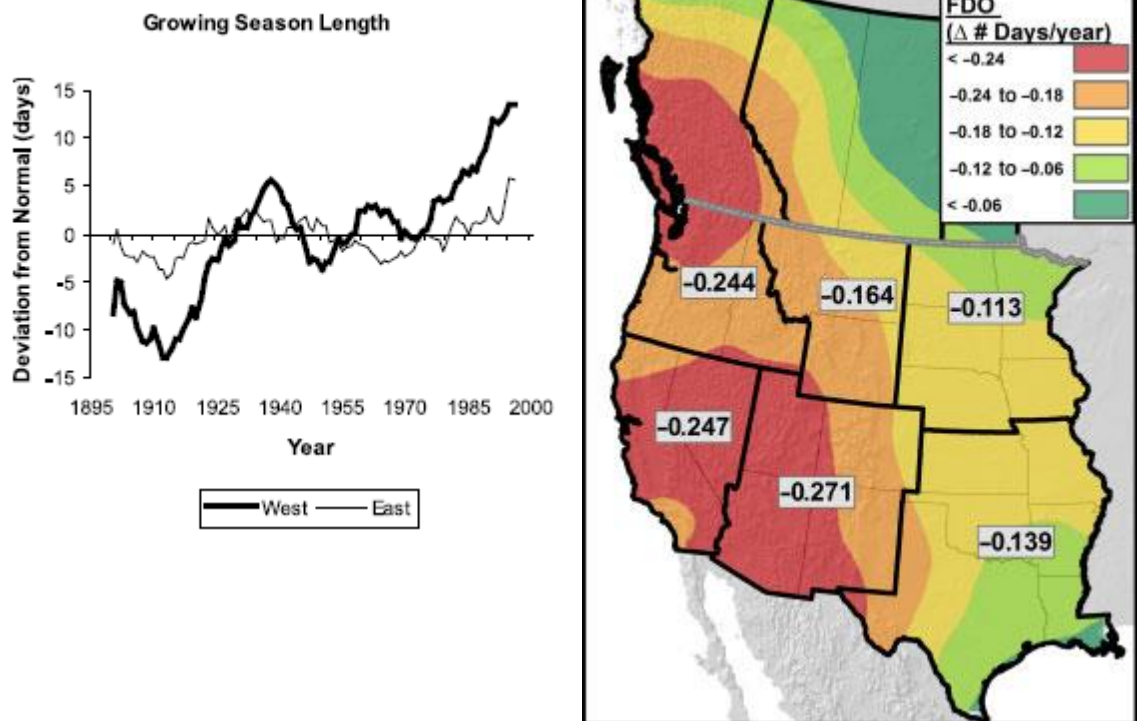


Figure 3. Examples of growing season changes in the western United States. The image on the left documents longer growing seasons in the western United States (thick line on graph) using climate records from 1895 to 2000 (figure from Kunkel et al. 2004). The image on the right (after Booth et al. 2012) spatially displays a portion of that trend using records from over 400 weather stations from 1950 to 2005. The map shows trends in the number of frost days (FDO), which is an indicator of the length of winter. The trend is reported as average change (Δ) occurring every year over this time period, measured as days per year. As an example, it shows that the number of frost days has decreased in the southwestern United States by an average of 0.271 days per year during that time period. This equates to about 2 fewer weeks of frost days.

2010, Bowers 2005). In ecosystems limited by temperature rather than water, there may be higher productivity due to longer growing seasons (Menzel et al. 2006, Myneni et al. 1997); however, across the globe many forested ecosystems are experiencing water limitations and drought- and heat-induced tree mortality (Allen et al. 2010).

Changes in climate may result in vegetation biome shifts or the development of non-analog communities, as species respond individually to form novel ecosystems (Williams and Jackson 2007, Williams et al. 2012). Monitoring the variability and trends in the timing and intensity of vegetation phenology may provide early indicators of climate trends that represent increased stress or vulnerability for plants, or may presage gradual or sudden vegetation community shifts. Phenological monitoring also provides

a means of understanding the stressors at work by revealing how timing affects overall seasonal productivity at the landscape scale (Thoma et al. 2016; Witwicki et al. 2016). At park and regional scales, the greatest power may prove to be when phenological monitoring across landscape scales can be paired with site specific information about individual plant and animal taxa, soil conditions, climate, and disturbance or conversion events. For example, when phenological changes are represented through satellite data alone, we may not be able to distinguish whether trends of decreased greenness represent an overall decrease in vegetation vigor or the death of individual vulnerable plants; however the persistence of either condition may foreshadow some form of vegetation die-off or disturbance.

3 Monitoring Phenology

Monitoring landscape processes, such as snow cover and vegetation phenology, provides information on observed changes, as well as support for ecological forecasts that alert park managers to future issues of management concern, such as the potential for ecological invasions, or wildland fires (Schlaepfer et al. 2012). Trends in vegetation cover and snow extent will track changes in regional climate because they integrate the effects of weather over long periods. Thus, tracking their trends will provide information on the extent and severity of changes that affect terrestrial and aquatic systems. The information obtained from monitoring provides a broader context for understanding other vital sign dynamics, thereby improving our ability to understand and manage complex interactions and proactively anticipate or avert undesirable consequences.

Humans have monitored phenological and other seasonal events for centuries. Historical observations of abiotic factors include the timing of the first and last frost, lake ice cover and river ice cover, peak stream-flow, and the timing of rainy season onset (Schwartz 2003, Benson et al. 2012). Biotic observations are generally site-based and focus on observations of specific plant or animal species phenomena, such as bud-burst, flowering, and senescence for plants; and migratory arrival, nesting, reproduction, and migratory departure for animals. CPNs have chosen to monitor land surface phenology using timing, duration, and intensity of vegetation greenness and snow cover as vital signs, because (1) both can be measured over broad areas using freely available, carefully processed satellite data, (2) vegetation forms the structural foundation and primary productivity of most terrestrial ecosystems, and (3) in the southwestern United States snow cover is an indicator of early season water availability and temperature limitations.

3.1 Using remote sensing to monitor phenology

With the development of satellite technology it is possible to monitor phenology across wider areas with high temporal resolution and without the need for a physical observer to repeatedly visit many sites throughout the growing season. Satellite sensors measure different types of energy coming from the earth, which, in turn, provide scientists with valuable information about the earth's ecological, hydrological, and meteorological conditions. When solar radiation hits the earth, it may be absorbed or reflected, depending upon the surface that it has hit. Satellites passing overhead can collect and record information about the reflected energy. This information is then transmitted to a receiving station in the form of data that are processed into an image. Additionally, when light is absorbed by an object it may raise the object's temperature, and some of that energy may then be emitted as long wave 'thermal' infrared radiation, which can also be measured by satellite sensors.

Different materials reflect and absorb solar radiation differently, and at different wavelengths. This property of matter allows us to separate distinct cover types based on how they reflect light of a given wavelength. Vegetation has a unique spectral signature which allows it to be easily distinguished from other types of land cover in an image using multiple spectral bands in the red, green, and near infrared wavelengths. Chlorophyll, a chemical compound in leaves, strongly absorbs radiation in the red and blue wavelengths, but reflects green wavelengths. Leaves appear "greenest" to us in the summer, when chlorophyll content is at its maximum.

In addition to a sensitive vegetation index, phenology monitoring requires a relatively short return interval between successive passes of a satellite over the target area, ideally days to weeks, in order to track patterns

in sufficient temporal detail. It also requires that we track processes that occur at spatial scales large enough to encompass widespread vegetation types across a region. We can use remotely-sensed data to interpret and analyze these processes at broad spatial and high-frequency temporal scales.

Phenology research using remote sensing techniques has been conducted since the 1970's (Badhwar 1984, Lloyd 1990, White et al. 1997, Reed et al. 2003). Widespread changes in indices of vegetation greenness (e.g., Normalized Difference Vegetation Index [NDVI]) and biomass (Myneni et al. 1997), as well as changes in the timing of

growing season onset in regions of North America, Asia, and Europe have been observed using satellite-derived measurements (Piao et al. 2005, Stockli and Vidale 2004, Hicke et al. 2002, Menzel et al. 2006). Early work with Advanced Very High Resolution Radiometer (AVHRR) data included the derivation of metrics for onset of greenness, time of peak NDVI, rate of senescence, and integrated NDVI (Reed et al. 1994). MODIS vegetation index data have been used to identify transition dates within annual time series, enabling investigators to monitor vegetation dynamics at large scales (Zhang et al. 2003).

4 Monitoring Objectives

The primary objectives for monitoring vegetation phenology and condition and snow cover phenology in the Northern and Southern Colorado Plateau networks using remote sensing are to

- determine annual status, interannual variability, and long-term trends in growing season as measured in NDVI (start, end, and peak of season dates; duration and intensity of growing season) within select ecosystems
- determine annual status, interannual variability, and long-term trends in the timing and duration of snow cover (establishment of snowpack, persistence, time and rate of melt) within select ecosystems

4.1 Monitoring questions

Meeting these objectives will allow us to address a variety of monitoring questions that are relevant to park management across a range of conditions and at multiple scales of interest. For example,

- What are the regional temporal and spatial patterns in vegetation greenness and productivity within and among the predominant cover types across the Colorado Plateau? For a given cover type,
 - track changes in NDVI through the growing season.
 - track changes in cumulative annual NDVI and length of season.
 - track changes in date and magnitude of maximum NDVI.
- Can we integrate the patterns of intensity and duration of greenness seen from phenology data with species-specific vegetation data collected from the CPN's ground-based monitoring plots to describe in detail (1) whether individual species are changing and (2) whether changes are predominantly changes in plant vigor across multiple species or (3) whether they represent individual plant die-off or new plant establishment.
- Can we likewise use MODIS greenness patterns to improve analyses of other ground-based monitoring efforts (e.g. birds, mammals, insects)?
- Which plant communities (e.g., grasslands, shrublands, woodlands, riparian areas) are experiencing changing growth patterns in response to disturbance events, such as fire, drought or insect damage?
- How are riparian and upland phenology responding differently as the climate changes?
- Do grazing status and differences in fire occurrence and intensity affect trends in vegetation greenness and productivity?
- Are similar trends in vegetation greenness and productivity occurring across all Colorado Plateau parks? Are similar trends in vegetation greenness and productivity occurring within similar cover types across all Colorado Plateau parks?
- Are there trends in timing and duration of snow cover?
- The most widespread and pervasive influence of climate on biological systems is through primary production of vegetation, which dramatically affects the flow of energy and water through a system. Can we use MODIS data coupled with climate data to model climate/vegetation relationships? If so this would be fundamental to understanding the influence of climate at landscape scales which can also provide context for climate influence on other vital signs.

5 Monitoring Land Surface Phenology Using MODIS

We have chosen to use multispectral satellite data acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) to monitor the landscape processes of phenology and snowmelt because MODIS offers a unique combination of features:

- It detects reflected wavelengths useful for vegetation and snow monitoring.
- It takes measurements every day from two satellites that are composited over several days to minimize cloud and atmospheric interference.
- It is well-researched and has extensive quality control checks during processing.
- It is delivered with quality metrics that can be used to screen pixel values.

This continual, comprehensive coverage enables the MODIS sensors onboard both the Aqua and Terra satellites to complete an electromagnetic picture of the globe in multiple bands, at spatial resolutions of 250 and 500 m every day.

A variety of processed products have been created using MODIS data. These products usually incorporate some kind of temporal compositing that takes the highest or best quality value over a period of 7-16 days. This compositing step is useful because on any given day there may be atmospheric features that reduce the quality of the reflected signal (clouds, aerosols, dust). Images derived from MODIS data can be analyzed with algorithms to provide information about landscape processes. This protocol documents applications for MODIS data developed for the CPNs.

5.1 MODIS data properties

MODIS-Terra and MODIS-Aqua have provided multispectral data for the entire Earth surface every 1 to 2 days since 2000 and 2002, respectively. The 2,330 km wide image scans are collected at approximately 10:30 am local time (Terra) in a north to south overpass, and at approximately 1:30 pm local

time (Aqua) in a south to north overpass. Morning overpass times are often preferred for terrestrial applications to minimize cloud interference during times of year when afternoon water vapor builds due to evapotranspiration and when convective storms are most likely. Data are downloaded from the satellite to processing centers where geo-location, cloud screening and land image products are generated for distribution to the science community by the EROS Land Processes Distributed Active Archive Center (LP DAAC 2016) and by the National Snow and Ice Data Center (NSIDC DAAC). eMODIS data, also produced by EROS, have NDVI and quality control values derived from the same source collection, but are processed directly from the satellite swath into a usable grid projection with a weekly product covering the continental United States, and a separate product covering Alaska. The MODIS 250 m vegetation products and 500 m snow cover products are pre-processed to provide consistency for spatial and temporal comparisons by accounting for variation in sun angle, and cloud and atmospheric influences. An important byproduct of the pre-processing is quality assurance metadata that can be used to help interpret or to screen image products (Huete et al. 1999).

5.2 Quality assurance/quality control and validation

The MODIS sensor advances quantitative operational remote sensing over earlier-generation satellite sensors in several ways. First, the MODIS sensor collects information in 36 spectral bands, some of which are used specifically for measuring atmospheric properties and snow cover. This information is used to adjust reflectance in other spectral bands of primary interest to ecologists to simulate what reflectance would be at the ground surface if not influenced by variable atmospheric conditions and snow cover. This greatly facilitates detection of real change across land surfaces through time.

Second, a large investment in coordinated product development has automated image processing that minimizes human bias and issues of continuity in image processing, both important considerations in long-term monitoring. Quality assurance and control has been a major element of the MODIS product development. For a summary of the types of processing QA/QC that have been implemented, see an overview of the Land Data Operational Product Evaluation (http://landweb.nascom.nasa.gov/cgi-bin/QA_WWW/newPage.cgi). Similarly, many of the standard MODIS products have undergone validation experiments. The MODIS Land Processes Validation web site summarizes many of these efforts (<http://landval.gsfc.nasa.gov/index.php>). A description of the specific MODIS products currently used by the networks for monitoring is provided in the SOPs for each network.

Third, the combination of daily data collection with higher resolution provides better spatial resolution than the earlier AVHRR sensors, which had ~1 km pixels, and better temporal resolution than sensors, such as Landsat, with return intervals > 2 weeks, although Landsat provides higher 30 m spatial resolution.

5.3 Compositing and temporal resolution

Clouds and their shadows often obscure clear views of the Earth's surface, and pixels affected by clouds must be removed before image analysis. Typically clouds depress the ratio of reflectance in wave bands used for vegetation analysis. Cloud reflectance is high in short-wave infrared wavelengths, while snow reflectance is low. These differences in cloud reflectance allow clouds to be identified and removed in image processing.

Mechanically, cloud removal is accomplished by evaluating on a pixel-by-pixel basis multiple images collected over a fixed time interval. The final pixels are compiled in a new composite image called the constrained view angle maximum value Composite (CV-MVC) that represents a

combination of the best view angle and maximum NDVI value for the time interval. So, although images are collected daily, land surface process analysis is generally done using the CV-MVC, which represents fixed time blocks of 16 days (LPDAAC-MODIS) or 7 days (eMODIS) for vegetation products and 8 days for snow cover products. The compositing process has been progressively improved for the different MODIS collection versions, and we would expect to rerun processing for the entire MODIS time series when a new collection version is released.

5.3.1 Spatial resolution

The vegetation index product pixel resolution analyzed in this report is 250 m with an estimated +/- 50 m registration error (Wolfe et al. 2007). The spatial resolution combined with registration error makes the effective minimum mapping unit approximately 350 m. The snow product pixel resolution is 500 m. The estimated registration error for the snow product is not known, but may be similar to that of the vegetation product because similar registration procedures are used for both products. The minimum mapping unit for this protocol is the base resolution of the product plus approximately 100 m to account for a possible 50 m misregistration. For example, the vegetation index data (250 m resolution) has a minimum mapping unit of approximately 350 m. The extent of landscape change may be less than 350 m, but such change will still be detectable if it is sufficient to impact the reflectance characteristics of the pixel footprint covering the full map unit.

The level of change detectable is determined by the temporal and spatial resolution of the various products (Table 1). The phenology results are supplied as annual summaries (i.e., one summary value for each of the phenology metrics for each year). The metrics are either day of year, length in days, or an NDVI value: i.e., the start and end of season metrics are expressed as Julian date, duration of growing season is expressed as number of days, and seasonally integrated NDVI is expressed in daily accumulated NDVI units

Table 1. Data acquisition process and the spatial, temporal and spectral characteristics of some MODIS products and derived metrics used by Colorado Plateau Networks. The specific products used by each network are described in network SOPs.

Process		Reflectance-corrected data from the Aqua and Terra satellites				→ converted to	Gridded NDVI and Snow cover products of varying temporal and spatial resolution. These are downloaded by networks for processing and analysis.					→ derived	Metrics of interest for vegetation and snow cover phenology and vegetation condition				
		Band or layer ^a	Spatial resolution of product (m)	Band-width (nm)	Key use	→	Product name	Monitoring objective	Availability	Temporal resolution of product (days)	Quality screening data provided?	→	Derived metrics	Units of derived metrics ^b	Temporal resolution of derived metrics		
Product Information		Vegetation	1 (red)	250	620–670		Vegetation & chlorophyll	NDVI from MOD13Q1 or eMODIS counterpart	Vegetation phenology and condition	Feb-2000 (Terra) Jul-2002 (Aqua) to present	MOD13Q1=16 eMODIS=7		yes	end of growing season	DOY	annual	
			2 (NIR)	250	841–846		Clouds & vegetation							duration of growing season	days	annual	
							peak of growing season							DOY	annual		
							peak NDVI							DOY	annual		
Snow Cover			4 (vis)	500	545–565		Snow covered extent	MOD10A2 (Terra) MYD10A2 (Aqua)	Snow timing and duration	Feb-2000 (Terra) Jul-2002 (Aqua) to present	8		yes	seasonally integrated NDVI	NDVI units	annual	
			6 (SWIR)	500	1628–1652									cumulative NDVI	NDVI units	annual	
														snow on date	DOY	annual	
														snow off date	DOY	annual	
													duration of snow cover	days	annual		
		a red = red wave band, NIR = near infrared wave band, vis = visible wave band, SWIR = short wave infrared wave band															
		b DOY = day of year															

(Table 1).

5.4 MODIS data sources

There are multiple sources of processed MODIS data (Table 2). These sources differ primarily in the number of days included in a single composite, in the type of smoothing, in the level of processing, and in the speed with which data are made available. At the time of this report, the CPNs are using 3 sources of data:

- MODIS vegetation index data distributed by the EROS Land Processes Distributed Active Archive Center (LP DAAC)
- eMODIS vegetation index data also produced by EROS
- snow cover data produced by the National Snow and Ice Data Center (NSIDC) DAAC

In the future, other MODIS data sources may be used depending on network needs and availability of different MODIS products. The exact products used will be described and updated in the SOPs for each network.

5.5 Measuring vegetation greenness

The satellite-based measures of vegetation greenness rely on the strong absorption of red (600-700 nm) wavelengths by photosynthetically active pigments in green vegetation, and the strong reflectance of near infrared (700-1100 nm) wavelengths by internal leaf and canopy structures (Huete et al. 1999). The Normalized Difference Vegetation Index (NDVI) is one of the most commonly used indices and is the index used in this protocol. NDVI is useful in arid

ecosystems because it is sensitive to changes in greenness in sparsely vegetated areas. However, as a result, it saturates (becomes less responsive) at higher greenness levels and may not be suitable in heavily vegetated ecosystems. Other vegetation indices are available through MODIS and by calculation from individual bands, and these may be considered in the future as we identify indices best suited to specific ecosystems. The reasons for choosing the vegetation index currently used by the CPNs are explained in the SOPs for each network.

The calculation of NDVI is based on the increased contrast between red and near infrared reflectance that occurs with increasing amounts of green vegetation in a pixel. The NDVI exploits this contrast as a ratio defined as

$$NDVI = [(\rho_{NIR} - \rho_{red}) / (\rho_{NIR} + \rho_{red})]$$

where ρ_{NIR} = MODIS band 1 (620-670 nm) and ρ_{red} = MODIS band 2 (841-876 nm)

Because NDVI is a continuous gradient variable it can be displayed as gray scale or in color but first is usually scaled to a range more easily displayed in color images using the following equation:

$$\text{Scaled NDVI} = 100(NDVI + 1)$$

Thus an NDVI value of 0.025 becomes a scaled NDVI value of 102.5. After scaling, index values that initially ranged between -1 and 1 now range between 0 and 200. Scaled NDVI values below 100 represent clouds, snow, water and other non-vegetated surfaces. Green vegetation NDVI on the Colorado Plateau is typically between 120 and 170. The accuracy of 16-day scaled NDVI products is

Table 2. Examples of some MODIS data sources and characteristics.

MODIS Data Source	Smoothed	Phenology metrics calculated	Composite days/ Bands per year	Availability
LP DAAC	NO	NO	16 / 23	Within a week
eMODIS	NO	NO	7 / 52	Within a week
MODIS4NACP	YES	YES	8 / 46	Episodic, unscheduled
LANCE-MODIS	NO	NO	Daily	Within hours

+/- 2.5 scaled NDVI units (NASA 2010).

5.6 Snow extent change

The basis for detecting snow using MODIS is that snow strongly reflects visible (500-700 nm) wavelengths and strongly absorbs short-wave infrared (1000-4000 nm) wavelengths (Hall et al. 2001). The techniques used in the snow mapping algorithms are threshold-based criteria tests that use a combination of reflectance ratios in visible and near infrared wavelengths and a reflectance threshold in the visible and thermal wavelengths. The Normalized Difference Snow Index (NDSI) is defined as,

$$\text{NDSI} = [(\rho_{\text{vis}} - \rho_{\text{NIR}}) / (\rho_{\text{vis}} + \rho_{\text{NIR}})]$$

where ρ_{vis} = MODIS band 4 (545-565 nm)

and ρ_{NIR} = MODIS band 6 (1628-1652 nm) .

A pixel is mapped as snow if the NDSI value is > 0.4 and the reflectance in MODIS band 4 is $\geq 10\%$. However, if the MODIS band 4 reflectance is $< 10\%$, then the pixel will not be mapped as snow, even if the other criteria are met. Reflectance in bands 1 and 2 used to calculate NDVI aid mapping snow in forests, preventing false mapping of snow for beach sand or other light colored mineral surfaces, and evaluation of thermal bands prevent some instances where snow would otherwise be mapped in tropical forests. The multi-step algorithm results in a mean absolute error of less than 10% (Hall et al. 2001, Salomonson and Appel 2004).

6 Pixel-based Processing

The appropriate target spatial extent for computing phenology metrics depends on ecosystem properties and analysis goals that must balance trade-offs between radiometric and spatial resolution. In practice, this requires analysts to decide if phenology and condition metrics will be computed for each pixel, which can be averaged up to the ecosystem scale, or if the spatially averaged pixel values will be used to compute phenology metrics. The specific methods used are described in the SOPs for each network.

Single pixel approaches should be used with caution in low productivity environments. Two characteristics are useful for identifying these environments: (1) phenological metrics are often not returned by pixel-based algorithms, or (2) metrics are returned that have a high degree of spatial variability that does not reflect real landscape differences. When color-coded, this spatial variability results in a speckled or noisy image across areas that should be similar, while in ecosystems with strong signal-to-noise ratios, maps of phenological metrics are typically spatially

consistent and usually only change abruptly across ecosystem boundaries or areas of disturbance.

Timesat software may also be used to compute phenology metrics by pixel which can then be averaged spatially (Jönsson and Eklundh 2002). However the computationally intensive nature of pixel-based analysis limits its use to relatively small geographic areas. As tested in Arches National Park (ARCH), this approach resulted in null values returned for phenology metrics for the majority of pixels in the park because they did not exhibit sufficient annual amplitude for use in the Timesat phenology algorithms. This is further complicated in bi-modal precipitation regimes where precipitation is insufficient in one or both seasons to induce a substantial vegetation response, as happened in late summer 2009 over large areas on the Colorado Plateau. For these reasons, alternatives to the pixel-based approach were developed that group homogenous ground target areas comprising many pixels, which effectively increase the signal to noise ratio.

7 Target Area Processing

A pixel represents the integrated reflectance of all ground components in the pixel's ground "footprint" and to some degree reflectance from adjacent pixels (Tan and Woodcock 2011). In semi-arid environments the range of reflectance intensity between peak of greenness and complete senescence is often small (especially in dry years or sparsely vegetated areas) and can be confused with noise. So, whereas pixel level calculation of phenology metrics is possible in higher productivity environments, a different approach, which we refer to as the target-area method, is needed in arid or sparsely vegetated environments.

For much of CPN analysis the target area

processing sequence will be used. Target areas are typically ecosystem-focused land areas of similar vegetation (biotic) and soil and climate (abiotic) characteristics. The spatial extent of a target area analysis can vary and the areas need not be spatially contiguous.

In contrast to the pixel-based method, which uses individual pixel time-series values to compute phenology metrics, the target area method groups pixels by analysis unit, computes their median or average value at each time step, and then uses the time series of averaged values to determine phenology metrics. The metrics then apply uniformly to all pixels in the analysis unit. These different approaches are needed to address limitations

of scale and radiometric resolution, which play out differently in arid and moist environments. Table 3 presents a comparison of pixel-based and target-area based analyses.

Spatial grouping of pixel values is not a new approach, and remote sensing studies typically use pixel clusters in relatively homogenous ground areas as the base unit of analysis to minimize instrument-induced variability, registration error, and natural variability (eg Turner et al. 2003, Gu et al 2007, Hyer et al. 2012). The CPNs will use target areas based on predominant upland ecosystems. Riparian ecosystems may also be targeted to provide a greenness signal that is dependent primarily on temperature rather than moisture stress (Buyantuyev and Wu 2012). An additional approach that will be explored by the CPNs in the future is the use of clustering algorithms to define groups of pixels based on the phenological characteristics of the data.

Because of the radiometric issues in dry environments, the CPNs will incorporate some form of pixel aggregation into much of the MODIS NDVI processing. The type of grouping depends on the natural resource question being asked, and on the assumption that the grouped data are similar and therefore suitable for reporting as a single analysis unit. The choice to aggregate pixels and the spatial scale of aggregation will be left to analyst discretion. There may be valid questions that require aggregating pixels across heterogeneous vegetation types.

7.1 Ecological site approach to target area processing

To allow integration of data among related

monitoring projects, the CPNs will use the same ecosystem approach for this protocol as the approach being used for two related ground-based monitoring protocols: the upland vegetation monitoring protocols for both networks (Witwicki et al. 2013, DeCoster et al. 2012), and for SCPN’s bird community monitoring protocol (Holmes et al. 2015). By using the same approach to define ecosystems, it will be possible to make comparisons between the monitoring results of each protocol. The ground-based data will inform the MODIS phenology analysis by providing statistically robust, plot-based measures of the abundances of individual plant species, plant functional groups, and tree seedlings and saplings, as well as measures of standing dead herbaceous material, tree mortality, and soil stability. The MODIS phenology data will in turn provide greater temporal context for the ground-based vegetation and bird abundance data, which are collected at a single time during the year, and may not be collected every year.

The approach chosen by the CPNs to identify target ecosystems uses the soil-based concept of ‘ecological sites’. An ecological site is a landscape division with specific physical characteristics that differs from other landscape divisions in its ability to produce distinctive types and amounts of vegetation and in its response to management (Task Group on Unity in Concepts and Terminology 1995). Ecological sites have characteristic soils, hydrology, plant communities, and disturbance regimes and responses (U.S. Department of Agriculture 2003). As defined, ecological sites are not expected to change, and CPNs are using them as strata to define upland target populations. Additionally,

Table 3. Comparison of the advantages of pixel-based and target area-based analysis.

Attribute	Pixel based	Target-area based
Can display phenology patterns at 250m resolution or as spatial anomaly maps	Yes	No
Can graph changes through time, allowing visual comparisons between multiple years	No, in low productivity environments	Yes
Aggregates temporal information at a scale of interest to land managers	Sometimes	Yes
In arid environment, good signal strength for metrics	No	Yes

ecological sites are characterized by state and transition models that describe vegetation dynamics and management interactions with each site. Ecological sites are not explicitly mapped in NRCS soil surveys. Instead, ecological sites are associated with specific map unit components as defined in the NRCS soil data system; those, in turn, are associated with 'map units', which are the finest spatially defined features. Each map unit may contain multiple map unit soil components, and the soil survey includes an estimate of the proportion of each soil component (and therefore ecological site) within a map unit. The methods used to identify target ecological sites and aggregate the MODIS data from them into target groups are described in more detail in the SOPs.

Two additional landscape divisions may be identified in combination with ecological sites. These are divisions based on land management or ownership as well as divisions based on the history of disturbance (usually fire or grazing).

There are not sufficient resources to support ground-based upland vegetation and bird monitoring for all ecological sites present in all park units. Consequently park resource managers and I&M network staff worked together to prioritize ecological sites for ground-based monitoring (Thomas et al. 2006). For each ecological site chosen, the networks have established a spatially distributed set of long term monitoring plots within individual park units. Plot information is collected either on an annual or a rotating basis. All data from these efforts are entered into long term databases and quality control checked, and annual report summaries are provided for metrics.

7.1.1 Riparian ecological sites

Riparian ecosystems, while very limited in size, can play an important role in phenological monitoring in arid environments. Temperate arid upland ecosystems have a complex phenological signal that depends on both growing season length and on water availability during the growing season

(Jenerette et al. 2010, Walker et al. 2012). The southwestern United States has high inter-annual variability in precipitation (Arriaga-Ramírez and Cavazos 2010), a factor that may be responsible for the high variability seen in start and end of season metrics on the Colorado Plateau (Thoma 2011). Riparian ecosystems in non-water limited areas do not exhibit such high variability, and have strong correlation between satellite vegetation indices and temperature (Nagler et al. 2005, Buyantuyev and Wu 2012). Consequently, riparian ecosystems may provide a more constrained estimate of trends or changes in season length that are caused by changes in temperature. Because of the importance of documenting temperature-driven changes in growing season length, the CPNs may include riparian ecological sites as target areas for this protocol. Because of the 250 m MODIS pixel size, target riparian areas selected must have a sufficiently wide expanse of riparian vegetation. Because the absorbing effects of water on infrared light will affect NDVI, the area selected must not be inundated for long periods during the target analysis period (such as adjacent to fluctuating reservoirs). Finally, the riparian area must not be substantially affected by disturbance (floods, insects, fires).

7.1.2 Radiometric resolution

When an image is acquired on film or by a sensor, its sensitivity to the magnitude of the electromagnetic energy determines the radiometric resolution (Tucker 1980). The radiometric resolution describes the ability of an imaging system to detect very slight differences in energy. The finer the radiometric resolution, the more able a sensor is to detect small differences in reflected or emitted energy. In high productivity environments, the strong, unambiguous change in signal strength during the growing season results in large annual amplitudes or "strong signals" that have a range much larger than the sensitivity limits of the sensor. This results in a large signal to noise ratio. In low productivity environments, such as the drier parts of the Colorado Plateau, the amplitude of annual

NDVI curves is small (often < 3 scaled NDVI units, or 0.03 unscaled NDVI units) resulting in “weak signals” (Verbesselt et al. 2010) or a small signal to noise ratio. In Stage 3 validation¹ experiments the sensitivity of 16-day scaled NDVI products was +/- 2.5 scaled NDVI units. The imperfect sensitivity primarily results from variation in atmospheric conditions that affect reflectance in the red band (NASA 2010). This has implications for vegetation phenology monitoring in the CPNs that will be discussed in Figure 4 (shaded box). Although this is the expected result from semi-arid areas with a large proportion of bare ground or exposed bedrock, it makes discerning change over time difficult when temporal change in a weak vegetation signal is near the sensitivity limit of the satellite sensor.

Real but subtle change in vegetation condition can be confounded further by image-to-image misregistration of up to 50 m in any direction (Wolfe et al. 2007). Natural variability decreases with smaller spatial scales, but in low productivity environments, signal variability increases when real change is near the limit of sensor sensitivity. For this reason analysts must balance tradeoffs between analysis scales, spatial heterogeneity, and signal strength from ground targets. Presently this is a subjective evaluation that should be made on an ad hoc basis using iterative approaches, such as the nested analysis scale method described in Figure 4 (shaded box).

7.1.3 Spatial averaging caveats

When high spatial variability is encountered among pixels within a polygon, one should re-examine whether a polygon represents

1 Stage 3 Validation: Uncertainties in the product and its associated structure are well quantified from comparison with reference in situ or other suitable reference data. Uncertainties are characterized in a statistically rigorous way over multiple locations and time periods representing global conditions. Spatial and temporal consistency of the product and with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature (<https://landval.gsfc.nasa.gov/>).

the target of interest, and the possible sources of variability. The algorithms used in this protocol require a minimum range in seasonal amplitude in order to calculate some phenology metrics. If that minimum range is not achieved for a given pixel in any year, those phenology metrics algorithms fail for that pixel for that year. In some CPN parks (eg ARCH) this condition exists for most pixels in dry years (eg 2009). Analysts should typically start by trying to compute pixel-level phenology metrics because the pixel-scale analysis offers the highest degree of spatial resolution. If the phenology metrics cannot be computed at the pixel-scale then analysts may consider the target-area method with the understanding that the spatial resolution will be degraded to the target area. The target-area approach is consistent with the spatial averaging approach used to report data collected from the CPN's ground-based vegetation monitoring protocols, which are not reported as individual plot statistics but are instead aggregated to the ecosystem level. While spatial averaging of pixel values at each time-step is part of the target area analysis process, information concerning unique or interesting outliers within target area boundaries is lost. Thus a-priori knowledge of spatial variability should be considered before using the target area approach.

7.2 Vegetation phenology metrics at landscape scales

When deriving phenology metrics from remote sensors, the measured object is not species, population, or even community-specific phenology, but rather the characteristics of individual pixels or groups of pixels. For this reason satellite derived phenology metrics are classified as Land Surface Phenology (LSP) as opposed to traditional species-centric phenology (de Beurs and Henebry 2010). Within LSP are a variety of potential phenological metrics, most of which have advantages and drawbacks, depending on the ecosystem to which they are applied.

7.2.1 Metric calculation methods

Phenology variables that may be estimated

Figure 4. Optimizing spatial and radiometric resolution: An example of nested analysis scales

Analysis of single pixel NDVI time-series in ARCH indicated that the vegetation signal in the park was much weaker than signals from more productive parts of the landscape (Figures 4a & 4b). This does not imply that there is no measurable temporal signal from arid landscapes, but that small changes in vegetation require working within a smaller range of NDVI. When the working range of annual NDVI is less than 3 scaled NDVI units, the issue of sensor sensitivity becomes apparent. This is because incremental change in low-productivity conditions may be close to the spectral sensitivity limit of the sensor, except during periods of “substantial” change, which may not occur every year in arid environments.

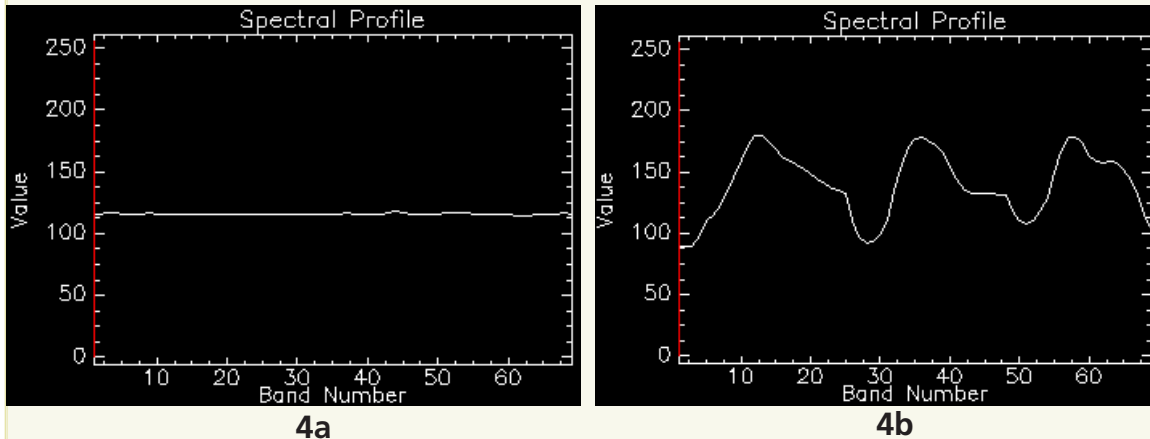


Figure 4a. (left) Three year temporal variation in a single pixel’s NDVI value over time from Arches NP near Moab, UT, and 4b (right) from the La Sal Mountains near Moab, UT, 2000–2002; the y-axis scale obscures minor seasonal fluctuations in the low productivity Arches pixel. For all figures, 4a–4d, 16 days are composited into a band, resulting in 22 bands per year, for a total of 66 bands covering 3 years.

In semi-arid environments, phenology metrics can be misleading if calculated from a single pixel because NDVI fluctuates between scaled integer values during periods of slow change. This complicates the determination of annual events like SOS and EOS. However, when groups of pixels are spatially averaged, seasonal patterns in NDVI typically emerge, providing the expected smooth patterns of seasonal growth and senescence (Figure 4c), even when stimulated by erratic precipitation events. Spatial averaging does not appear to be necessary for higher productivity environments on the Colorado Plateau because the incremental change in vegetation condition between observation periods is enough to induce an unambiguous monotonic change (upward for growth, downward for senescence) in spectral response (Figure 4d).

Meaningless phenology values could arise when insufficient sensitivity coupled with spatial misregistration cause the single-pixel signal from a stable vegetation condition to “bounce around”. Even if a “bouncy” signal from a single pixel is temporally smoothed, the randomness of fluctuations could result in a smoothed signal that does not reflect the timing of real change in vegetation condition.

The targeted ecosystem-based analysis approach reduces variability in the temporal signal and improves the ability to determine the timing of important phenology events. Spatial averaging also increases sample size, and thus, for a given level of variance, increases the statistical power to detect change (Thoma et al. 2008). It is not clear what the “minimum” spatial scale is that should be used for analysis in low productivity environments because an idealized annual signal is a function of sample size and signal amplitude over time. The example in Figure 4c indicates that single pixel time-series would be difficult to evaluate for phenology (due to fluctuations near the limits of sensitivity and perhaps due to misregistration), but the 9 pixel scale provides improved signal characteristics for analysis that is not dramatically different from the 49 pixel signal. Part of the analyst’s decision process will be to consider employing larger analysis footprints with due caution given to including more variable land surfaces as footprint area increases.

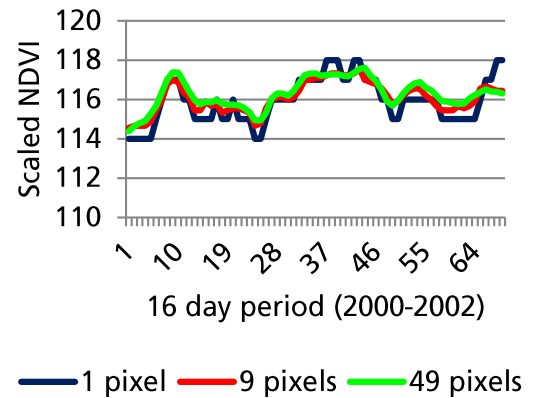
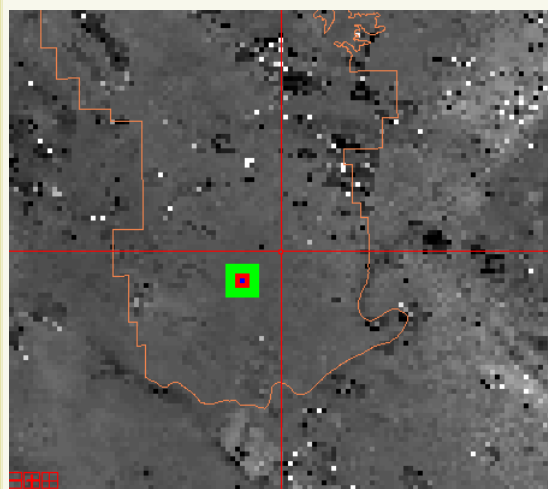


Figure 4c. Nested analysis scales in Arches NP demonstrate how spatial averaging incrementally larger areas centered on the same geographic point can improve the ability to discriminate seasonality in low productivity environments. The left panel shows examples of 1, 9 and 49 pixels around a single point. The right hand panel shows the equivalent NDVI signals for those 1, 9, and 49 pixels, allowing us to see the progression from a very 'noisy' single pixel to a smoother group of 9 and 49 pixels. In these cases we believe that in dryland areas with low signal NDVI signal, the signal to noise ratio will be improved by using small groups of pixels.

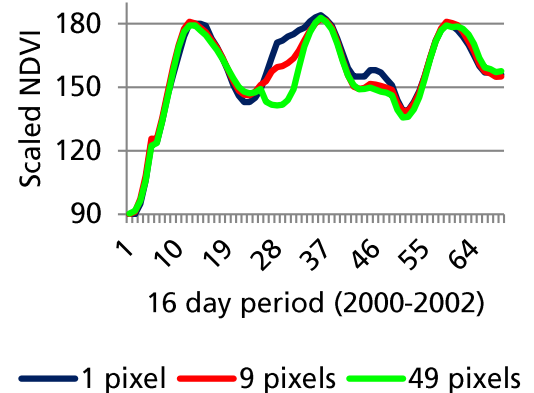
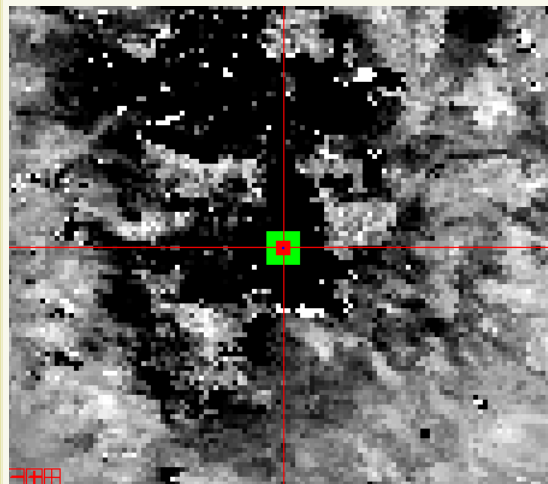


Figure 4d. Nested analysis scales in the high elevation La Sal Mountains demonstrate how spatial averaging in high productivity environments has less effect on the ability to discriminate seasonality than in semi-arid low-productivity environments because the biological change between periods is large enough to induce an unambiguous sensor response. Note the difference in NDVI scale from Figure 4c.

from satellite remote sensing are

- day of the year for the start of the growing season (SOS)
- day of the year of peak growth
- day of the year for the end of the growing season (EOS)

- growing season length (GSL) (White et al. 2009, de Beurs and Henebry 2010, Hudson and de Beurs 2011).

These values all focus on the timing of events. Additional values that are often calculated are

- intensity or amplitude of seasonal events, including the amount of greenup
- peak greenness value
- minimum greenness value
- rate of greenup
- rate of senescence ('browndown')

The various approaches that have been used for calculating phenology metrics from satellite data can be grouped into four types: (1) thresholds, (2) derivatives, (3) smoothing functions, and (4) fitted models (de Beurs and Henebry 2010). Classifying methods into these categories is somewhat arbitrary because some methods use concepts embodied in more than one approach. For example, most approaches described in this protocol incorporate some form of gap filling and smoothing, which may create a fitted curve by using an appropriate mathematical function. The equation for the fitted curve is then used to calculate metrics.

As evidenced by the abundance of methods for deriving LSP it should be apparent that it is a nuanced and challenging task to identify the best method for a given purpose and location. As pointed out by de Beurs and Henebry (2010) and others (White et al. 2009) the quantification of a phenology metric is dependent, not only on the calculation methodology, but also on the characteristics of the target. That is, most metrics predict some aspect of a ground-measured observation well in some biomes but not equally well in all biomes, or under all productivity levels. This is an important point with implications for how phenology metrics can be used by the CPNs and is a reoccurring theme that is addressed by presenting various methods for analysis in the standard operating procedures of this protocol. Although we describe four possible methods for calculating phenology metrics, and give detailed descriptions within the SOPs for two methods, the CPNs do not advocate a particular method.

7.2.1.1 The threshold approach is the simplest and most commonly used methods for determining phenology metrics (de Beurs

and Henebry 2010). This approach uses either a pre-defined or a relative reference value for defining the start of season. Start of season (SOS) is designated once the NDVI value exceeds the threshold in spring and likewise, end of season (EOS) is established when NDVI drops below the threshold in the fall. The duration of time between SOS and EOS defines the length of growing season. Threshold values can be used to define local SOS values, but it is very difficult to determine meaningful threshold values that apply to many pixels across broad areas in environments with different soil background characteristics, or in variable land cover types like those on the Colorado Plateau. Another factor that complicates using absolute threshold values on the Colorado Plateau relates to the bi-modal seasonality in precipitation which results in two distinct growing seasons. A modification of the threshold method that compensates for this factor sets the threshold relative to the maximum annual amplitude of NDVI for each pixel. (Figure 5, Jönsson and Eklundh 2002, 2004).

7.2.1.2. The derivative approach, or inflection point identification, involves evaluating the rate and direction of change between observations. One example is that of Zhang et al. (2003), whose algorithm is based on finding when the curvature of the NDVI time-series changes from one linear stage to another, i.e. from decreasing to increasing or increasing to decreasing sections. The points with maximal curvatures are where the phenology changes phase. The North American Carbon Program estimates MODIS phenological metrics using derivative-based methods in combination with a forced flat winter smoothing that uses the MODIS snow and land surface temperature products to identify time periods with below freezing temperatures (Tan et al. 2011).

7.2.1.3. The curve smoothing approach seeks to identify where the vegetation index (VI) data exhibit a rapid, sustained change. For example, Reed and colleagues (1994) determine SOS by employing a backward-looking moving average. NDVI values are

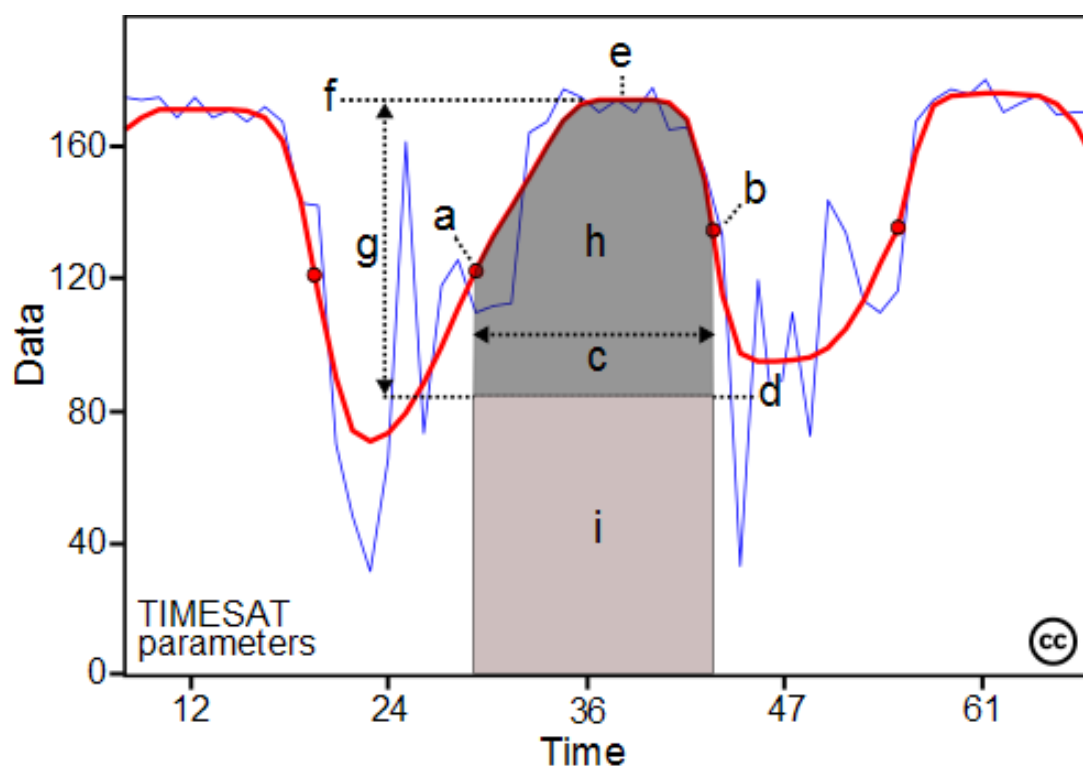


Figure 5. Some of the seasonality parameters generated in TIMESAT: (a) beginning of season, (b) end of season, (c) length of season, (d) base value, (e) time of middle of season, (f) maximum value, (g) amplitude, (h) small integrated value, (h+i) large integrated value (From Eklundh, L. and Jönsson, P. 2015. TIMESAT: A Software Package to analyse time-series of satellite sensor data. Accessed 4 January 2017 from <http://web.nateko.lu.se/timesat/timesat.asp?cat=0>). This figure is licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 2.5 Sweden License.

compared to the average of the previous n observations to identify departures from the established trend. A trend change is defined as when the NDVI values become larger than those predicted by the moving average of the previous n observations. This is one of the methods that has been used by the NCPN for this protocol. However, it has limitations in parts of the Colorado Plateau where vegetation responds erratically to rain events and typically exhibits a bi-modal growing season (de Beurs and Henebry 2010).

7.2.1.4. The fitted model approach approximates the variable and complex patterns in NDVI annual curves. Various model coefficients are derived from the fitted functions that correspond with phenology events. In some cases complex models are used to smooth noisy NDVI curves before using threshold methods to extract phenology

metrics (de Beurs and Henebry 2010, Jönsson and Eklundh 2002).

7.2.2 Snow phenology metrics

Snow phenology metrics are related to temperature, timing of precipitation, persistence of temperatures that sustain snow packs, and the amount of precipitation and temperatures during the spring melt. The snow-specific SOPs in this protocol describe methods to derive the date of persistent snow cover, date of snow cover loss below a user-defined threshold, rate of snow melt, and duration of snow cover. These metrics can be used to help interpret status and trends in vegetation phenology and stream flows that vary with precipitation and temperature.

7.3 Associated climate data

Because of the dependence of vegetation on

climate, it is desirable to obtain precipitation and temperature data at the same time composite steps as the corresponding NDVI series. This makes it possible to evaluate climate drivers together with vegetation response (Frank and Hoffman 1989, Bentz et al. 2010). However, analysts should use caution when interpreting station data with NDVI analysis that may be geographically large and far afield from available stations locations.

7.4 Evolving technology and integrative uses

Technology will continue to change, and it is anticipated that each part of this protocol will be subject to changes and improvements. We anticipate major changes in the coming years, and will respond to these as they develop. Some anticipated changes in Land Surface processing techniques and workflows include

- transition to Visible Infrared Imaging Radiometer Suite (VIIRS) satellite data
- possible development of regional or national data processing workflows
- better methods to report and integrate climate data climate statistics
- methods to allow near-realtime metric calculation and reporting
- methods to use the patterns within the phenological data itself to identify ecologically important spatial patterns

This protocol and/or its Standard Operating Procedures will be revised to reflect these changes as they are made.

7.4.1 Transition to VIIRS

We do not know how long MODIS data will continue to be collected and processed. VIIRS, the anticipated replacement sensor, is already being tested and validated against other datasets, including MODIS. The transition to VIIRS will have a major effect on the processing and reporting of data, as it will change the footprint and lower the spatial resolution of the data (the highest resolution of VIIRS data is 375 m for the bands includ-

ed in NDVI). However, for both MODIS and VIIRS data, there continue to be processing improvements and greater levels of quality control screening.

7.4.2 Workflows at regional or national levels

Whenever possible, we should take advantage of national and regional efforts to report Land Surface Phenology data. Already, some of these efforts provide phenological metrics similar to those described in this protocol. The most advanced of these at the time of this writing is the North American Carbon Project product, called MODIS4NACP (Wolfe et al. 2007), which provides a variety of phenological calculations and accounts for dual peak growing seasons. So far, none of these products accounts for the difficulties in single-pixel processing encountered in arid landscapes, but as this situation changes we expect to take advantage of any streamlined processing made possible by national or regional efforts.

7.4.3 Integration of climate data

Climate and weather play a primary role in determining phenology within and across years. The number of potential climate variables controlling ecosystems is very large, and includes both short and long term conditions, minimums, maximums, frequency of extremes, shifts in average values, and magnification (or minimization) of these effects depending on soils or other local conditions. We are developing scripts to automate water balance calculations and drought duration and precipitation magnitude from weather stations and gridded climate data sets that will be added to this protocol in future updates.

7.4.4 Methods to allow near realtime calculation and reporting

A known difficulty is that many phenological metric calculation methods require not only data to the end of a single season, but a full year of data beyond that to allow curve fitting information to continue into the next season. To deal with this problem, provisional metrics can be created that use this

year's data in place of next year's; however, even these methods cannot provide metric calculation until the end of the calendar year. Many land managers would appreciate information about the timing and intensity of greenness for each season expressed as an anomaly from 'normal' conditions with information current to the most recent week or month.

Researchers are developing methods to address this (for example, see the ForWarn MODIS viewer tool of the Eastern Forest Environmental Threat Assessment Center at <http://www.forestthreats.org/research/tools/forwarn/>). In the coming years, the CPNs will need to consider and adjust the information that is presented in the form of annual reports, trend reports, or regularly updated status pages on the internet.

7.4.5 Choosing spatial groupings by analysis of phenological data

A promising area for further analysis is the use of clustering algorithms to identify patterns in space and time to delineate areas displaying similar phenological characteristics. This methodology has been developed for larger areas called phenoregions (White et al. 2005). It may provide improvements to the aggregation methods based on soil or vegetation map layers by identifying natural breaks in analysis areas or outliers that may represent incorrectly mapped areas.

7.4.6 Analyses outside the scope of this protocol

The interpretation of land surface phenology data is inherently integrative and may be pursued using a variety of methods, each of which may require different phenological metrics calculations. Examples include climate effects modeling, short and long term water-balance modeling, integration with ground-based vegetation data, integration with wildlife migration patterns, integration with wildlife abundance patterns, and integration with insect outbreaks. For each of these, the appropriate temporal scale of phenological metrics varies and may include annual, seasonal, monthly, and daily time scales. Similarly, the appropriate spatial scale of phenological metrics can range from regional scales to park scales to pixel scales. Because the possibilities are so numerous and difficult to predict, a complete description of integrated analysis techniques falls beyond the scope of this protocol, although some examples of likely analyses have been given.

8 Data Management

Data management is a critical component of phenology monitoring as the number of datasets and data diversity will be inherently complex. Data management will be required at two levels: operational and archival.

Operational data management includes the routine acquisition and processing of MODIS data and handling the subsequent data analysis. Archival data management includes handling the databases that will serve as baselines for vital sign monitoring and the long-term data sets that are created during analysis.

8.1 Operational data management

The purpose of operational data management is to organize the pertinent data products for transfer to the archival data management. Secondary concerns will include handling the raw data products from the LP DAAC and NSIDC DAAC, efficient yet conservative management of temporary files, production and storage of analysis files, and deletion of temporary files. The operational data management will be the responsibility of the ecologists, and will include ongoing communication and revision to the process with the data management specialist.

The operational data management will include the following steps:

1. downloading source data
2. implementing the standard data processing scripts
3. conducting data analysis
4. transferring the archival data to data manager

As operational data management will be conducted in a PC environment, a suggested organizational structure for operational data management follows. It is assumed that the primary disk drive will be D:\ in this example:

- D:\CP\MODIS_VI_16day\yyyy
- D:\CP\MODIS_Phenology\yyyy

- D:\CP\MODIS_SNOW_8day\yyyy

where yyyy is the year the data are collected. Each of these file folders is where the primary data processing will take place approximately every month. Under normal conditions, the set of processes should be completed in two to three days.

Because a number of ancillary files are necessary for the routine processing of the snow and vegetation index products, files with the following file extensions will be present within each of the file folders listed above:

- *.txt text documents containing file names for input to data processing scripts
- *.prm parameter files that are necessary for reprojecting files
- *.tif output image files that are to be placed into the data management archive

These files should be maintained in the operational system, but only the *.tif files should be delivered to archival data management.

As mentioned earlier, in addition to the routine data processing, the research ecologists will be conducting exploratory analysis on a regular basis that should not involve data housed in the file folders listed above. A conservative data management structure that does not endanger any of the routinely processed files is recommended. Therefore, for the exploratory data analysis, the following parallel file structure is suggested:

- D:\CP\Analysis\MODIS_VI_16day\yyyy
- D:\CP\Analysis\MODIS_Phenology\yyyy
- D:\CP\Analysis\MODIS_SNOW_8day\yyyy

8.2 Archival data management

Archival data management will be required on all the baseline (standard) data sets, as well as for important intermediate data, such as output from image processing steps that result from resource intensive applications.

The completed data products will be stored long-term as read-only files on the NPS data file servers. These data will be managed by the CPN data managers and will adhere to CPN GIS requirements. These data will be available to CPN NPS staff by using the ArcGIS Manager or by direct access to the data file server. Public access to these files will be by request or may be developed as part of the ongoing process of making NPS data available through data centers. Backup procedures for all data sets should follow the NPS' normal procedures for working files and archived files.

8.3 Documentation

One metadata record per image type will be produced and will meet the Federal Geographic Data Committee (FGDC) Content Standards for Digital Geospatial Metadata (CSDGM). The metadata records should cite this protocol in the 'Larger Work Citation' field.

9 Analysis

9.1 Overview of analysis methods

Although the MODIS image record beginning in 2000 is short, it precedes many of the CPN monitoring programs. Over time it provides the opportunity to analyze trends in seasonal and annual vegetation change (Reed 2006) that may be evaluated with commensurate change observed in other CPN monitoring programs. Satellite image time series provides opportunities to examine both temporal and spatial trends. In the temporal realm for a geographic location we can evaluate seasonal as well as annual vegetation dynamics (for example see Figure 6, Tables 4 and 5). In the spatial realm large image extents enable analysis of spatial patterns that may reflect land use, disturbance or extremes in weather from year to year. In more complex scenarios we could examine the combination of both temporal and spatial dynamics.

The scientific literature provides the foundation for methods of analyzing data generated using this protocol. Most of the descriptive methods for reporting tabular, graphical and statistical outputs used by the CPNs have been developed by others to demonstrate trends in time series and correlations with biophysical variables (Jenerette et al. 2010, White et al. 2009, Wang et al. 2003, Déry et al. 2005).

It is important to recognize the difference in analysis techniques for annual phenology metrics (both vegetation and snow) and continuous time series. Trends in annual metrics can be determined via simple linear regression if the response variance is constant and is linear with time, but residual and variance tests should be performed to verify. If phenological response is not linear with time, other approaches, such as transformations or addition of additional explanatory variables should be considered. Annual phenology metrics are generally not autocorrelated but this assumption should be tested. Phenology trends should always be interpreted in a broad context that considers long-term

weather cycles, disturbance and land use. Analyzing the joint behavior of continuous variables like 16 day NDVI and precipitation require more complex methods, such as cross correlation and lagged regression, that are more advanced and not covered here (Shumway and Stoffer 2011).

A starting point for understanding the data structure of time-series and annual metrics should be via exploratory data analysis. This step is necessary to help identify erroneous or anomalous results that may come about if analysis procedures are not followed properly, or if there are errors in the raw data, or unintentional inclusion of dramatically different land surfaces in an analysis area that is expected to be homogenous. Following evaluation of descriptive summary products, analysts may need to pursue increasingly complex analysis techniques that include aspects of both time and space. Some of these techniques are presented in scripts in the appendices and some examples can be found in the SOPs, but analysts will surely want to expand on the provided scripts as need and interests demand.

It is not the intent to provide a comprehensive suite of analysis tools with this protocol, but rather to discuss potential analytical methods here and provide tools to create summarized and formatted data products that can be used for more sophisticated analysis. Thus analysis scripts are provided to create NDVI summary tables and figures on a seasonal and annual basis (See Appendices). Scripts are also provided in the appendices that summarize precipitation and temperature data binned to conform to image periodicity that can aid the interpretation of changes in the seasonal and annual NDVI values. Output from these scripts is used in statistical analysis of correlation between phenology, NDVI time-series and weather data. Due to the complexity and wide range of questions (various habitat types, spatial and temporal scales) that could be addressed with these data, those analyses to answer

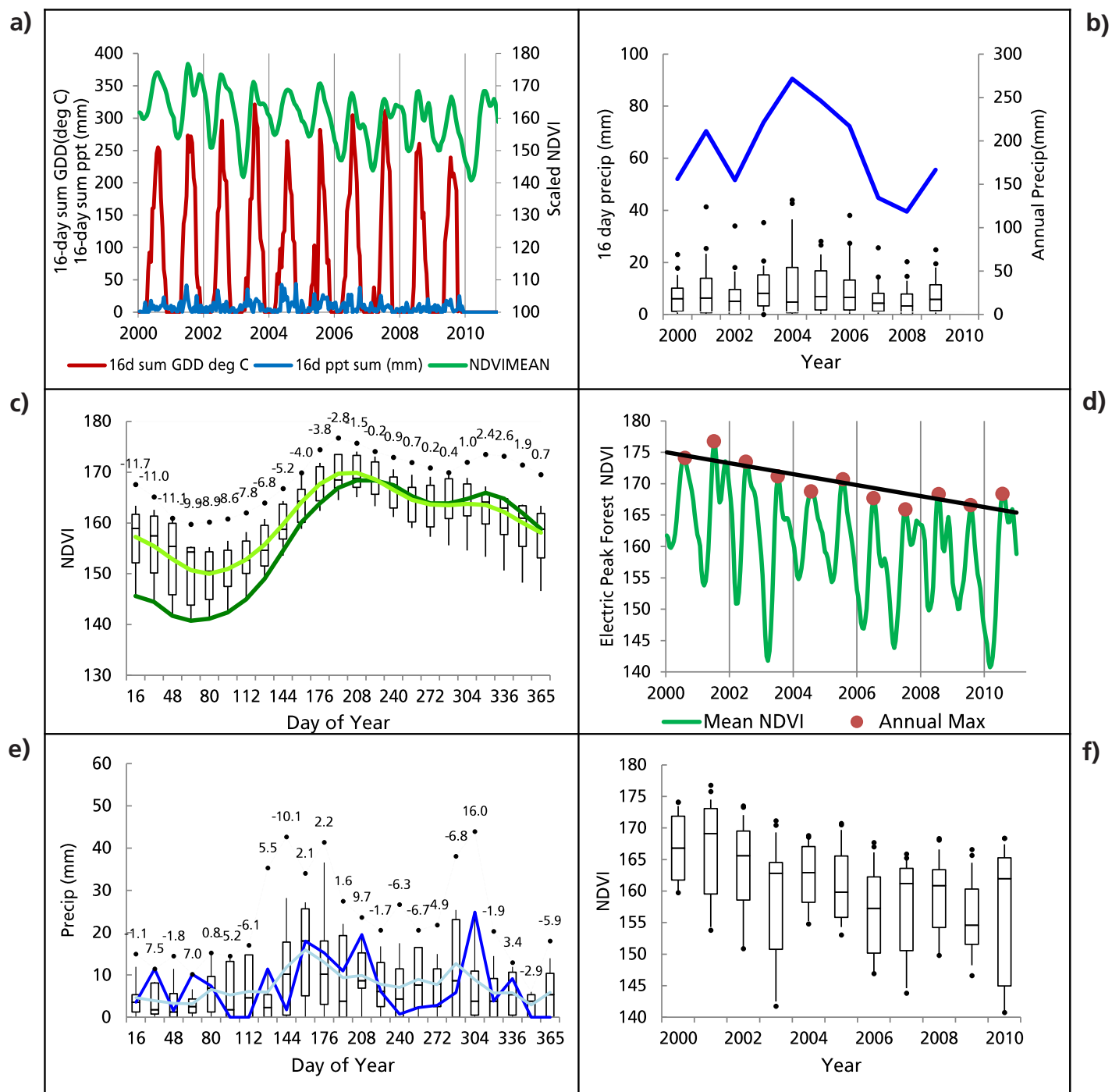


Figure 6. A “dashboard” view of charts created from custom Excel scripts. These data are from a forested area affected by disease. a) time-series showing NDVI seasonal cycles (secondary axis) and corresponding cycles in precipitation (ppt) and growing degree days (GDD) computed from a nearby weather station; b) box plots showing the range in 16-day precipitation totals throughout the year with cumulative annual precipitation as a solid line; c) NDVI in year 2010 versus the long-term average NDVI 2000 through 2010 with box plots showing the range in period NDVI for 2000-2010; difference between current and long term average is indicated in labels above the box plots; d) linear trend in annual NDVI peak value; e) 2010 precipitation and its departure from 2000 to 2010 average binned by NDVI image period for direct comparison with Figure 6c; f) box plots of NDVI by year for the disease affected area, showing the range and central tendency of time series in Figure 6d.

Table 4. Example of Excel script output for NDVI summary statistics from the forested area used in the Figure 6 example.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	166.6	166.8	174.1	159.8	14.37	3832
2001	166.2	169.1	176.8	153.8	22.97	3823
2002	163.9	165.6	173.5	150.9	22.62	3770
2003	158.8	162.8	171.2	141.8	29.39	3652
2004	162.4	162.9	168.8	154.8	14.00	3735
2005	161.1	159.8	170.7	153.1	17.64	3705
2006	156.5	157.3	167.7	146.9	20.78	3600
2007	157.6	161.2	165.9	143.8	22.07	3625
2008	159.6	160.9	168.4	149.8	18.54	3670
2009	155.8	154.6	166.6	146.6	19.97	3583
2010	156.9	162.0	168.4	140.8	27.63	3609

Table 5. Example of Excel script output for NDVI phenology metrics derived from Timesat. The Excel script formats the table and determines linear trend. The statistics are from linear regression of Year as the x-axis variable and other columns as y-axis variable. Additional scripts can automate charting of values in this table. DOY = day of year.

Year	Start (DOY)	End (DOY)	Length (Days)	Peak (DOY)	Integral (NDVI)	Ampl (NDVI)
2000	117	397	280	229	3188	17.28
2001	126	424	299	265	3530	22.82
2002	129	402	273	238	3119	26.33
2003	120	384	264	199	2931	21.45
2004	112	390	278	216	3113	13.88
2005	130	374	245	216	2762	19.46
2006	118	384	266	200	2858	21.34
2007	109	443	335	275	3685	18.32
2008	139	376	236	206	2731	17.27
2009	123	366	243	218	2675	19.59
correlation	0.13	-0.47	0.96	0.83	0.89	0.07
slope	0.37	-1.24	1.18	0.74	11.55	0.00
p-val slope	0.73	0.36	0.39	0.53	0.22	0.43
intercept	-621.34	545.97	-194.94	26.27	447.27	17.61
p-val intercept	0.77	0.33	0.37	0.50	0.20	0.42

specific questions are left to the discretion of ecologists. However, a few examples of integrated NDVI and weather analysis are provided below. Current script examples are provided and updated within the SOP's.

9.2 Temporal analysis

Analyses of change through time can be done using phenological date metrics or

annual, monthly, or seasonal aggregations of vegetation index values and snow cover extent values. Because there are too many possible analyses and covariates to detail here, we present examples of typical analyses.

9.2.1 Vegetation Index

Once per year phenology metrics for both NDVI and snow cover extent can be evaluated for trend via simple linear regression, and

Table 6. Example of Excel script output for snow metrics and statistics. The statistics are from linear regression of Year as the x-axis variable and other columns as y-axis variable. The percentage cover is a user defined threshold. Values in bold are statistically significant when p-value ≤ 0.10 .

Year	Snow off	Snow on	DOY $<6.4\%$ cover	DOY $\geq 6.4\%$ cover	Days snow free	Days snow covered
2000	7/2/2000	9/12/2000	184	256	72	293
2001	6/25/2001	7/27/2001	176	208	32	333
2002	7/4/2002	7/20/2002	184	200	16	349
2003	7/5/2003	10/9/2003	184	280	96	269
2004	7/5/2004	7/21/2004	184	200	16	349
2005	5/19/2005	7/22/2005	136	200	64	301
2006	5/28/2006	10/11/2006	144	280	136	229
2007	5/21/2007	10/4/2007	136	272	136	229
2008	6/30/2008	10/12/2008	176	280	104	261
2009	6/7/2009	10/5/2009	152	272	120	245
2010	6/8/2010	10/14/2010	152	280	128	237
correlation			-0.62	0.55	0.71	-0.71
slope			-3.78	6.18	9.96	-9.96
intercept			7747	-12147	-19893	20258
p-val slope			0.04	0.08	0.01	0.01
p-val intercept			0.04	0.08	0.01	0.01

include correlation and p-values for slopes and intercepts (Tables 5, 6). Seasonal trends can be evaluated via non-parametric methods such as the seasonal Kendall test. From the basic statistics it is possible to generate box and whisker plots and time series plots that indicate differences between historic averages and the current year by day of year (DOY) (Figure 6).

In the following example, persistent decline in maximum annual, as well as seasonal NDVI values tracks tree mortality due to forest disease. The current year seasonal NDVI and precipitation from a nearby weather station is quantitatively compared to the previous 10-year average. The charts show that 2010 was drier than normal early in the season, with above normal mid-year precipitation, and ending with an above normal pulse of precipitation near DOY 304. The above normal mid-year precipitation resulted in late season 2010 NDVI exceeding the long-term average for that time of year.

9.2.2 Snow cover

Snow cover accumulation/depletion curves relate the percent of a basin or zone that

is covered by snow to elapsed time during both the snow accumulation and snow melt seasons. Such curves help provide an indication of the temporal and spatial extent of seasonal snow pack and its potential impact on water resources. A steep decrease in snow-covered area can be indicative of either shallow snow pack or high melt rates. On the other hand, a slow decrease results from either a deep snow cover or slow melt rates most likely due to low temperatures. Plotting snow cover versus growing degree days can help reduce this ambiguity and is possible with output from the customized climate summary scripts.

Scripts are provided within the Appendices to determine the extent and duration of snow cover in time-series. These are called snow ablation curves (Déry et al. 2005). The defined zone could represent an ecoregion, drainage basin, park or some other delineation for which snow covered area would be a meaningful metric. For example, snow duration and extent can be summarized by ecoregion or land cover type within parks (Nowacki et al. 2003) using the 8-day snow cover composites (Figure 7, Table 6).

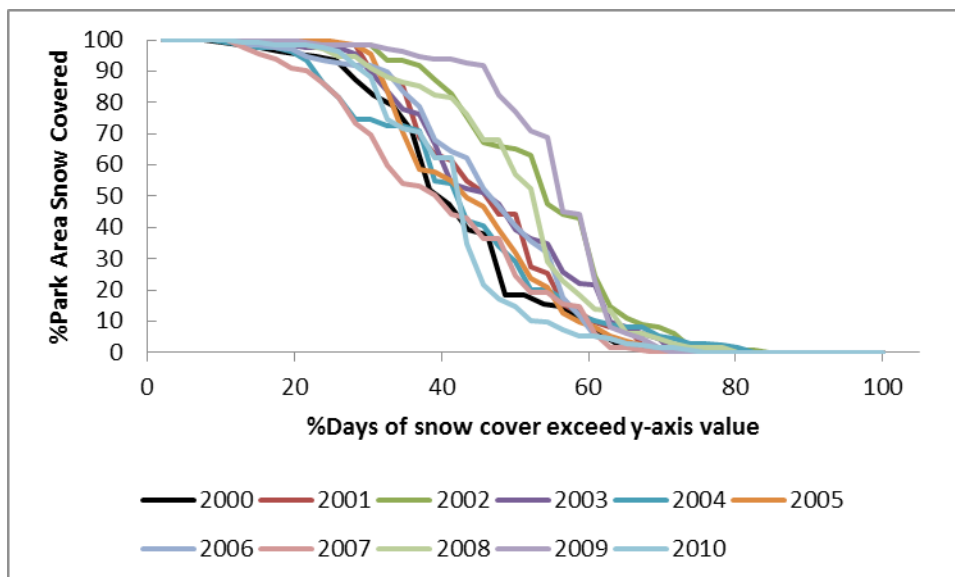
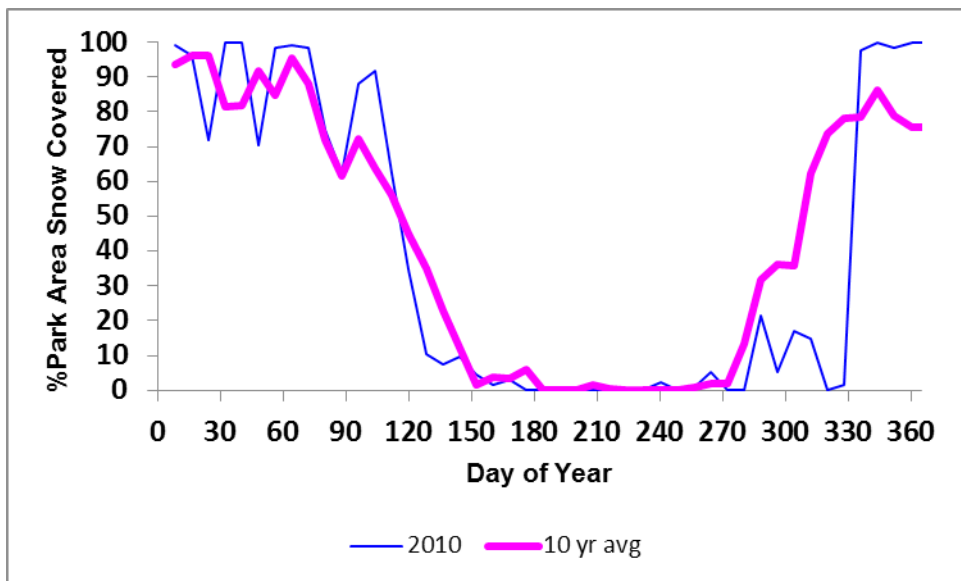


Figure 7. (top) Example snow depletion and accumulation curves created from custom Excel scripts for recent year and long-term average, and (bottom) snow persistence curves on a calendar-year basis. These can also be displayed on a water-year basis for hydrologic applications.

10 Report Types and Schedule

Reporting of monitoring results will change through time and may occur through annual summary reports, multi-year synthesis reports, and online custom or near-realtime reports. Annual reporting may consist of snow cover (dates of first measurable snowfall, establishment of permanent snowpack, beginning of melt, end of melt) and productivity metrics (dates for start and end of season, maximum NDVI, integrated NDVI) for selected study areas determined by the monitoring questions. In addition, spatial variation in these metrics may be recorded (e.g., extent of snow cover) and a range of values provided for each metric across the Network (e.g., variation in date of snow onset across the Network). Any observed anomalies, or any conditions that may confound interpretation of the data, will be noted. Synthesis reports could include results of time-series analyses, graphical representation of selected metrics, and/or mapped regions of change (e.g., areas experiencing a shorter or longer growing season. Table 7 outlines metrics that may be included in annual and multi-year reports. The feasibility of reporting on the metrics and summary statistics that can be generated by SOPs in this protocol has been demonstrated in pilot projects and an annual report that evaluated park-wide trends in NDVI and snow cover with corresponding weather station data (Thoma 2011).

Ancillary data used during data analysis and interpretation and verification may include climate/temperature records, results of other vital signs monitoring conducted by a network, and informal reports from network and park staff.

Table 7. Potential metrics to report for landscape processes vital signs.

Vital sign	Metrics and graphs
Snow cover	For a given park and/or target ecosystem: • date of first measurable snow cover • date of snowpack establishment – onset • date of first measurable snow melt • end of snow melt – snow-free • graph of percent area with snowcover plotted against the day of year • tables and graphs showing multi-year comparisons and/or multi-ecosystem comparisons Across network: • range of snow onset and melt dates across study areas
Productivity	For a given study area or ecosystem: • start of season date • growing days up to maximum NDVI • end of season date • duration of growing season • maximum NDVI • integrated NDVI – ‘large’ and ‘small’ integrals Across the Colorado Plateau: • range of start and end of growing season dates across study areas

11 Personnel Requirements and Training

The implementation of this protocol requires a diverse skill set, including expertise in remote sensing, geographic information systems, data management, and landscape ecology (Tables 8 and 9). A high level of

competence is necessary to implement the protocol and standard operating procedures and maintain them through the initial stages of the project. Once operational, the on-going nature of pre-processing tasks will

Table 8. Tasks and responsible personnel for phenology and snow cover monitoring.

Task	Suggested personnel
Data acquisition: • Routine downloads • Semi-automated preprocessing	Data Technician (0.1 FTE)
Data processing: • Custom processing, enhancements	Ecologist or Remote Sensing Specialist (0.1 FTE)
Data analysis and interpretation: • Manual or automated determination of metrics	Ecologist, with assistance from GIS Specialists, Remote Sensing Specialist, and Statistician (0.2 FTE)
Manual interpretation of metrics: • Spatial analyses • Trend analyses • Data summaries	
Reporting	Ecologist (0.5 FTE)
Data management: • Copy new files to Central Data Server • Manage data formats, directory structure, archiving • Maintain consistent data characteristics and software compatibility with other CPN data sets	Data Manager, GIS Specialist, and Ecologist (0.1 FTE)
Backups	All Users (local) and IT staff (archives)
Minor protocol revisions and documentation	Remote Sensing Specialist and/or Ecologist
Development of alternative processing scenarios: major protocol revisions	RS or GIS staff or similar expertise

Table 9. Initial personnel qualifications for monitoring of landscape processes.

Personnel	Qualifications/Experience
Data Manager	• Experience with data stewardship and developing applications for data analysis
Remote Sensing Analyst	• Extensive experience with MODIS products and specialized software (MODExtract, MODIS Reprojection Tool (MRT), MODIS quality assurance tool - Land Data Operational Product Evaluation (LDOPE)) or MODIS handling tools in R • Experience with image processing, including ENVI or R software • Experience in regional-scale remote sensing applications • Experience in deriving phenology metrics • Experience with time-series analysis
GIS Specialist/Analyst	• Experience in assembling data sets with disparate characteristics (e.g., raster/vector, map projections, data formats) and harmonizing them
Ecologist/Analyst	• Familiarity with CPN landscapes and landscape processes, including field experience • Experience in manual interpretation of satellite imagery and derived products • Ability to synthesize information from multiple data sets to develop summary reports of short- and long-term variation in phenology metrics
Data Technician	• Experience with GIS and data management

become routine. All personnel involved in this protocol should receive professional enhancement training in relevant software on a one to two year schedule. However, an ongoing high level of expertise by ecologists

will be required throughout the duration of this protocol, as data interpretation cannot be automated and novel ways of using the results to address new monitoring questions will invariably arise.

12 Operational Requirements

12.1 Workload/acquisition schedule

Vegetation Index data downloads and processing can be done on an annual basis. For near-realtime reporting, downloads and processing would be automated to run on a more frequent basis. These tasks will require an estimated 7 to 10 days/year. The analysis, interpretation and reporting phases will require approximately 0.5 FTE by the ecologists and remote sensing/GIS specialists combined (see Table 8).

Because these data are processed and stored at their respective archive centers, the timing of data download is not as crucial as in field-based protocols. Nevertheless, maintenance of an up-to-date archive of CP data sets will require adherence to a regular download and processing schedule. Table 10 provides the composite period length and the number of days after the close of the composite period, when products are typically available for download.

12.2 Hardware capability

The current hardware requirements for processing, storage, and analysis of MODIS satellite imagery include a personal computer with a minimum of 2.0 GHZ processor and 2.0 GB or greater of memory. These are minimum requirements; to achieve maximum performance in processing and manipulation of imagery, more powerful processors and memory are necessary. A minimum hard drive capacity of 4 TB is recommended for MODIS processing and storage. These requirements are likely to change through time.

12.3 Software requirements

Software required for the data processing and analysis varies greatly depending on workflow and can be expected to change through time. The CPNs initially pursued a processing workflow using proprietary image processing and geographic information system (GIS) software coupled with special-purpose free software provided by USGS. Further manipulation and summarization of processed data and graphics creation was done using graphics software and spreadsheets with embedded macros. We are now in the process of shifting MODIS data processing to the R software environment as well as much of the summarization and graphing. These workflows, the associated software, and any changes to them will be documented in the SOPs.

Table 10. Approximate timing of when remotely sensed data become available after collection.

Product	Composite Length	Days after collection	Source
Vegetation Index	16-day	5-7	LP DAAC
Vegetation Index	7-day	4-10	EROS
Snow Cover Extent	8-day	3-4	NSIDC DAAC

13 Literature Cited

- Alcaraz-Segura, D., J. Cabello, J. M. Paruelo and M. Delibes. 2009. Use of descriptors of ecosystem functioning for monitoring a national park network: a remote sensing approach. *Environmental Management* 43:38-48.
- Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. T. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. Lim, G. Allard, S. W. Running, A. Semerci and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259:660-684.
- Arriaga-Ramírez, S. and T. Cavazos. 2010. Regional trends of daily precipitation indices in northwest Mexico and southwest United States. *Journal of Geophysical Research:Atmospheres* 115:D14111.
- Badhwar, G. 1984. Use of Landsat-derived profile features for spring small-grains classification. *International Journal of Remote Sensing* 5:783-797.
- Benson, B. J., J. J. Magnuson, O. P. Jensen, V. M. Card, G. Hodgkins, J. Korhonen, D. M. Livingstone, K. M. Stewart, G. A. Weyhenmeyer and N. G. Granin. 2012. Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). *Climatic Change* 112:299-323.
- Bentz, B. J., J. Régnière, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negrón and S. J. Seybold. 2010. Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *Bioscience* 60:602-613.
- Booth, E. L. J., J. M. Byrne and D. L. Johnson. 2012. Climatic changes in western North America, 1950-2005. *International Journal of Climatology* 32:2283-2300.
- Bowers, J. E. 2005. Effects of drought on shrub survival and longevity in the northern Sonoran Desert. *Journal of the Torrey Botanical Society* 132:421-431.
- Buyantuyev, A. and J. Wu. 2012. Urbanization diversifies land surface phenology in arid environments: Interactions among vegetation, climatic variation, and land use pattern in the Phoenix metropolitan region, USA. *Landscape and Urban Planning* 105:149-159.
- Churkina, G. and S. W. Running. 1998. Contrasting climatic controls on the estimated productivity of global terrestrial biomes. *Ecosystems* 1:206-215.
- de Beurs, K. M. and G. Henebry. 2010. Spatio-temporal statistical methods for modeling land surface phenology. Pages 177-208 in I. L. Hudson and M. R. Keatley, editors. *Phenological research*. Springer, Netherlands.
- DeCoster, J. K., C. L. Lauver, M. E. Miller, J. R. Norris, A. E. C. Snyder, M. C. Swan, L. P. Thomas and D. L. Witwicki. 2012. Integrated upland monitoring protocol for the Southern Colorado Plateau Network. NPS/SCPN/NRR-2012/577. National Park Service, Fort Collins, Colorado.
- Déry, S. J., V. V. Salomonson, M. Stieglitz, D. K. Hall and I. Appel. 2005. An approach to using snow areal depletion curves inferred from MODIS and its application to land surface modelling in Alaska. *Hydrological Processes* 19:2755-2774.
- Eklundh, L. and Jönsson, P. 2015. TIMESAT: A Software Package for Time-Series Processing and Assessment of Vegetation Dynamics. In *Remote Sensing Time Series*, eds. C. Kuenzer, S. Dech and W. Wagner, Springer International Publishing. 22, pp. 141-158.
- Frank, A. B. and L. Hofmann. 1989. Rela-

- tionship among grazing management, growing degree-days, and morphological development for native grasses on the Northern Great Plains. *Journal of Range Management* 42:199-202.
- Garfin, G. M., J. K. Eischeid, M. Lenart, K. L. Cole, K. Ironside and N. Cobb. 2010. Downscaling climate projections to model ecological change on topographically diverse landscapes of the arid southwestern United States. Pages 21-44 in C. van Riper III, B. F. Wakeling and T. D. Sisk, editors. *The Colorado Plateau IV: Shaping conservation through science and management*. University of Arizona Press, Tucson, Arizona.
- Geil, K.L., Y.L. Serra and X. Zeng. 2013. Assessment of CMIP5 model simulations of the North American monsoon system. *Journal of Climate* 26: 8787-8801.
- Gonzalez, P., R. P. Neilson, J. M. Lenihan and R. J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography* 19:755-768.
- Gu, Y., J. F. Brown, J. P. Verdin and B. Wardlow. 2007. A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States. *Geophysical Research Letters* 34:L06407.
- Hall, D. K., G. A. Riggs, V. V. Salomonson, J. Barton, K. Casey, J. Chien, N. Di-Girolamo, A. Klein, H. Powell and A. Tait. 2001. Algorithm theoretical basis document (ATBD) for the MODIS snow and sea ice-mapping algorithms. <http://modis-snow-ice.gsfc.nasa.gov/atbd.html>. Hydrological Science Branch, NASA.
- Hicke, J. A., G. P. Asner, J. T. Randerson, C. Tucker, S. Los, R. Birdsey, J. C. Jenkins and C. Field. 2002. Trends in North American net primary productivity derived from satellite observations, 1982–1998. *Global Biogeochemical Cycles* 16:10-1—10-14.
- Holmes, J., M. J. Johnson, C. L. Lauver, J. R. Norris, A. E. C. Snyder and L. P. Thomas. 2015. Habitat-based bird community monitoring protocol for the Southern Colorado Plateau Network. NPS/SCPN/NRR—2015/1041. National Park Service, Fort Collins, Colorado.
- Hudson, D. A. and K. M. de Beurs. 2011. Land surface phenology of North American mountain environments using moderate resolution imaging spectroradiometer data. *Remote Sensing of Environment* 115:1220-1233.
- Huete, A., C. Justice and W. Van Leeuwen. 1999. MODIS vegetation index (MOD 13). Version 3. Algorithm theoretical basis document. Technical report, http://modis.gsfc.nasa.gov/data/atbd/atbd_mod13.pdf. Goddard Space Flight Center, Greenbelt, MD.
- Hyer, E. J., J. S. Reid, E. M. Prins, J. P. Hoffman, C. C. Schmidt, J. I. Miettinen and L. Giglio. 2012. Patterns of fire activity over Indonesia and Malaysia from polar and geostationary satellite observations. *Atmospheric Research* 122:504-519.
- Jenerette, G. D., R. L. Scott and A. R. Huete. 2010. Functional differences between summer and winter season rain assessed with MODIS-derived phenology in a semi-arid region. *Journal of Vegetation Science* 21:16-30.
- Jolly, W. M., R. Nemani and S. W. Running. 2005. A generalized, bioclimatic index to predict foliar phenology in response to climate. *Global Change Biology* 11:619-632.
- Jönsson, P. and L. Eklundh. 2002. Seasonality extraction by function fitting to time-series of satellite sensor data. *IEEE Transactions on Geoscience and Remote Sensing* 40:1824-1832.
- Jönsson, P. and L. Eklundh. 2004. TIMESAT—a program for analyzing time-series of satellite sensor data. *Computers & Geosciences* 30:833-845.

- Kunkel, K. E., D. R. Easterling, K. Hubbard and K. Redmond. 2004. Temporal variations in frost-free season in the United States: 1895–2000. *Geophysical Research Letters* 31(3) doi:10.1029/2003GL018624.
- Liang, X., J. Zhu, K. E. Kunkel, M. Ting and J. X. L. Wang. 2008. Do CGCMs simulate the North American Monsoon precipitation seasonal-interannual variability? *Journal of Climate* 21(17):4424–4448.
- Liu, F., R. C. Bales, M. H. Conklin and M. E. Conrad. 2008. Streamflow generation from snowmelt in semi-arid, seasonally snow-covered, forested catchments, Valles Caldera, New Mexico. *Water Resources Research* 44, W12443, doi:10.1029/2007WR006728.
- Lloyd, D. 1990. A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. *International Journal of Remote Sensing* 11(12):2269–2279.
- LP DAAC. 2016. Land Processes Distributed Active Archive Center. (Accessed 12/18/2016) https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13q1_v006.
- Lundquist, J. and J. Roche. 2009. Climate change and water supply in western national parks. *Park Science* 26(1):31–33.
- Lundquist, J. D., and S. P. Loheide. 2011. How evaporative water losses vary between wet and dry water years as a function of elevation in the Sierra Nevada, California and critical factors for modeling. *Water Resources Research*, 47, W00H09, doi:10.1029/2010WR010050.
- McAfee, S. A. and J. L. Russell. 2008. Northern annular mode impact on spring climate in the western United States. *Geophysical Research Letters* 35, L17701, doi:10.1029/2008GL034828.
- Menzel, A., T. H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kübler, P. Bissolli, O. Braslavská, A. Briede, F. M. Chmielewski, Z. Crepinsek, Y. Curnel, Å. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatzak, F. Måge, A. Mestre, Ø. Nordli, J. Peñuelas, P. Pirinen, V. Remišová, H. Scheffinger, M. Striz, A. Susnik, A. J. H. van Vliet, F. Wielgolaski, S. Zach and A. Zust. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology* 12(10):1969–1976.
- Mitchell, V. L. 1976. The regionalization of climate in the western United States. *Journal of Applied Meteorology* 15:920–927.
- Muhlfeld, C. C., J. J. Giersch, F. R. Hauer, G. Pederson, G. Luikart, D. Peterson, C. Downs and D. Fagre. 2011. Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change* 106(2):337–345.
- Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar and R. R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386(6626):698–702.
- Nagler, P. L., J. Cleverly, E. Glenn, D. Lampkin, A. Huete and Z. Wan. 2005. Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. *Remote Sensing of Environment* 94(1):17–30.
- NASA. 2010. Land team validation, Status for: Vegetation Indices (MOD13). [Available on line at <https://landval.gsfc.nasa.gov/ProductStatus.php?ProductID=MOD13>]
- NOAA. 2004. The North American Monsoon. Reports to the nation on our changing planet. NOAA/National Weather Service. [Available on line at: http://www.cpc.noaa.gov/products/outreach/Report-to-the-Nation-Monsoon_aug04.pdf]
- Nowacki, G. J., P. Spencer, M. Fleming, T. Brock and T. Jorgenson. 2003. Unified ecoregions of Alaska; 2001. USGS-OFR 02-297. U.S. Geological Survey, USGS Alaska Geospatial Data Clearinghouse.

- Pederson, G., S. Gray, C. A. Woodhouse, J. L. Betancourt, D. B. Fagre, J. S. Littell, E. Watson, B. H. Luckman and L. J. Graumlich. 2011. The unusual nature of recent snowpack declines in the North American Cordillera. *Science* 333:332-335.
- Peng, S., S. Piao, P. Ciais, J. Fang and X. Wang. 2010. Change in winter snow depth and its impacts on vegetation in China. *Global Change Biology* 16:3004-3013.
- Piao, S., J. Fang, L. Zhou, B. Zhu, K. Tan and S. Tao. 2005. Changes in vegetation net primary productivity from 1982 to 1999 in China. *Global Biogeochemical Cycles* 19:16 pp..
- Reed, B. C. 2006. Trend analysis of time-series phenology of North America derived from satellite data. *GIScience & Remote Sensing* 43:24-38.
- Reed, B. C., J. F. Brown, D. VanderZee, T. R. Loveland, J. W. Merchant and D. O. Ohlen. 1994. Measuring phenological variability from satellite imagery. *Journal of Vegetation Science* 5:703-714.
- Reed, B. C., M. White and J. F. Brown. 2003. Remote Sensing Phenology. Pages 365-381 in M. D. Schwartz, editor. *Phenology: An Integrative Environmental Science*. Springer Netherlands.
- Rosenberg, N. J. and J. A. Edmonds editors. 2005. *Climate change impacts for the conterminous USA: an integrated assessment*. Springer Netherlands.
- Salomonson, V. V. and I. Appel. 2004. Estimating fractional snow cover from MODIS using the normalized difference snow index. *Remote Sensing of Environment* 89:351-360.
- Schlaepfer, D. R., W. K. Lauenroth and J. B. Bradford. 2012. Ecohydrological niche of sagebrush ecosystems. *Ecohydrology* 5:453-466.
- Schwartz, M. D. 2003. *Phenology: an integrative environmental science*. Springer Netherlands.
- Shumway, R. H. and D. S. Stoffer. 2011. *Time Series Analysis and Its Applications: With R Examples*, third edition. Springer, New York.
- Stephenson, N. L. 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography* 25:855-870.
- Stockli, R. and P. L. Vidale. 2004. European plant phenology and climate as seen in a 20-year AVHRR land-surface parameter dataset. *International Journal of Remote Sensing* 25:3303-3330.
- Swets, D. L., B. C. Reed, J. D. Rowland and S. E. Marko. 1999. A Weighted Least-squares Approach to Temporal NDVI Smoothing. Pages 17-21 in *Proceedings of the 1999 ASPRS Annual Conference: From Image to Information*, Portland, Oregon.
- Tan, B., J. T. Morisette, R. E. Wolfe, F. Gao, G. A. Ederer, J. Nightingale and J. A. Pedelty. 2011. An enhanced TIMESAT algorithm for estimating vegetation phenology metrics from MODIS data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 4:361-371.
- Tan, B. and C. E. Woodcock. 2011. Influence of image registration on validation efforts. Pages 24-34 in J. LeMoigne, N.S. Netanyahu and R.D. Eastman, editors. *Image Registration for Remote Sensing*. Cambridge University Press, Cambridge, United Kingdom.
- Task Group on Unity in Concepts and Terminology. 1995. New concepts for assessment of rangeland condition. *Journal of Range Management* 48:271-282.
- Thoma, D. P. 2011. Remote sensing of vegetation phenology and snow-cover extent in Northern Colorado Plateau Network parks: status and trends 2010. *Natural Resource Technical Report*. NPS/NCPN/NRTR—2011/455. National Park

Service, Fort Collins, Colorado.

- Thoma, D.P., M.S. Moran, R. Bryant, M. Rahman, C.D. Holifield Collins, T.O. Keefer, R. Noriega, I. Osman, S. M. Skrivin, M. A. Tischler, D. D. Bosch, P. J. Starks and C. D. Peters-Lidard. 2008. Appropriate scale of soil moisture retrieval from high resolution radar imagery for bare and minimally vegetated soils. *Remote Sensing of Environment* 112:403-414.
- Thoma, D. P., Munson, S. M., Irvine, K. M., Witwicki, D. L., & Bunting, E. L. (2016). Semi-arid vegetation response to antecedent climate and water balance windows. *Applied Vegetation Science*, 19, 413–429. <http://doi.org/10.1111/avsc.12232>
- Thomas, L., M. Hendrie (ed.), C. Lauver, S. Monroe, N. Tancreto, S. Garman, and M. Miller. 2006. Vital signs monitoring plan for the Southern Colorado Plateau Network. Natural Resource Report NPS/SCPN/NRR— 2006/002. National Park Service, Fort Collins, Colorado.
- Tucker, C. J. 1980. Radiometric resolution for monitoring vegetation. How many bits are needed? *International Journal of Remote Sensing* 1(3):241-254.
- Turner, D. P., W. D. Ritts, W. B. Cohen, S. T. Gower, M. Zhao, S. W. Running, S. C. Wofsy, S. Urbanski, A. L. Dunn and J. Munger. 2003. Scaling gross primary production (GPP) over boreal and deciduous forest landscapes in support of MODIS GPP product validation. *Remote Sensing of Environment* 88:256-270.
- U.S. Department of Agriculture. Natural Resource Conservation Service. 2003. Chapter 3, Section 1: Ecological Sites for Rangeland and Forest Land. in *National range and pasture handbook*. U.S. Department of Agriculture, Washington D.C.
- Verbesselt, J., R. Hyndman, G. Newnham, and D. Culvenor. 2010. Detecting trend and seasonal changes in satellite image time series. *Remote Sensing of Environment* 114(1):106-115.
- Walker, J. J., K. M. de Beurs, R. H. Wynne and F. Gao. 2012. Evaluation of Landsat and MODIS data fusion products for analysis of dryland forest phenology. *Remote Sensing of Environment* 117:381-393.
- Wang, J., P. M. Rich and K. P. Price. 2003. Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *International Journal of Remote Sensing* 24: 2345–2364.
- Weiss, J. L., C. L. Castro and J. T. Overpeck. 2009. Distinguishing pronounced droughts in the southwestern United States: Seasonality and effects of warmer temperatures. *Journal of Climate* 22:5918-5932.
- White, M. A., P. E. Thornton and S. W. Running. 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles* 11:217-234.
- White M. A., F. M. Hoffman, W. W. Hargrove, and R. R. Nemani. 2005. A global framework for monitoring phenological responses to climate change. *Geophysical Research Letters* 32, L04705, doi:10.1029/2004GL021961.
- White, M. A., K. M. de Beurs, K. Didan, D. W. Inouye, A. D. Richardson, O. P. Jensen, J. O’Keefe, G. Zhang, R. R. Nemani, W. J. D. van Leeuwen, J. F. Brown, A. de Wit, M. Schaepman, X. Lin, M. Dettinger, A. S. Bailey, J. Kimball, M. D. Schwartz, D. D. Baldocchi, J. T. Lee and W. K. Lauenroth. 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology* 15:2335-2359.
- Williams, A. P., C. D. Allen, C. I. Millar, T. W. Swetnam, J. Michaelsen, C. J. Still and S. W. Leavitt. 2010. Forest responses to increasing aridity and warmth in the

southwestern United States. Proceedings of the National Academy of Sciences 107:21289-21294.

- Williams, A. P., C. D. Allen, A. K. Macalady, D. Griffin, C. A. Woodhouse, D. M. Meko, T. W. Swetnam, S. A. Rauscher, R. Seager, H. Grissino-Mayer, J. S. Dean, E. R. Cook, C. Gangodagamage, M. Cai and N. G. McDowell. 2012. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* 3:292-297.
- Williams, J. W. and S. T. Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology & the Environment* 5:475-482.
- Witwicki, D. L., Munson, S. M., & Thoma, D. P. (2016). Effects of climate and water balance across grasslands of varying C 3 and C 4 grass cover. *Ecosphere*, 7:e01577.
- Witwicki, D., H. Thomas, R. Weissinger, A. Wight, S. Topp, S. Garman, and M. E. Miller. 2013 Integrated Upland Monitoring Protocol for the Park Units in the Northern Colorado Plateau Network. Northern Colorado Plateau Network Unpublished Report. Moab, Utah.
- Wolfe, R. E., F. Gao, J. T. Morisette, G. A. Ederer and J. A. Pedelty. 2007. Improving access to MODIS biophysical science products for NACP investigators. *IEEE International Geoscience and Remote Sensing Symposium*. Pages 1012-1015.
- Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, J.C.F. Hodges, F. Gao, B. C. Reed, and A. Huete. 2003. Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment* 84:471-475.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

National Park Service
U.S. Department of the Interior



Natural Resource Stewardship and Science

1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov