



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



ON THE COVER

The “blue marble” image generated from the MODIS sensor on the Terra Satellite. Viewed from space, the Colorado Plateau (at image center) reveals a rust-red appearance that represents its unique geographic provenance, sparse vegetation cover, and both the challenge and promise of remote sensing in semi-arid landscapes (<http://visibleearth.nasa.gov/>).

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Executive Summary

Remote sensing of vegetation condition and snow extent provides information essential to understanding and managing change at broad scales by describing important aspects of ecological and hydrological processes that have cascading effects on other natural resources. The spatial and temporal pattern of satellite-derived NDVI (Normalized Difference Vegetation Index), or “greenness,” and vegetation is indicative of long-term climate conditions to which vegetation on the Colorado Plateau have adapted. NDVI also responds to short-term changes in weather and cycles annually with seasons. Changes in precipitation and temperature may cause changes in the spatial distribution of vegetation over time, and changes in NDVI may imply a response to changing climate or changing land condition brought about by human activities or natural disturbance.

For this report, MODIS snow-cover extent and NDVI image products from 2000 through 2009 were processed and analyzed for 16 national park units on the Northern Colorado Plateau. Significant NDVI image-processing steps involved masking for clouds, aerosols, and snow, then smoothing annual curves with weighted least-squares regression. NDVI summary statistics were determined at the park scale, as were weather station data where they were available. NDVI time-series data were used to calculate phenology metrics with Timesat software. Areal snow-cover extent was determined as a percentage of park area covered by snow at eight-day intervals. Temporal trend analysis at the park scale was determined via linear regression for phenology and snow-cover metrics.

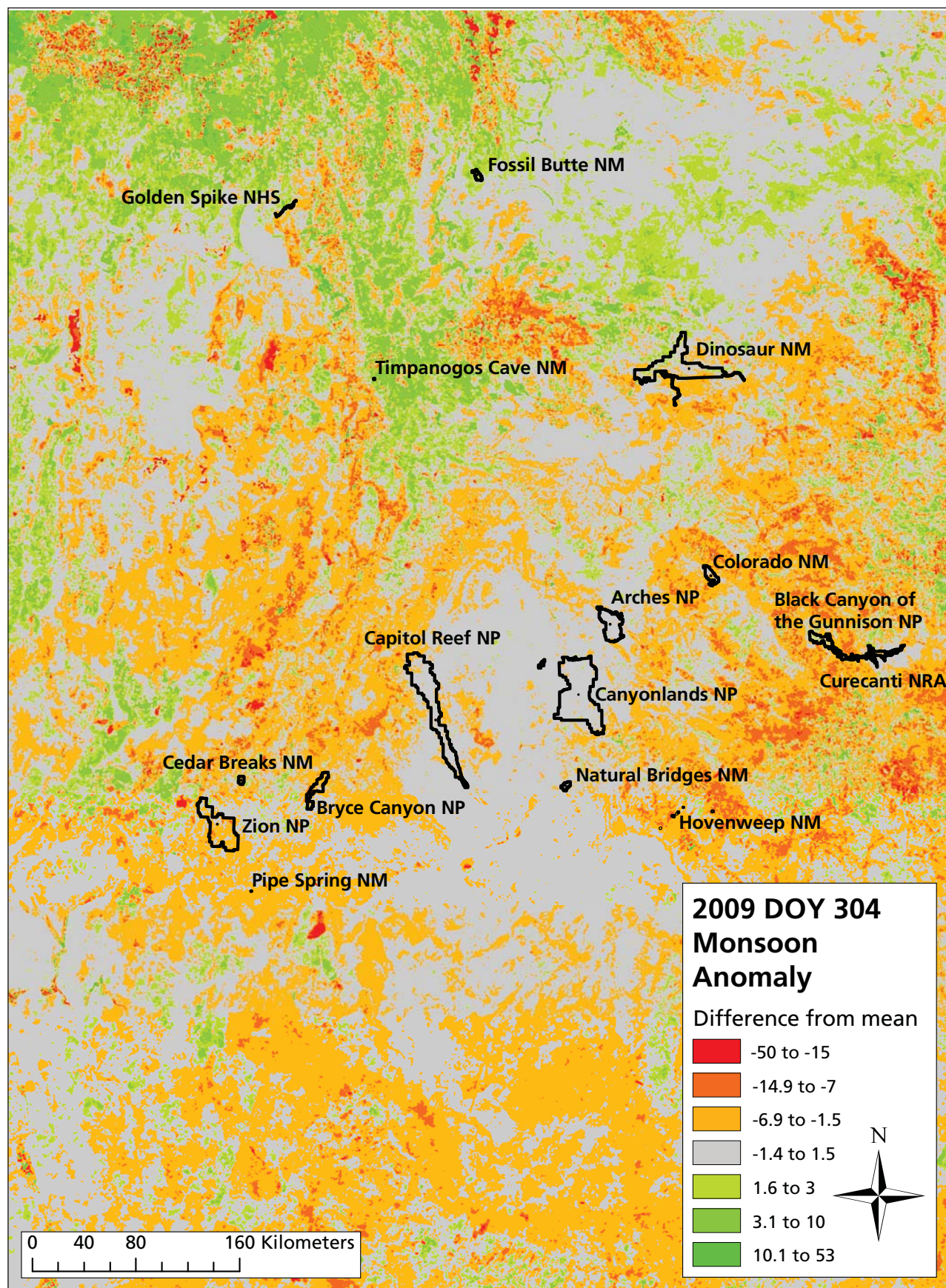
Relationships between precipitation abundance and timing, as well as temperature, with NDVI were apparent for most parks where NDVI response mirrored, but lagged precipitation by 2–4 weeks, depending on season. The importance of winter soil-moisture recharge was made apparent by below-normal NDVI in years of lower-than-normal winter precipitation. There were clear spatial trends in the 2009 monsoon NDVI anomaly (see map, next page), both within parks and across the Colorado Plateau, likely related to monsoon storms tracking a more northerly direction than in previous years. Trends in NDVI and snow cover (p -value < 0.10) at the park scale were inconsistent in direction and generally weak, which is not unexpected for a short, 10-year record across disparate parts of the Colorado Plateau landscape—even if significant change may have occurred.

In this report, statistical significance does not imply biological or physical significance. This is because “step-trends” can occur, in which several years of consistent values might be followed by a “jump” to a different, but equally consistent value for several years. Step trends are expected with quasi-periodic fluctuations in climate that tend to cycle at irregular intervals of between two and seven years.

The most frequent trends in phenology were for (1) end-of-season date, which came earlier at three parks (Capitol Reef National Park, Colorado National Monument, and Hovenweep National Monument) and later at two parks (Golden Spike National Historic Site and Dinosaur National Monument); and (2) day of peak NDVI, which came later at three parks (Arches National Park, Black Canyon of the Gunnison National Park, and Dinosaur National Monument) and earlier at one park (Natural Bridges National Monument) (see table, page xvii).

The most frequent trends in snow cover were for (1) day of complete snowmelt, which came later for two parks (Bryce Canyon National Park and Golden Spike National Historic Site), and (2) number of snow-free days, which increased for one park (Canyonlands National Park) and decreased for another (Curecanti National Recreation Area). A statistically significant inverse relationship between day of snowmelt and start of growing season occurred for two parks (Arches National Park and Natural Bridges National Monument).

The processing steps for analysis of NDVI, phenology, and snow-cover extent, as well as linear trend assessments, have been automated. This makes it possible to use this report as a proof-of-concept that should stimulate more informed analysis by vegetation type, land use, or other unit of interest. Some of the potential uses and challenges of MODIS data are identified in the conclusions of this report.



Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31).

Statistically significant linear trends in phenology and snow cover for NCPN park units, 2000–2009.

NDVI phenology							Snow-cover extent			
Park	SOS	EOS	LOS	DMAX	I-NDVI	A-NDVI	Snowmelt	First snowfall	Days snow-free	Days snow-covered
ARCH				L (spg)						
BLCA				L						
BRCA							L			
CANY								E	F	M
CARE		E								
CEBR										
COLM		E (spg)								
CURE									M	F
DINO	L (spg)	L (spg)		L (spg)						
FOBU										
GOSP		L (spg)	M (spg)		M (spg)		L			
HOVE		L (spg) E (mon)	F (mon)	L (spg)	F (mon)					
NABR				E						
PISP										
TICA										
ZION										

See page xviii for park acronyms.

E = significant trend occurring earlier

F = fewer days/units

L = significant trend occurring later

M = more days/units

spg = trend limited to spring season

mon = trend limited to monsoon season

SOS = start of season; EOS = End of Season; LOS = Length of Season or SOS – EOS; DMAX = day of year when maximum NDVI value observed; I-NDVI = integrated area under the annual NDVI curve; A-NDVI = amplitude of annual NDVI curve; Snowmelt = day of year when area becomes snow free in spring; First snowfall = day of first snowfall; Days snow-free = count of days when snow does not cover ground; Days snow-covered = count of days when snow covers ground; SOS vs melt DOY = slope of regression line for SOS regressed on DOY when snowmelt s in spring.

Acronyms

General acronyms and abbreviations

A-NDVI	amplitude of annual NDVI curve
AZ	Arizona
CO	Colorado
DMAX	day of year when maximum NDVI observed
DOY	day of year
EOS	end of senescence (day of year when senescence ends)
EROS	Earth Resources Observation and Science
EVI	Enhanced Vegetation Index
GDD	growing degree days
I-NDVI	Integrated area under the annual NDVI curve
LOS	length of season (in days)
LPDAAC	Land Processes Distributed Active Archive Center
m	meters
MODIS	Moderate Resolution Imaging Spectrometer
MVC	Maximum Value Composite
NACP	North American Carbon Project
NASA	National Aeronautics and Space Administration
NCPN	Northern Colorado Plateau Network
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NHS	national historic site
nm	nanometer
NM	national monument
NP	national park
NPS	National Park Service
NRA	national recreation area
NWS	National Weather Service
SCPN	Southern Colorado Plateau Network
SOP	standard operating procedure
SOS	start of season (day of year when growing season starts)
USGS	U.S. Geological Survey
UT	Utah
WY	Wyoming

NCPN park units

ARCH	Arches National Park
BLCA	Black Canyon of the Gunnison National Park
BRCA	Bryce Canyon National Park
CANY	Canyonlands National Park
CARE	Capitol Reef National Park
CEBR	Cedar Breaks National Monument
COLM	Colorado National Monument
CURE	Curecanti National Recreation Area
DINO	Dinosaur National Monument
FOBU	Fossil Butte National Monument
GOSP	Golden Spike National Monument
HOVE	Hovenweep National Monument
NABR	Natural Bridges National Monument
PISP	Pipe Springs National Monument
TICA	Timpanogos Cave National Monument
ZION	Zion National Park

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1 Introduction

Broad-scale vegetation condition and snow-cover extent are important ecological factors that respond to climate and support other ecosystem processes and functions. The ability to efficiently monitor such important elements with satellite remote-sensing techniques over vast areas provides new ways of understanding spatial patterns and temporal change available in no other way. Furthermore, the information obtained from this monitoring provides a broader context for understanding other vital sign dynamics, thereby improving our ability to manage complex interactions and proactively avert undesirable consequences (Alcaraz-Segura et al. 2009; Peng et al. 2010).

For the Northern Colorado Plateau Network (NCPN), the large areas and remote character of some national parks, plus the freely available and frequent global coverage of image products, make monitoring these important ecosystem variables from satellite platforms especially appealing. Additionally, satellite remote sensing has a data record that precedes most current vital signs monitoring and can be linked with climate data to help us understand broad-scale and long-term relationships between vegetation and snow patterns and local and regional climate.

Climate change may result in warmer temperatures, decreased precipitation, and longer droughts on the Colorado Plateau (Garfin et al. 2010). Such changes would likely affect vegetation and snow dynamics, which may in turn have a cascading effect on ecosystem productivity, timing and amount of runoff, erosion, fires, floods, and exotic-species spread. Understanding the relationship between vegetation condition, snowpack dynamics, and affected resources gives managers tools to more effectively manage for resilience and resistance, both spatially and temporally. Understanding these relationships at multiple scales should provide impetus for cooperation in land management beyond park boundaries.

1.1 Scope

The scope of this report is limited to a parkwide descriptive analysis of temporal snow cover and Normalized Difference Vegetation Index (NDVI), based on weather-station observations from a single point in each park summarized for the same duration and time step as NDVI imagery. The weather data provide a means of interpreting the NDVI at a coarse level and are used to imply, but not quantify, cause-and-effect relationships between precipitation and vegetation productivity. Determining causal mechanisms and relationships could potentially be useful in scenario planning and management and could be a logical outgrowth of this exercise. As a demonstration of capability, the relationship between snowmelt and start of season was determined for each park unit. It is possible to investigate other relationships between vegetation condition and landscape attributes, and with input from park staff, the most important relationships can be identified for further analysis.

1.2 Goals

The goals of NCPN monitoring of vegetation condition and snow-cover extent are to:

- 1) Determine variability and long-term trends in the timing and duration of snow cover (establishment of snowpack; snowmelt);
- 2) Determine variability and long-term trends in growing-season metrics (e.g., start and end of season; duration; productivity);
- 3) Demonstrate qualitative patterns of precipitation and vegetation response; and
- 4) Demonstrate qualitative patterns in snow-cover extent and vegetation response,

at multiple scales. This initial report demonstrates our capability to achieve these goals, starting at the park scale.

2 Methods

2.1 MODIS overview

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra satellite has provided 36 bands of multispectral data for Earth's entire surface every 1–2 days since it was launched by NASA in December 1999. The image scans, 2,330 km wide, are collected at approximately 10:30 a.m. local time in a north-to-south overpass. Data are downloaded from the satellite to processing centers, where geolocation, cloud-screening, and land-image products are generated for distribution to the science community by the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Land Processes Distributed Active Archive Center (LP-DAAC) and by the National Snow and Ice Data Center. The MODIS products, created at 250-m pixel resolution for vegetation and 500-m pixel resolution for snow cover, are pre-processed to provide consistency for spatial and temporal comparisons by accounting for variation in sun-angle, cloud, and atmospheric influences. An important byproduct of the pre-processing is quality assurance metadata that can be used to help interpret image products (Huete et al. 1999).

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. Those measurements can then be used to adjust reflectance in other wave bands of primary interest to ecologists, in order to simulate what reflectance would be at the ground surface if it was 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 led to automated image processing, which minimizes human bias and issues of continuity in processing—both important considerations in long-term monitoring. The NDVI products used in this report are MOD13Q1, Version 5, Validated Stage 2, meaning that accuracy has been validated over a wide range of ground targets over time, making the data ready for scientific use (LPDAAC 2010). The snow cover products are MOD10A2-V5 (Hall et al. 2006).

2.2 Compositing and temporal resolution

Clouds and their shadows often obscure clear views of Earth's surface and 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 during image processing. Mechanically, cloud removal is accomplished by evaluating, on a pixel-by-pixel basis, multiple images collected over a fixed time interval. The maximum-value pixels are compiled into a new composite image, called the Maximum Value Composite (MVC), which represents the maximum value for the time interval. So, although images are collected daily, land surface process analysis in this report is done using the MVC that represents fixed time blocks of 16 days for vegetation products and 8 days for snow-cover products.

2.3 Spatial resolution

The NDVI product pixel resolution analyzed in this report is 250 m, with an estimated ± 50 m registration error. 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. Additional specifications are shown in Table 2-1.

2.4 Theory

Index calculation relies on minimizing the influence of atmospheric conditions, such as clouds, aerosols, and snow cover. NDVI is a continuous variable between -1 and 1, whereas the index for snow cover is binary (0 or 1). The compositing process for vegetation products results in a continuous range of potential maximum values during a compositing interval. Alternatively, the compositing process for snow-cover products results in a maximum area of snow cover, because if a pixel is snow-covered on only one day of the compositing interval, it is mapped as a snow-covered pixel for the entire interval. Pixels in the vegetation product that were influenced by snow,

Table 2-1. MODIS product technical specifications.

Product name	Band ¹	Bandwidth (nm)	Spatial resolution (m)	Temporal resolution (days)	Key use
NDVI (MOD13Q1-V5)	1 (red)	620–670	250	16	vegetation / chlorophyll
	2 (nir)	841–876	250	16	clouds / vegetation
Snow extent (MOD10A2-V5)	4 (vis)	545–565	500	8	green vegetation
	6 (swir)	1,628–1,652	500	8	snow / cloud differences
250m 16 days VI Quality detailed QA			250	16	masking poor quality NDVI pixel values

¹ red = red wave band, nir = near infrared wave band, vis = visible wave band, swir = short wave infrared. Availability of all products is February 24, 2000–present.

as identified in the data reliability layer, were removed before NDVI statistics were processed to avoid confounding change in NDVI with dynamic and highly variable changes in snow cover.

2.4.1 Vegetation

The basis for differentiating green vegetation from non-vegetated surfaces relies on strong absorption of red (600–700-nm) wavelengths by photosynthetically active pigments and strong reflectance of near-infrared (700–1,100-nm) wavelengths by internal leaf-and-canopy structures (Huete et al. 1999). Increasing amounts of green vegetation in a pixel increase the contrast between red and near-infrared reflectance. The Normalized Difference Vegetation Index exploits this contrast as a ratio, defined as:

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}$$

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 either as grayscale or in color, but first must be scaled to a range more easily displayed in color images using the following equation: 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 previously 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 typically ranges between

120 and 170. The sensitivity of 16-day scaled NDVI products is +/- 2.5 scaled NDVI units. The imperfect sensitivity primarily results from variation in atmospheric conditions that affect reflectance in the red band (NASA 2010).

2.4.2 Snow cover

Snow strongly reflects visible (500–700-nm) wavelengths and strongly absorbs shortwave infrared (1,000–4,000-nm) wavelengths (Hall et al. 2001). Therefore, the techniques used in 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:

$$NDSI = \frac{\rho_{vis} - \rho_{nir}}{\rho_{vis} + \rho_{nir}}$$

where ρ_{vis} = MODIS band 4 (545–565 nm) and ρ_{nir} = MODIS band 6 (1,628–1,652 nm).

A pixel is mapped as snow if the NDSI value is >0.4 and the reflectance in MODIS band 4 is ≥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 snow-mapping in forests and prevent false mapping of snow for beach sand or other light-colored mineral surfaces. Evaluation of thermal bands can prevent snow from being mapped in tropical forests. The multi-step algorithm results in mean absolute error of less than 10% (Hall et

al. 2001; Salomonson and Appel 2004). The root mean square errors for MOD10A1 binary and fractional snow cover were 0.35 and 0.26, respectively, with ranges of 0.18–0.51 and 0.14–0.39 (Rice et al. 2010).

2.5 Image acquisition and processing

As they become available, the NCPN downloads and processes composited vegetation data products (MOD13Q1). These data are distributed by the LPDAAC, located at the USGS EROS Center (lpdaac.usgs.gov). Snow-cover data products (MOD10A2) (Salomonson and Appel, 2004; Hall et al. 2006) are distributed by the National Snow and Ice Data Center (NSIDC, <http://nsidc.org/data/mod10a2v5.html>).

Data are first mosaicked into a continuous image for the Colorado Plateau. Poor-quality pixels influenced by clouds are masked. Data are then projected from a sinusoidal to UTM coordinate system. Images are layered in annual stacks for smoothing; this eliminates masked values by substituting temporally interpolated values, using a weighted least-squares approach (Swets et al. 1999). The process of smoothing vegetation data is intentionally biased toward high NDVI values because cloud- and aerosol-influenced pixels typically have reduced NDVI values relative to non-influenced pixels.

The first MODIS vegetation data became available with day-of-year (DOY) 49 in year 2000, after initial testing and validation of sensor operation. The first snow data became available with DOY 64 in year 2000. Processing scripts used in this report rely on the availability of regularly spaced sequential imagery for smoothing NDVI. For this reason, the first three MVCs from 2001 were copied into the 2000 image directory, to “round out” or complete the temporal sequence of NDVI imagery available for smoothing in 2000. This has minimal impact on year 2000 NDVI statistics because little change in vegetation greenness is expected at this time of year in most parts of the Colorado Plateau. No image substitution was made for missing snow imagery in early 2000; rather, blank placeholders for missing imagery were used, because no smoothing algorithm is applied to the binary snow-cover variable.

2.5.1 Analysis units

The results in this first annual report are presented as average values for the entire area of each

park. For this report, the analysis unit is all land area within park boundaries, as defined by the spatial extent of rasterized park-boundary polygons at 250-m resolution. Pixel values within park boundaries were extracted from time-series image stacks and averaged to become the basic unit of NDVI information used in statistical analysis. The sum of snow-covered pixels was converted to area within park boundaries at each time-step to become the analysis unit for snow-cover extent statistics.

2.5.2 Effect of analysis unit size

Pre-processing imagery helps to mitigate factors that confound change detection caused by variation in clouds, aerosol, and snow, but some post-processing noise will inevitably affect analysis. This is partly related to imperfect image-to-image registration (± 50 m), which can be mitigated by spatially averaging over larger areas: the smaller the analysis unit, the greater the effect of misregistration on calculated mean values in heterogeneous areas.

This caveat has implications for the sparsely vegetated surfaces common on the Colorado Plateau. Successive satellite pixels measure reflectance from ground units that may be offset by up to 50 m in any direction between image acquisitions. In small parks (e.g., Hovenweep and Pipe Spring national monuments), the small number of pixels used in analysis will likely have larger variability in short temporal sequences due to image-to-image misregistration. The effects of noise are reduced in larger parks, where many pixels are spatially averaged at each time-step, but this parkwide averaging necessarily mixes distinct differences expected from distinct spatial patterns of vegetation. It is important to note that analysis can be made for spatial units of management interest that may extend well beyond boundaries for small parks and may consist entirely of selected vegetation types within boundaries for larger parks. The analysis scale depends more on the question of interest than the extent of park boundaries.

2.5.3 Censoring NDVI imagery for contamination by snow, aerosols, and clouds

Software tools provide a means to mask poor-quality pixels influenced by snow cover, aerosols, and clouds. The masking was carried out using the LDOPE processing tools provided by the

MODIS land quality assessment group (Roy et al. 2002). Specifically, the Vegetation Index Quality layer provided with each NDVI image file was evaluated for low-quality pixels in which aerosol quantity = “high,” mixed clouds = “yes,” and possible snow ice = “yes” were masked, or eliminated from analysis.

2.6 Climate-data processing

Daily climate data from weather stations in or near parks were aggregated, where available, to match the 16-day interval used for image compositing. Daily precipitation was summed for 16-day intervals, whereas daily maximum and minimum temperatures were used to determine cumulative growing degree days (GDD) for each 16-day interval. GDDs are often used in vegetation studies to evaluate the influence of cumulative heat available to support plant metabolism (Sun et al. 2008; Wang et al. 2003). Growing degree days are calculated as:

$$GDD = \left(\left\lfloor \frac{T_{max} + T_{min}}{2} \right\rfloor - T_{base}, 0 \right)$$

where T_{max} is daily maximum temperature, T_{min} is daily minimum temperature, and T_{base} = temperature below which growth essentially ceases. T_{base} was defined as 4.44°C (40°F).

$T_{max} - T_{min} / 2$ is the daily average temperature. If daily average temperature is less than T_{base} , then no growth occurs. GDD is set to zero if the result is negative.

2.7 Anomaly mapping

Anomaly is defined as the difference between a recent observation and the historical average. In this report, the 2009 NDVI anomaly was computed on a per-pixel basis as:

$$Anomaly_{2009} = NDVI_{2009} - \sum_{i=2000}^{2008} NDVI_i / (n)$$

where $NDVI_i$ = NDVI in year i for a single pixel, and n = number of years used to compute historical average.

For display purposes that would illustrate regional and broad-scale patterns more clearly, a 5 × 5-pixel median filter was passed over the dif-

ference image. Then the differences were binned into seven categories, with the middle category representing minimal difference from the mean and other categories representing divergence from the mean in NDVI units.

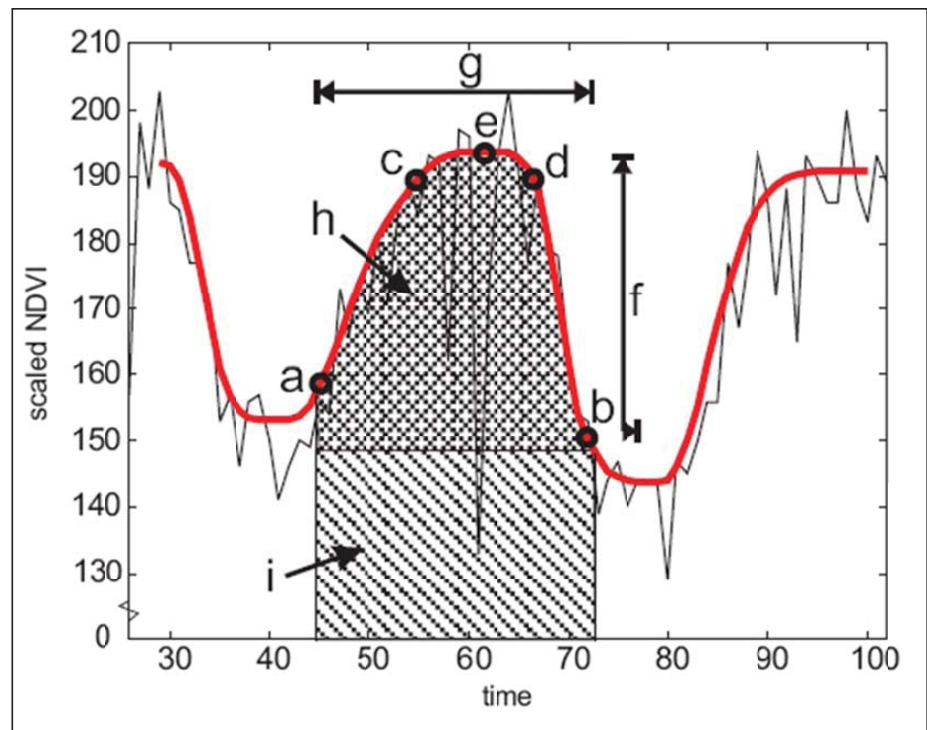
2.8 Phenology

Phenology metrics were determined using Timesat software (Jönsson and Eklundh 2002, 2004) that analyzes time-series data by fitting smoothed curves and then extracting seasonality metrics (Figure 2-1). In this report, the Savitzky-Golay (Savitzky and Golay 1964) smoothing filter method, with a window size of between 2 and 4, was chosen to fit curves to area-averaged, 10-year NDVI records for each park unit. This filter preserves important phenological features of distributions, such as maxima and width. Timesat derives $n-1$ years of phenology because in time-series NDVI, there are typically partial seasons on either end that cannot be used. Start of season (SOS) and end of senescence (EOS)* were defined as the day when 25% of the annual amplitude maximum was reached on the rising or falling limb. Length of season (LOS) is the difference in days between EOS and SOS. The integrated area under each annual NDVI curve (I-NDVI), or full integral, is the metric most often used as a measure of productivity (Gilmanov et al. 2004). The upper integral is used to minimize the residual effects of snow cover, clouds, or aerosols on NDVI. Other phenology metrics included in this report include the day of year when the maximum NDVI value is observed (DMAX) and amplitude of the annual NDVI curve (A-NDVI).

Timesat was used to determine phenology metrics for several reasons. Timesat calculates phenology metrics that are near the middle to high-end range of values derived using different methods, but Timesat most closely resembles the ensemble of seven different model SOS estimates (White et al. 2009). Timesat allows users to determine phenology metrics using area-averaged NDVI, as opposed to computing pixel-based phenology metrics prior to area averaging. Timesat allows users to select the number of annual growing seasons observed in the study area. The first consideration is important because pixel-based phenology metrics in semi-arid environments are subject to high degrees of variability in NDVI that

*Although EOS is often defined as end of season, for purposes of clarity in this report it represents end of senescence, instead.

Figure 2-1. Timesat-derived phenology metrics. Points (a) and (b) mark, respectively, start and end of the season. Points (c) and (d) give the 80% levels; (e) displays the point with the largest value; (f) displays the seasonal amplitude; and (g) the seasonal length. Finally, (h) and (i) are upper and lower integrals showing the cumulative effect of vegetation during the season. Modified from Eklundh and Jönsson (2009).



result primarily from the combination of heterogeneous ground conditions within pixels and temporal misregistration errors of up to 125 m. The second consideration is important in landscapes that experience two annual growing seasons—like much of the Colorado Plateau, where winter and monsoon precipitation often stimulate two distinct annual growing seasons. Parameters defined by users are saved in a parameter output file that documents how results were determined.

All phenology metrics, and the algorithms used to derive them, are affected by both natural and processing variability. Natural variability is determined by spatial and temporal heterogeneity of target features. Processing variability is affected by image-to-image misregistration, cloud screening, smoothing, and other factors that are typically minimized in processing before signal analysis, but that cannot be entirely eliminated. Natural variability decreases with smaller spatial scales, whereas processing variability increases. Optimum use of remote sensing tools, such as MODIS, requires balancing the tradeoffs between pixel resolution and spatial heterogeneity of ground targets. In this first report for the NCPN, the balance has not been achieved for all parks but the report has provided valuable indication of which scales are appropriate, in some

instances. Discussion with park staff and further analyses can help refine the optimum balance between target heterogeneity and analysis extent.

2.9 Snow cover

Snow cover was determined as a percentage of the area of interest covered at each time-step. The snow-cover metrics for DOY of snow-on and snow-off were determined using a threshold approach. Starting near the middle of each annual curve, the algorithm searches backward in time for snow-off, determined as the DOY when percent snow cover for the area of interest exceeds a threshold. Similarly, the algorithm searches in the forward direction from the middle of each year to determine DOY when snow cover rises above a user-defined threshold. This approach minimizes the influence of large changes in short-lived dustings in spring and fall. However, it is susceptible to noise in the data, as thresholds set below the noise level can lead to false positives in the assessment of snow-on and snow-off DOY. The user-defined threshold allows flexibility in determining snow metrics least influenced by noisy data and, more importantly, provides users the opportunity to select a percentage most appropriate for their applications.

2.10 Automation

Time-series and trend analysis of NDVI and snow-cover data have been automated to a great extent in order to facilitate understanding of dynamics and trends in vegetation and snow cover within the context of recent data collected at weather stations. Program code (in Visual Basic

for Applications and running in Excel) has been written to generate the tables, figures, and charts in this report. Not all aspects of this work can be automated easily; thus, some manual data management is still necessary but has been greatly reduced, making repeat analysis or comparative analysis possible.

3 Results

This first annual report on NCPN snow cover and NDVI demonstrates the potential for using MODIS products for understanding broad-scale vegetation condition and snow-cover extent on 16- and 8-day periods, respectively, since year 2000. All analytical post-processing steps have been automated so they can be repeated efficiently for any point, polygon, or discontinuous polygon on an ad-hoc basis anywhere in the Colorado Plateau region, depending on management need. The automation will also greatly facilitate repeat analysis in the future, as new imagery becomes available. For this first report, the spatial analysis unit is by park but data are presented at various temporal resolutions: 8-day, 16-day, and annual average. Caution is advised when evaluating annual NDVI against annual precipitation because of the strong linkage between precipitation timing, plant functional types, and phenology. Relationships on annual time scales are likely to show dramatic differences between extreme years, but more informative comparisons are likely using the higher temporal-frequency, 16-day observations.

3.1 Arches National Park

3.1.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrated a high degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.1-1). Vegetation condition in Arches National Park (NP) is strongly influenced by winter soil-moisture recharge and monsoon weather patterns, as indicated by a prominent bi-modal annual distribution in the NDVI curves that corresponds with timing, magnitude, and consistency of winter and monsoon-season precipitation patterns that charge soil moisture for plant growth at critical times.

The stacked annual curves illustrate differences in the magnitude and timing of significant growth periods between years (Figure 3.1-1b, c). The high productivity and strongly bi-modal signatures of 2005 and 2007 contrast with the lower productivity and much weaker bi-modal signature of 2000, when monsoon precipitation was insufficient to support vigorous late-season growth (Figure 3.1-1a). The opposite occurred in 2002, when a much stronger monsoon peak followed a relatively

weak spring growth season. The record precipitation in October 2006, which was largely responsible for the record 10-year annual sum that year, did not induce vegetation response in 2006, but recharged soil moisture for vigorous growth in spring 2007.

Although seasonal patterns are likely of highest interest and importance, given the strong monsoon coupling of precipitation and plant growth in Arches NP, descriptive statistics for annual NDVI that may be informative for extreme years are provided for inter-annual comparison. Annual average NDVI differed by 1.9% from its lowest, in 2000 and 2009 (116.6), to its highest (118.9), in 2005. The annual maximum NDVI differed by 2.4% from its lowest (117.7), in year 2000, to its highest (120.6), in 2005 (Table 3.1-1).

Year 2009 had the narrowest range in NDVI, and the second-lowest median NDVI, in the 10-year record (Table 3.1-1, Figure 3.1-2a). This corresponded to the second-lowest cumulative annual precipitation observed at the station for the same period and, perhaps more importantly, corresponded to one of the lowest cumulative winter soil-moisture recharge periods in the 10-year record (Figure 3.1-1a). Winter soil-moisture recharge is critically important to early season native vegetation on the Colorado Plateau, because it is generally the most reliable source of recharge (Comstock and Ehleringer 1992). The strong response to monsoon precipitation timing and magnitude is apparent in years like 2002, when 59 mm of precipitation fell at park headquarters in the 16 days preceding August 13—an optimal time for soil-moisture recharge for late season-adapted vegetation (Figure 3.1-1a). The winter recharge effect from the 108 mm of precipitation that fell in the 16 days preceding October 15, 2006, helped create the largest spring maximum NDVI of record (120.3), in spring 2007.

Weather data from the National Weather Service (NWS) Coop station at park headquarters were used to interpret NDVI variation (Figure 3.1-2b). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. It is likely that frontal winter precipitation recorded at the station is more representative of broader areas than summer convective precipitation associated with monsoon storms.

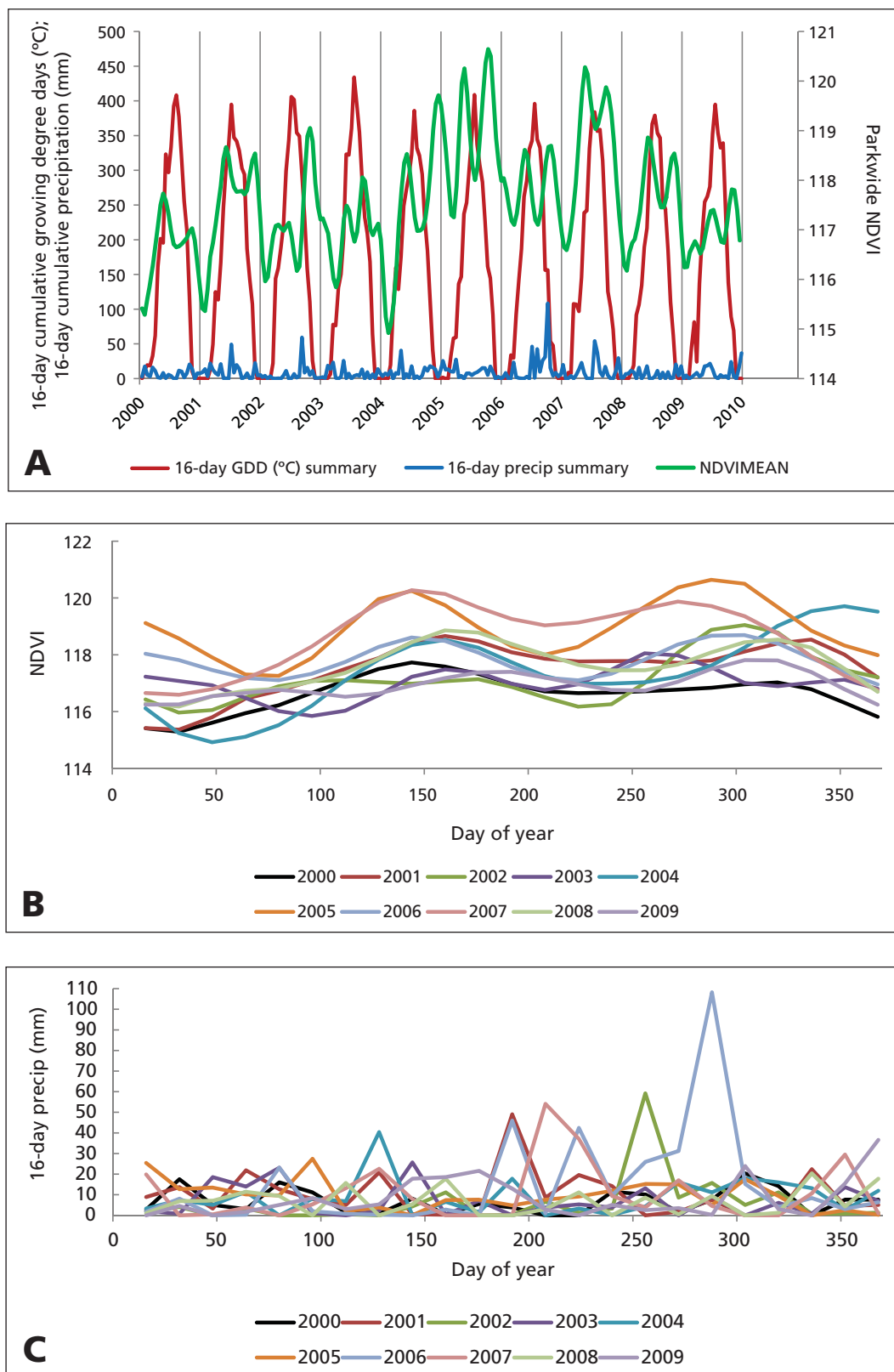


Figure 3.1-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at headquarters weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Arches NP.

Table 3.1-1. Descriptive statistics for parkwide average NDVI, Arches NP.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	116.6	116.7	117.7	115.3	2.44	2683
2001	117.5	117.8	118.7	115.4	3.30	2703
2002	117.2	117.0	119.0	116.0	3.09	2694
2003	117.0	117.0	118.1	115.8	2.21	2691
2004	117.4	117.2	119.7	114.9	4.79	2700
2005	118.9	118.9	120.6	117.3	3.39	2735
2006	117.8	117.8	118.7	117.0	1.74	2710
2007	118.6	119.1	120.3	116.6	3.68	2728
2008	117.6	117.6	118.9	116.2	2.68	2705
2009	116.9	116.8	117.8	116.2	1.57	2689

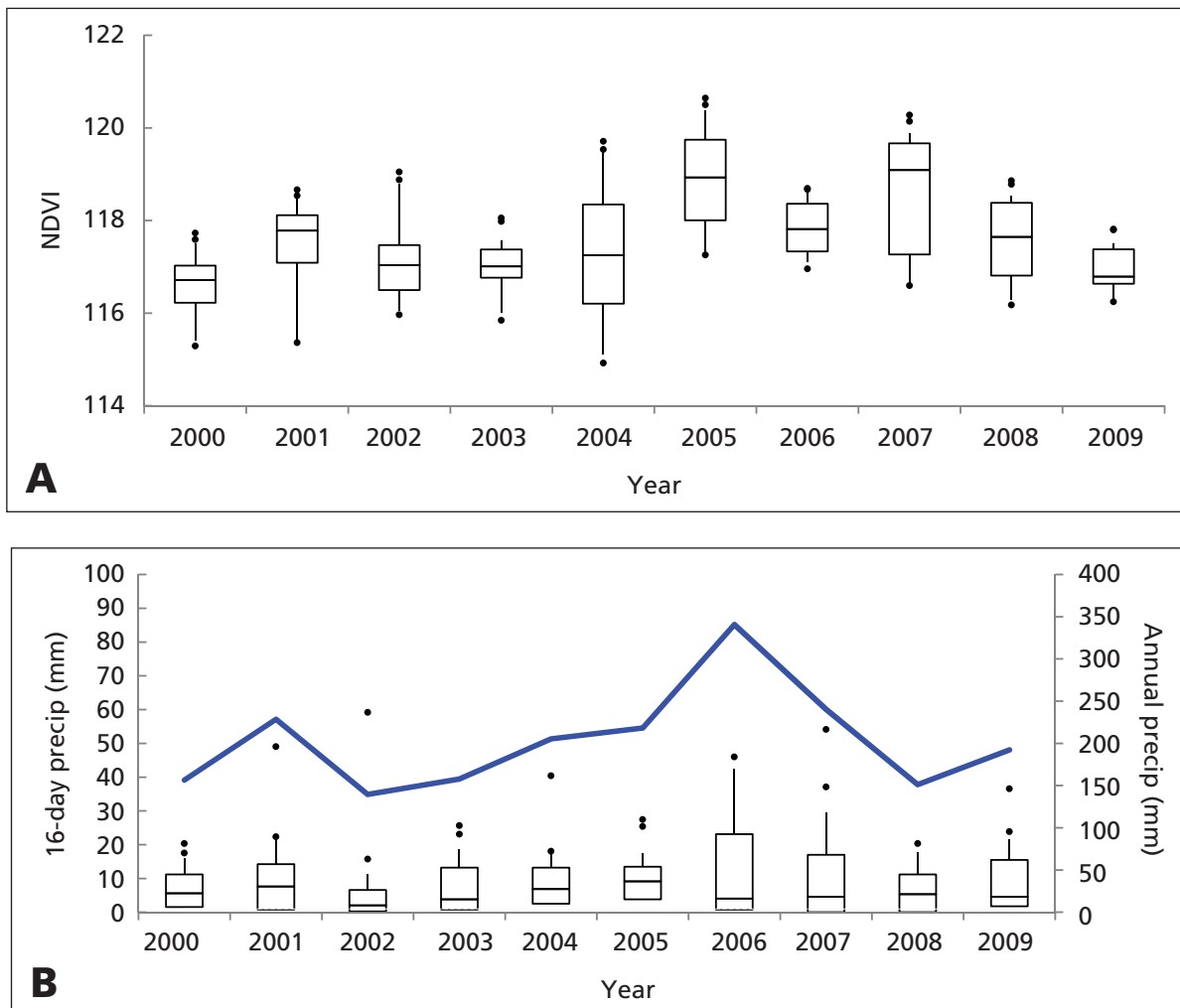


Figure 3.1-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Arches NP.

3.1.2 Recent NDVI conditions

The NDVI curve for 2009 was lower than the historical average at every 16-day interval (Figure 3.1-3a), exclusive of days-of-year 40–80 (February 9–March 21), and was 0.53% below average for the year. These measurements corresponded with a cumulative precipitation for 2009 of 5.3% below average. The early season curve in 2009 followed the long-term average, with what appeared to be normal winter soil-moisture recharge (Figure 3.1-1a), but fell below average, with little additional precipitation until DOY 144 (May 24) (Figure 3.1-3b). Later in 2009, precipitation followed long-term annual timing, but was less than average after DOY 192 (July 11), which may explain the lower than average NDVI for the remainder of the year.

The spatial distribution of below-average monsoon NDVI in 2009 was limited to the lower portion of Courthouse Wash and a few other isolated patches in the center of the park (Figure 3.1-3c). One isolated area of above-average NDVI occurred near the junction of Courthouse Wash and Seven Mile Canyon. On DOY 304 (October 31), most areas of Arches NP were within ± 1.5 NDVI units, or 2.8%, of the long-term average.

3.1.3 Phenology

In most years, there are two distinct growing seasons at Arches NP that represent the interaction of plant functional types (annual/perennial, early season/late season), phenology, and suitability of moisture for growth. The two seasons (spring and monsoon) are evaluated separately due to the distinct bi-modal nature of phenology observed in the park.

3.1.3.1 Spring

Over the 10-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 65, 42, 98, and 46 days, respectively. The most productive spring, based on I-NDVI, was 2009, while the least productive was 2003. Because LOS, rather than peak NDVI magnitude, is the primary determinant of annual productivity rankings, these productivity rankings are counterintuitive, considering the relative position of curves for those

years when compared to other years in the time series (Figure 3.1-1a) and in the stacked series (Figure 3.1-1b). Year 2009 had the longest growing season (175 days), while 2003 had the shortest (77 days)—98 days fewer than 2009. The most plausible explanation for the much longer growing season in 2009 is the early SOS date, in which 25% of the spring NDVI amplitude was achieved by DOY 53 (February 22). This remarkably early seasonal growth is explained by the early accumulation of growing degree days. Although 2009 got off to an early start, it was temporarily hampered by a cool weather spell that resulted in a dip in the NDVI signal near DOY 97 (April 7); at a time when GDD would typically be steadily increasing, NDVI dipped (approximately 25%) near that date. The only spring phenology metric that exhibited a statistically significant linear trend (p -value < 0.1) was DMAX ($R^2 = 0.32$) (Table 3.1-2). This trend was heavily influenced by years 2008 and 2009, and may be an artifact of a short record (Figure 3.1-4a).

3.1.3.2 Monsoon

Over the nine-year historical record, the ranges of monsoon SOS, EOS, LOS, and DMAX were 65, 68, 84, and 81 days, respectively. The most productive monsoon season, based on I-NDVI, was 2002, while the least productive was 2008. The monsoon-season historical record does not include 2009 because the EOS was expected to occur in early 2010, which was beyond the time scale evaluated in this report. There were no significant linear trends in monsoon phenology observed for this period of record (Table 3.1-3; Figure 3.1-4b).

3.1.3.3 Summary

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends, or perhaps only weak trends (Tables 3.1-2, 3.1-3; Figure 3.1-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

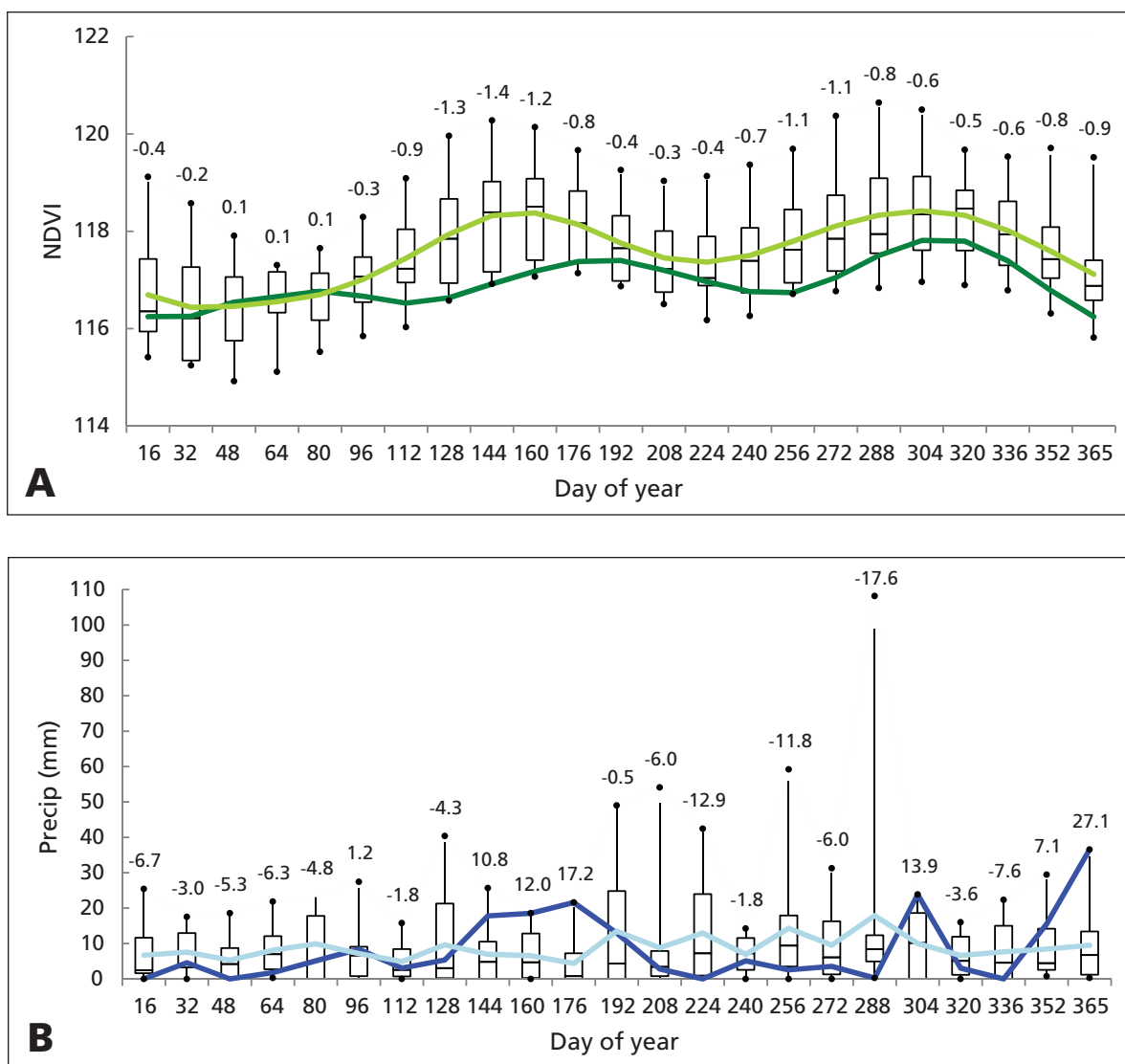


Figure 3.1-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Arches NP. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period.

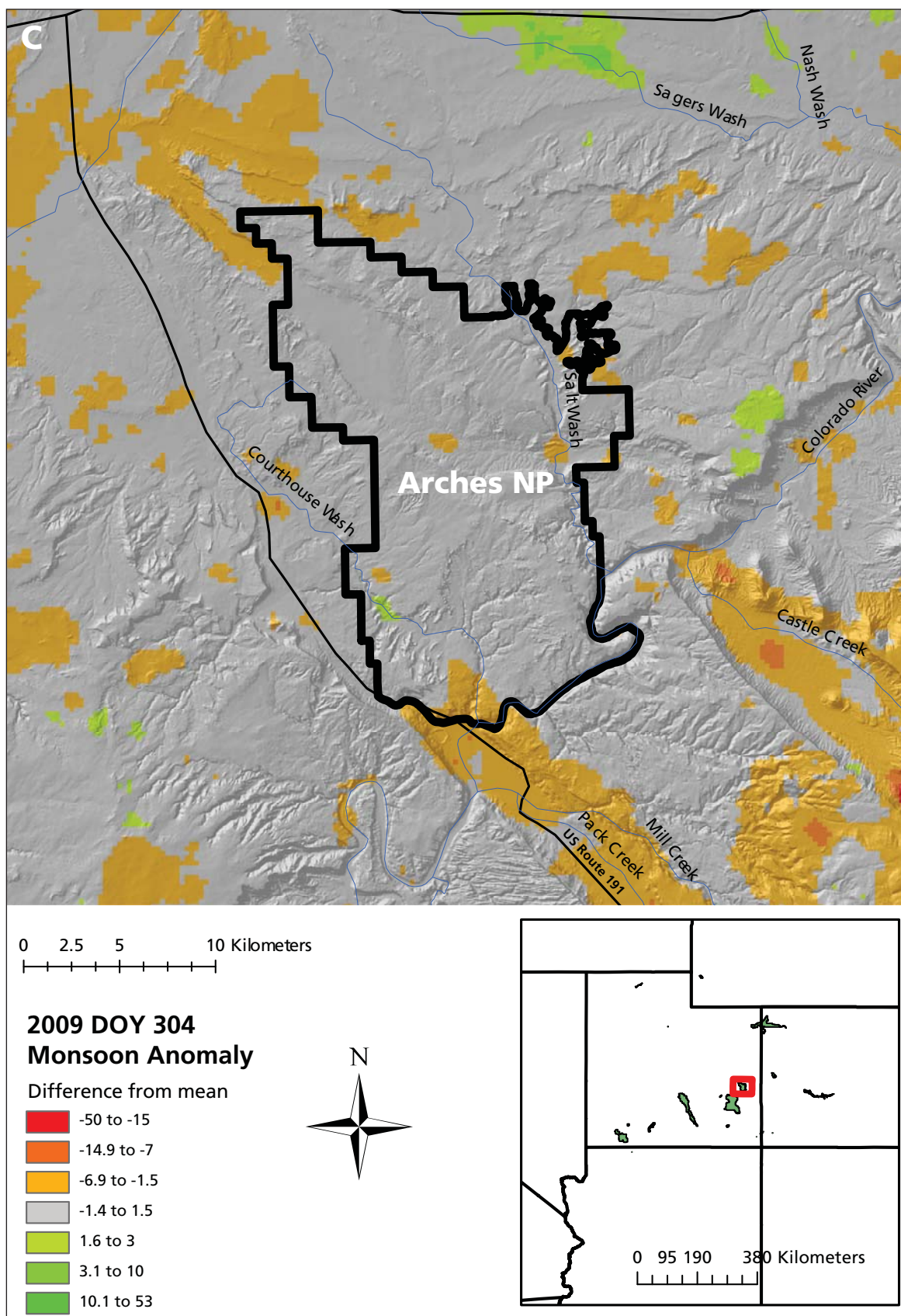


Figure 3.1-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Arches NP.

Table 3.1-2. Spring-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Arches NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	64	142	197	133	1285	1.71
2001	59	153	202	143	1293	2.07
2002	56	135	212	156	1401	1.01
2003	118	160	195	77	818	1.16
2004	87	152	205	119	1057	2.55
2005	98	141	186	88	834	2.54
2006	102	149	197	94	943	1.46
2007	75	142	189	113	1071	2.40
2008	83	163	218	134	1179	1.97
2009	53	181	227	175	1520	0.87
<i>correlation</i>	<i>0.11</i>	<i>0.57</i>	<i>0.36</i>	<i>0.07</i>	<i>-0.01</i>	<i>-0.01</i>
<i>slope</i>	<i>0.77</i>	<i>2.53</i>	<i>1.54</i>	<i>0.76</i>	<i>-1.10</i>	<i>0.00</i>
<i>p-val slope</i>	<i>0.77</i>	<i>0.09</i>	<i>0.31</i>	<i>0.84</i>	<i>0.97</i>	<i>0.97</i>
<i>intercept</i>	<i>-1463</i>	<i>-4915</i>	<i>-2880</i>	<i>-1397</i>	<i>3343</i>	<i>7</i>
<i>p-val intercept</i>	<i>0.78</i>	<i>0.10</i>	<i>0.34</i>	<i>0.85</i>	<i>0.95</i>	<i>0.96</i>

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

Table 3.1-3. Monsoon-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Arches NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	262	319	368	106	1049	0.98
2001	293	334	380	87	825	1.60
2002	253	304	425	172	1528	3.06
2003	228	271	392	164	1404	2.12
2004	288	352	416	128	1069	2.57
2005	234	291	378	144	1311	3.09
2006	245	299	362	117	1062	1.83
2007	232	283	357	123	1188	2.17
2008	274	318	366	92	825	1.67
<i>correlation</i>	<i>-0.28</i>	<i>-0.25</i>	<i>-0.42</i>	<i>-0.12</i>	<i>-0.16</i>	<i>0.20</i>
<i>slope</i>	<i>-2.45</i>	<i>-2.35</i>	<i>-3.64</i>	<i>-1.30</i>	<i>-13.83</i>	<i>0.05</i>
<i>p-val slope</i>	<i>0.47</i>	<i>0.51</i>	<i>0.27</i>	<i>0.76</i>	<i>0.69</i>	<i>0.61</i>
<i>intercept</i>	<i>5173</i>	<i>5021</i>	<i>7672</i>	<i>2733</i>	<i>28852</i>	<i>-98</i>
<i>p-val intercept</i>	<i>0.45</i>	<i>0.49</i>	<i>0.24</i>	<i>0.75</i>	<i>0.68</i>	<i>0.62</i>

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

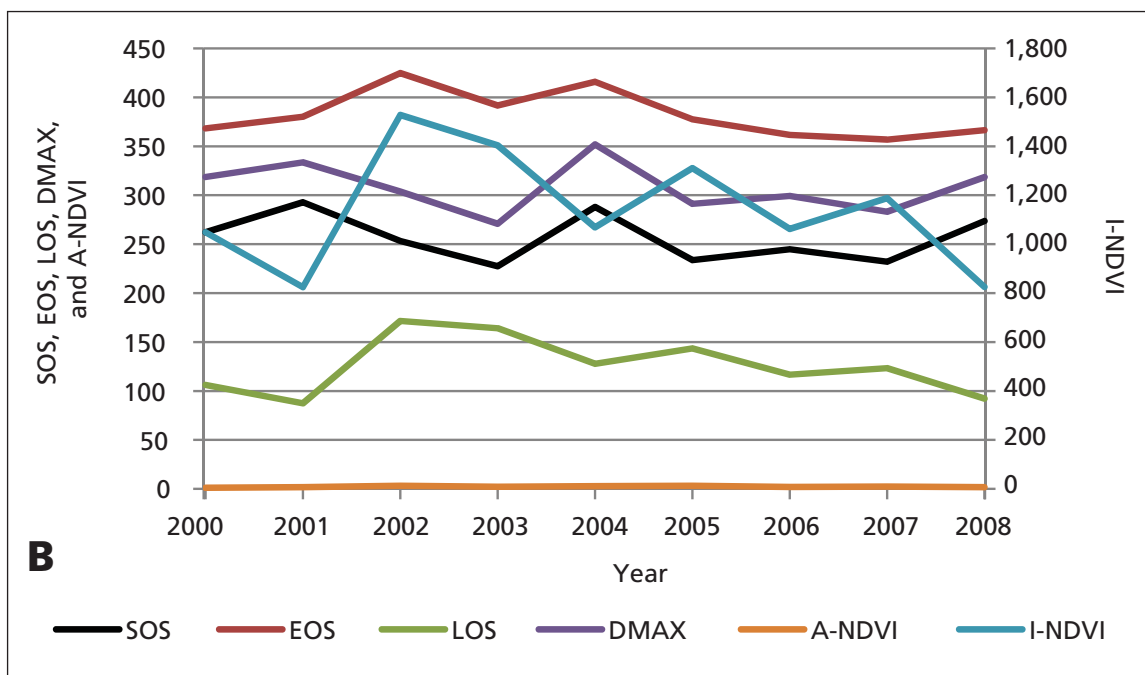
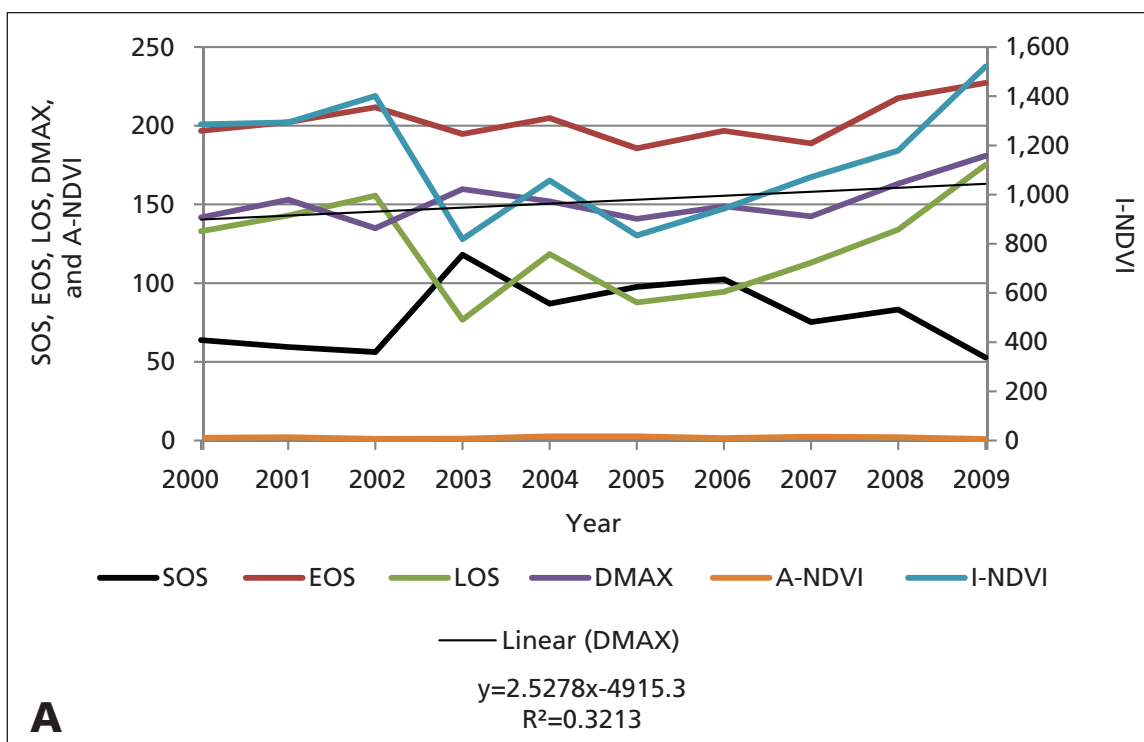


Figure 3.1-4. Annual (a) spring and (b) monsoon phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI and A-NDVI, Arches NP. For both figures, metrics were computed with TimeSat for a bi-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.1.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Arches NP (Figure 3.1-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also a small amount of noise in the snow-cover extent data, represented by spikes during times of the year when snow cover is exceedingly unlikely (e.g., DOY 224). The cumulative exceedance frequency curves show that 2009 exhibited the most snow cover for the longest duration in the record, followed by 2008 (Figure 3.1-5b). On average, the park has less than 3% snow cover by DOY 47 (February 17) and greater than 3% snow cover by DOY 335 (December 1). The 10-year average snow-free period, defined here as less than 3% coverage, was 289 days (Table 3.1-4).

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with lon-

ger snow cover corresponding to delayed SOS. However, an inverse relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.37$; Figure 3.1-6) for the eight years of record when snowmelt date and spring SOS could be determined. The rather strong inverse relationship between these variables in Arches NP suggests that temperature has more of an effect on spring SOS than snow cover. The relationship may be even more complex in colder years, when sublimation may account for a significant moisture loss that warmer temperatures might otherwise impart to the soil for spring growth. In a semi-arid environment like Arches NP, snow cover and temperature are not tightly coupled in all years, as may be the case at higher elevations that typically receive more snow when temperatures are low, and where sublimation may account for a smaller percentage of winter precipitation loss. The relationship between snow extent and SOS is further complicated by the high variability in annual snow-cover extent.

Table 3.1-4. Timing and duration of snow cover, Arches NP.

Year	Snow off	Snow on	DOY <3% cover	DOY >3% cover	Days snow-free	Days snow-covered
2000	-	11/7/2000	-	312	304	61
2001	3/5/2001	11/24/2001	64	328	264	101
2002	3/14/2002	11/9/2002	72	312	240	125
2003	1/10/2003	11/18/2003	8	320	312	53
2004	2/28/2004	11/26/2004	56	328	272	93
2005	2/20/2005	2/5/2006	48	389	317	48
2006	2/13/2006	11/28/2006	40	328	288	77
2007	2/22/2007	12/15/2007	48	344	296	69
2008	3/2/2008	12/23/2008	56	352	296	69
2009	2/7/2009	12/8/2009	32	336	304	61
<i>correlation</i>			-0.27	0.50	0.36	-0.36
<i>slope</i>			-1.87	3.81	2.89	-2.89
<i>p-val slope</i>			0.48	0.14	0.30	0.30
<i>intercept</i>			3790	-7306	-5506	5871
<i>p-val intercept</i>			0.47	0.15	0.32	0.29

¹ Snowmelt could not be determined in year 2000 because the first snow-cover extent image was available March 4, 2000. After that date in 2000, snow was not observed until after 11/7/2000. Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

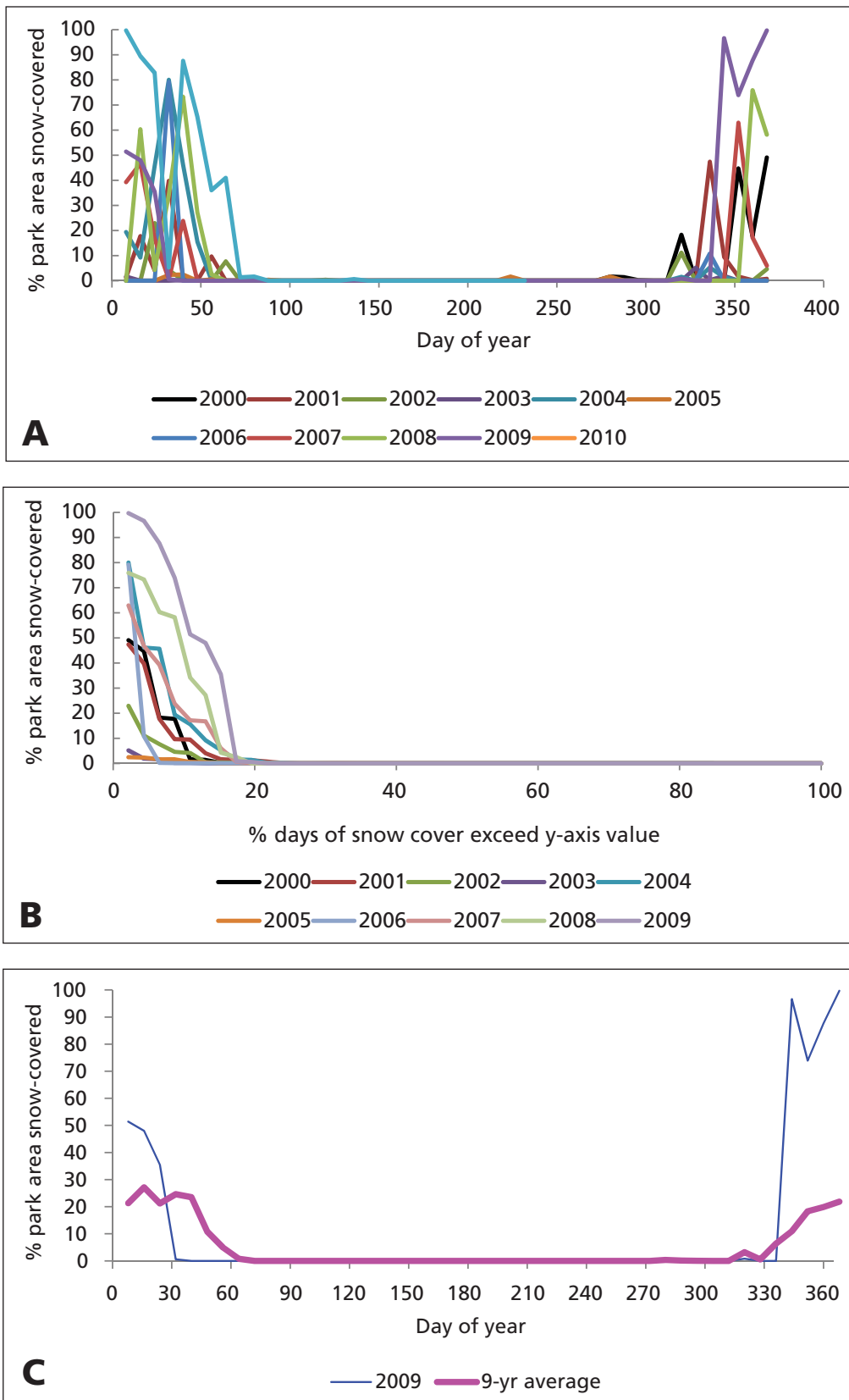


Figure 3.1-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Arches NP.

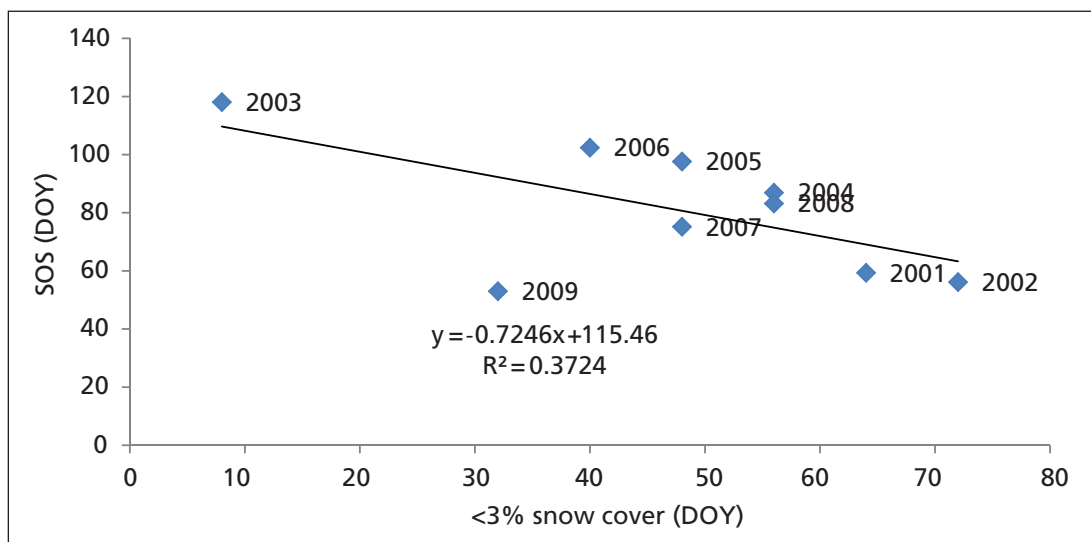


Figure 3.1-6. Relationship between snowmelt DOY and start of season (SOS), Arches NP.

3.2 Black Canyon of the Gunnison National Park

3.2.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.2-1a). In the 10-year time series, most years exhibit uni-modal or very weak bi-modal growing-season phenology. When annual curves are stacked (Figure 3.2-1b), a more direct, year-to-year comparison is possible, in which the weak, bi-modal signature (when present) becomes more apparent, as with years 2005 and 2006. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to lower-elevation NCPN parks, the NDVI annual curves for Black Canyon of the Gunnison NP are remarkably consistent, which may indicate that the park's precipitation is well-distributed, more abundant than elsewhere, and supports vegetation adapted to a single growing season.

Weather data from the park's NWS Coop station were used to interpret NDVI variation (Figure 3.2-2a, b). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative for evaluating extreme years, when the station generally tracks regional extremes. Year 2006 had the narrowest range in annual maximum and minimum NDVI (21.4) and the lowest maximum NDVI value (146.9) in the record (Table 3.2-1). This corresponds with what appears to be above-average moisture for the year; however, precipitation in 2006 between DOYs 112 (April 22) and 144 (May 24) was the lowest observed in the years between 2004 and 2009. Year 2004 had the lowest NDVI (115.3), but the minimum NDVI in the following years was not persistently low. This indicates that either the cause of the 2004 minimum was short-lived and vegetation recovered or, more likely, the 2004 extreme minimum was an artifact of the snow masking and smoothing completed during

image-processing steps prior to analysis. Support for the latter conclusion was provided via personal communication with park staff (Ken Stahlnecker), who indicated that nothing unusual happened in fall 2003 or winter 2003–2004 in terms of precipitation or disturbance.

Although weather data collection at the park's NWS Coop station started in 2003, the first full year for which data were collected was 2004. A local newspaper report summarizing a decade of significant events in 2010 indicated that 2002 was an extreme drought year for the region (Gunnison Country Times 2010). This information corresponded with the third-lowest maximum NDVI and sixth-lowest productivity ranking (see Tables 3.2-1 and 3.2-2).

3.2.2 Recent NDVI conditions

The 2009 NDVI curve was slightly above the historical average between DOYs 176 and 240 at every 16-day interval during the height of the growing season, but below average at other times (Figure 3.2-3a). Overall, in spite of achieving the highest NDVI in the 10-year record, NDVI in 2009 was 0.17% below average for the year. Cumulative precipitation for 2009 was 9.4% below average for the year, but response to precipitation explains both the high-magnitude mid-season peak and generally below-average late-season productivity. A precipitation pulse of 40.6 mm above average near DOY 96 (April 6) and mostly below-average precipitation after DOY 208 (July 27) help explain both the record-breaking NDVI and late-season fall-off in productivity.

The below-average monsoon NDVI in 2009 occurred primarily on north-facing aspects of the canyon and on the south aspect of Red Rock Canyon, while above-average NDVI was limited to south-facing aspects of the main canyon (Figure 3.2-3c). NDVI for the Bostwick Park area, just south of the park boundary, was well below average. On DOY 304 (October 31), most areas of Black Canyon of the Gunnison NP were within ± 1.5 NDVI units, or 2.8%, of the long-term average.

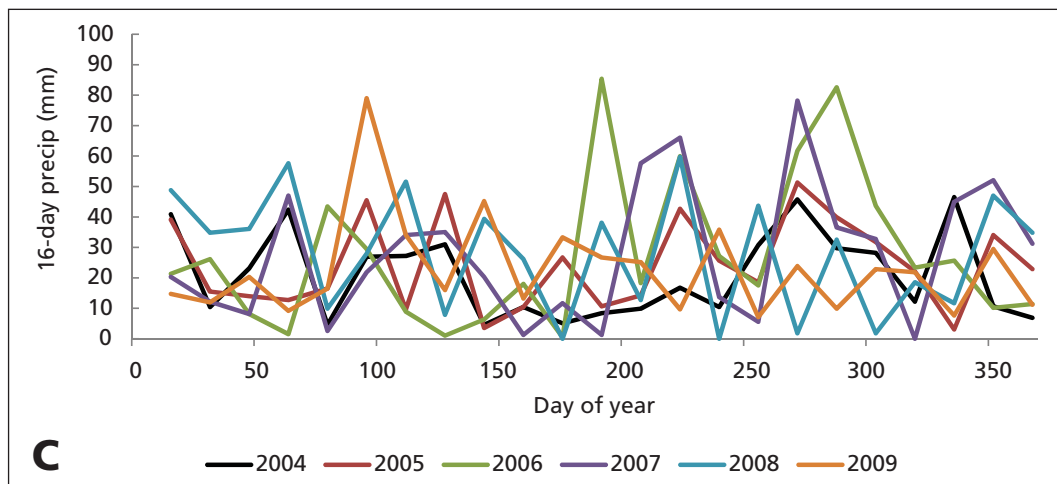
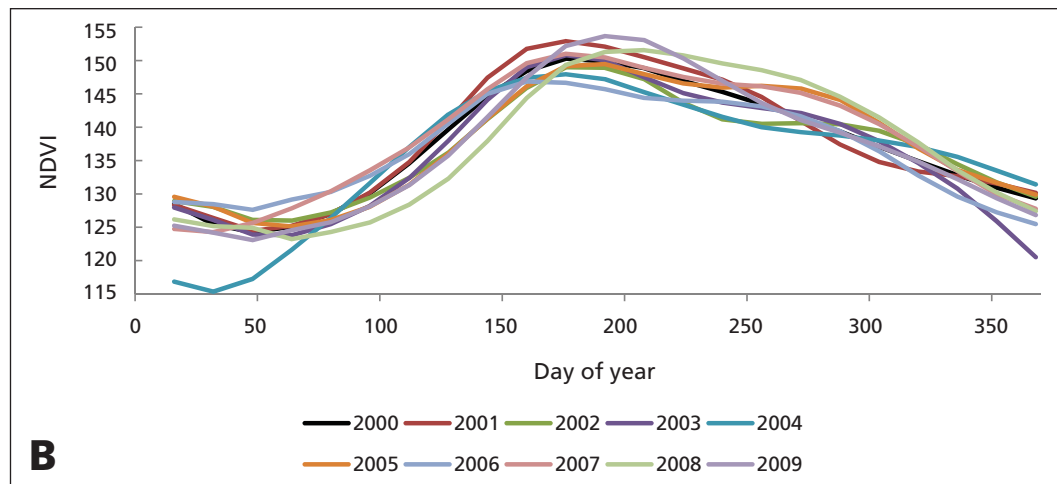
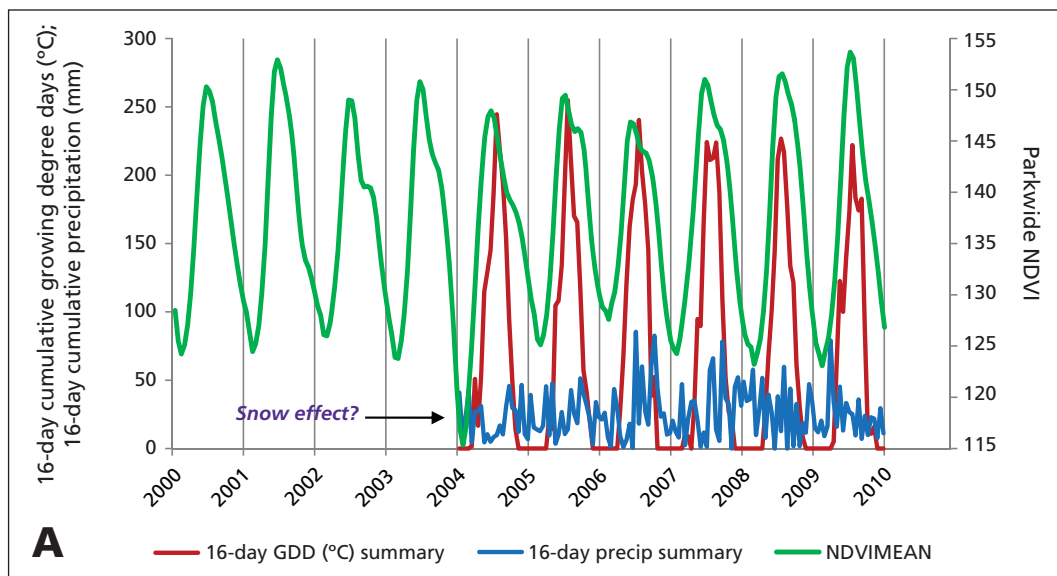


Figure 3.2-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Black Canyon of the Gunnison NP.

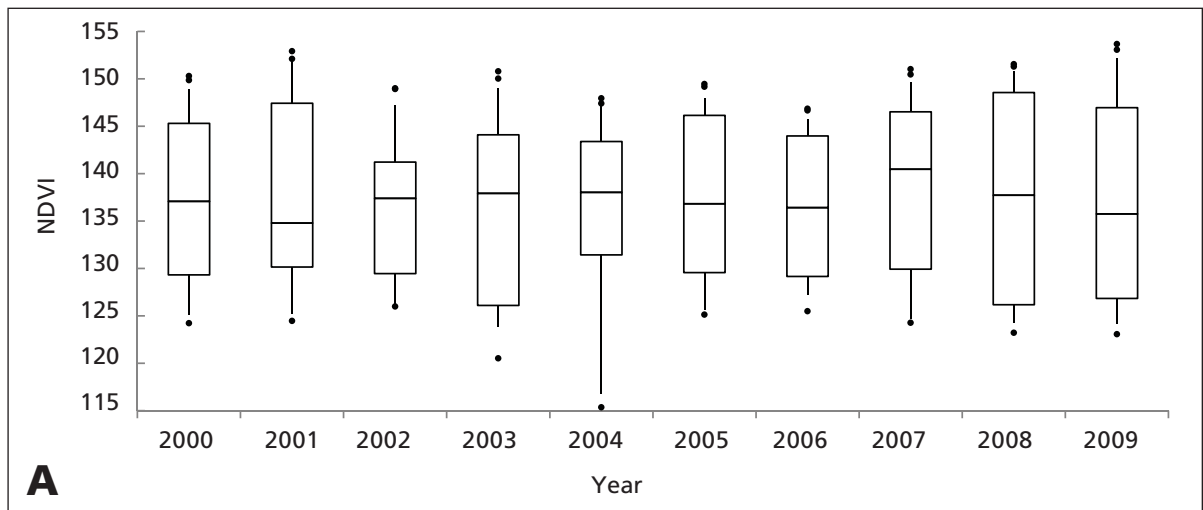


Figure 3.2-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Black Canyon of the Gunnison NP.

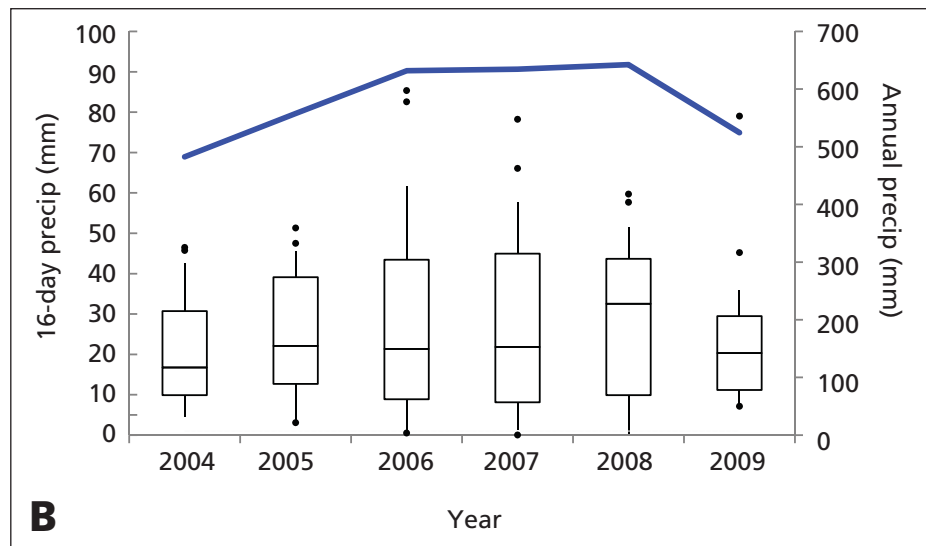


Table 3.2-1. Annual descriptive statistics for parkwide average NDVI, Black Canyon of the Gunnison NP.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	137.3	137.1	150.3	124.2	26.07	3158
2001	138.0	134.8	152.9	124.5	28.46	3173
2002	136.8	137.4	149.0	126.0	23.00	3146
2003	136.1	137.9	150.8	120.5	30.28	3131
2004	135.6	138.0	147.9	115.3	32.59	3120
2005	137.6	136.8	149.5	125.1	24.33	3165
2006	136.8	136.4	146.9	125.5	21.37	3146
2007	138.6	140.5	151.0	124.3	26.74	3188
2008	137.2	137.7	151.5	123.2	28.33	3156
2009	136.8	135.7	153.7	123.1	30.60	3147

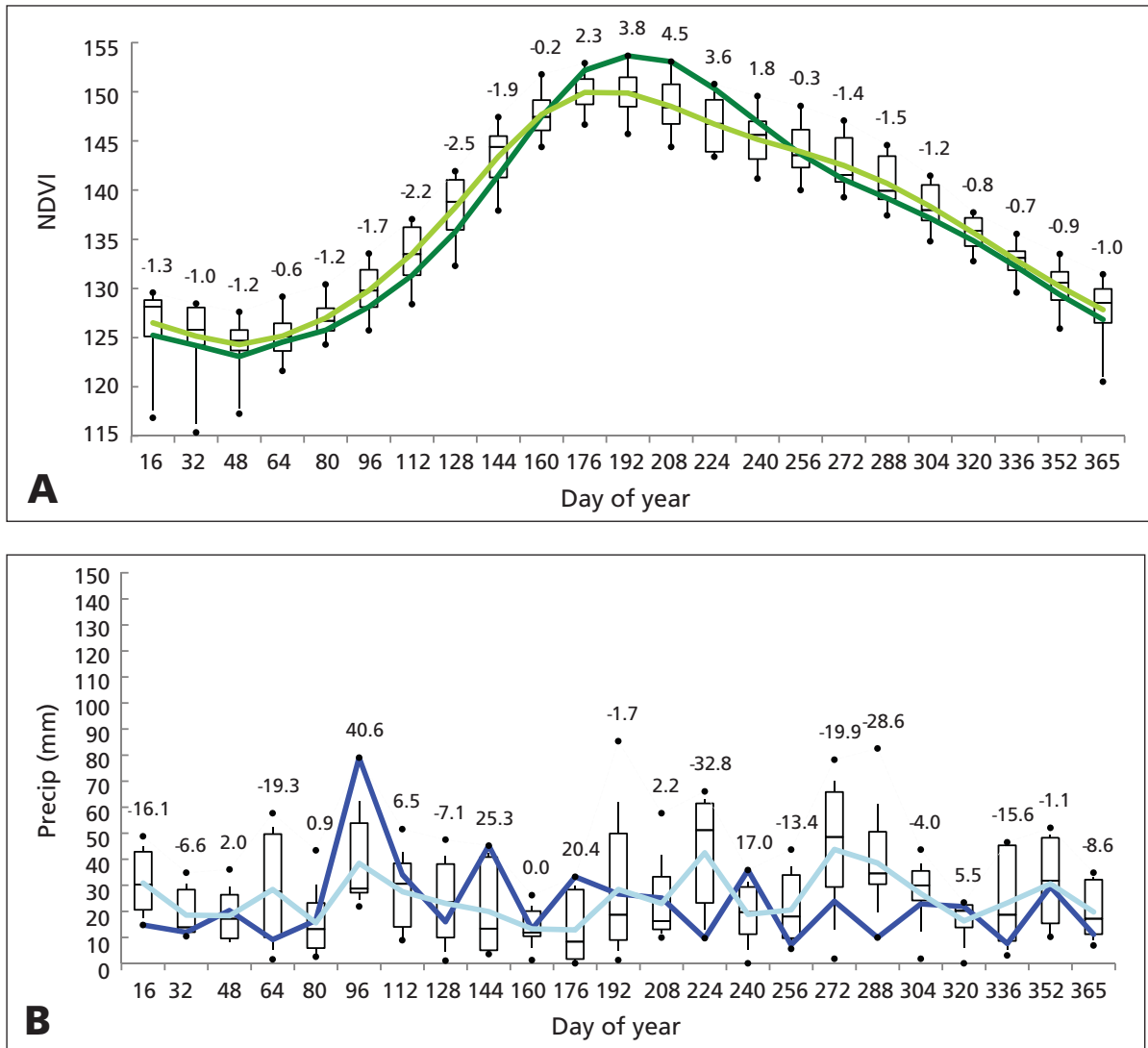


Figure 3.2-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Black Canyon of the Gunnison NP. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period.

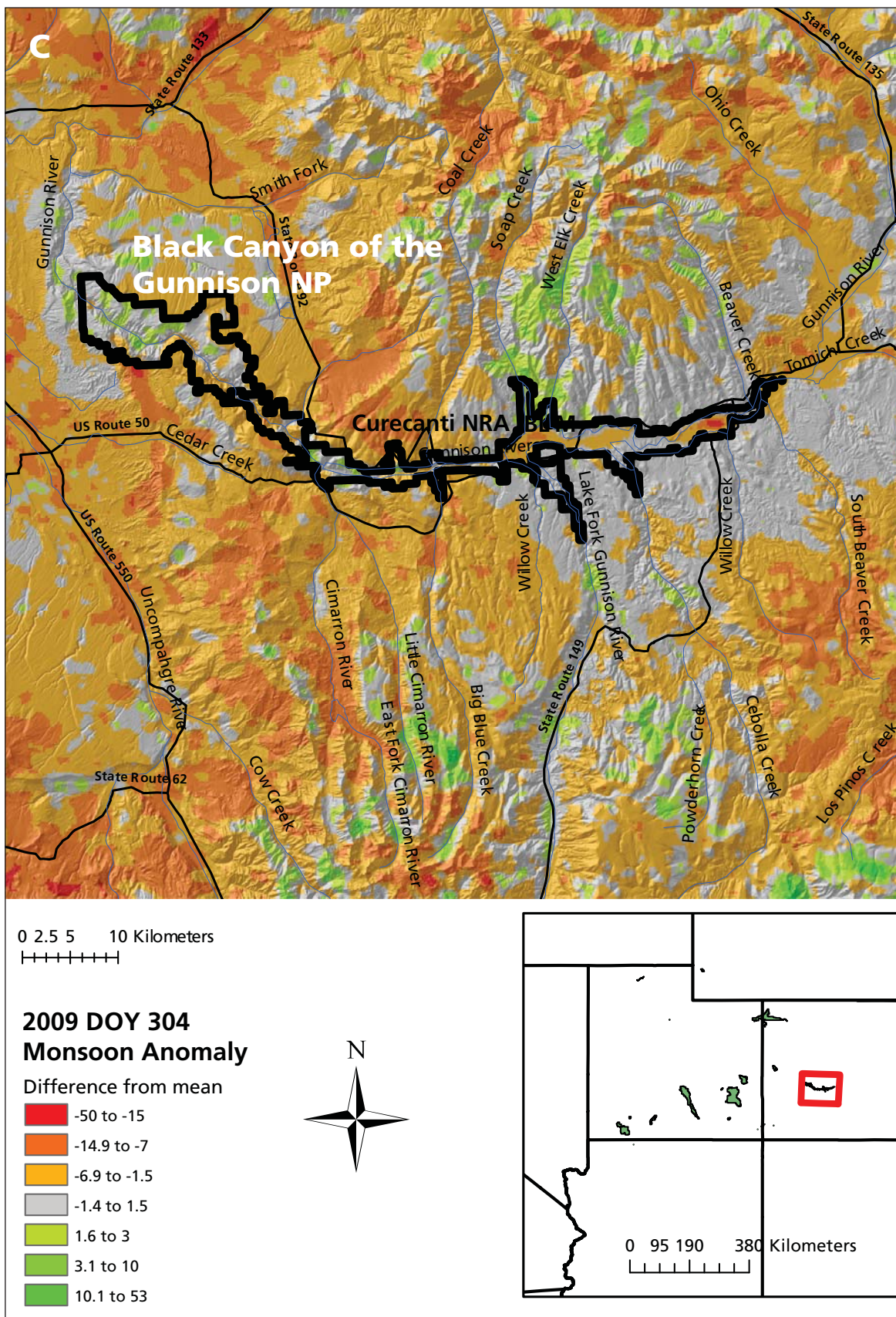


Figure 3.2-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Black Canyon of the Gunnison NP.

3.2.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 51, 40, 75, and 46 days, respectively. The most productive year, based on I-NDVI, was 2004, while the least productive was 2006 (Table 3.2-2). Year 2004 also had the earliest SOS (March 12). SOS in 2006 was very close to average but below-average spring precipitation that year substantially reduced annual productivity. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. Year 2004 had the longest growing season (302 days), while 2005 had the shortest (228 days), at 74 days fewer than 2004. The earlier SOS and correspondingly larger LOS and integral for year 2004 are clear in the time-series plot of phenology metrics (Figure 3.2-4).

The only statistically significant linear trend (p-value <0.1) in the phenology metrics was for

DMAX, which increased by 3.5 days per year during the period of record. The direction of this trend is inconsistent with warming temperatures, but could be related to the recent heavy snow years of 2008 and 2009, which caused snow to linger on the landscape longer than in previous years. This extended presence of snow may have delayed the onset of SOS and provided more soil moisture for delayed DMAX (Figure 3.2-5).

The 10-year MODIS record may be too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends, or perhaps only weak trends (Table 3.2-2, Figure 3.2-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

Table 3.2-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Black Canyon of the Gunnison NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	98	194	350	252	2399	25.53
2001	102	190	333	231	2280	27.52
2002	108	189	364	256	2509	24.17
2003	105	194	356	252	2504	31.10
2004	71	176	373	302	2900	27.63
2005	110	216	338	228	2401	22.76
2006	96	202	334	237	2249	20.50
2007	83	205	349	266	2557	26.84
2008	122	222	350	229	2279	27.89
<i>correlation</i>	0.06	0.66	-0.10	-0.09	-0.06	-0.12
<i>slope</i>	0.32	3.45	-0.50	-0.81	-4.53	-0.14
<i>p-val slope</i>	0.88	0.05	0.80	0.81	0.87	0.76
<i>intercept</i>	-539.67	-6705.83	1343.74	1864.20	11537.91	302.55
<i>p-val intercept</i>	0.90	0.06	0.73	0.78	0.84	0.74

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude.

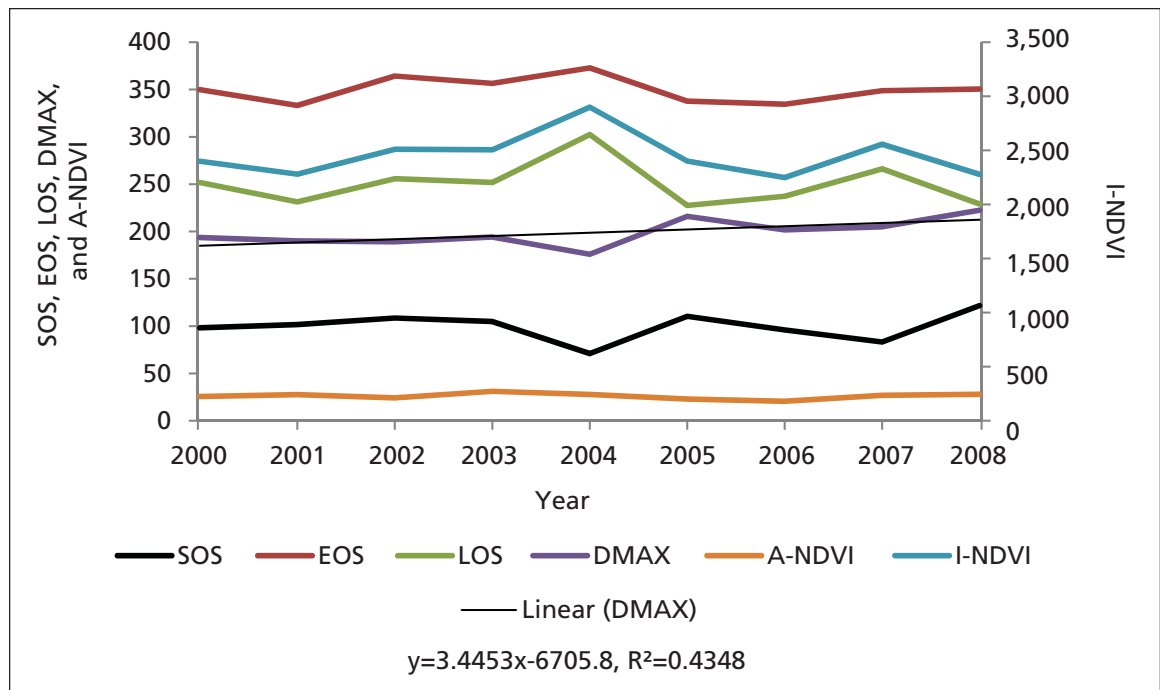


Figure 3.2-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Black Canyon of the Gunnison NP. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.2.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Black Canyon of the Gunnison NP (Figure 3.2-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short lived “dustings.” There is also noise in the data, indicated by occasional spikes during times of the year when snow cover is exceedingly unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2008 and 2009 had the most extensive and persistent snow cover (Figure 3.2-5b), and 2009 had more snow cover than average (Figure 3.2-5c). Although water content cannot be directly inferred from snow cover, they are related. Snow is also a physical barrier to SOS. For example, 2002 had one of the earliest snowmelt dates (DOY 88; Table 3.2-3) and one of the most productive growing seasons, as measured by NDVI (Table 3.2-2). Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both. Coupling these data with Snotel* and USGS streamflow data in the watershed could help answer that question.

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. Earlier snowmelt could result in an earlier SOS, but snow cover is not the only factor driving SOS, as shown by data from year 2002, which had the earliest snowmelt date but ranked seventh in the record for SOS. A weak positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.26$) for the eight years of record (data from Tables 3.2-2 and 3.2-3). Stronger relationships might occur at finer spatial scales if the canyon, where snowmelt/SOS coupling may be more mechanistic, was masked from analysis (Figure 3.2-6). However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Black Canyon, defined here as less than 5% coverage, occurred between DOYs 103 (April 13) and 280 (October 7). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.2-3).

*Snotel sites are operated by the U.S. Department of Agriculture Natural Resources Conservation Service.

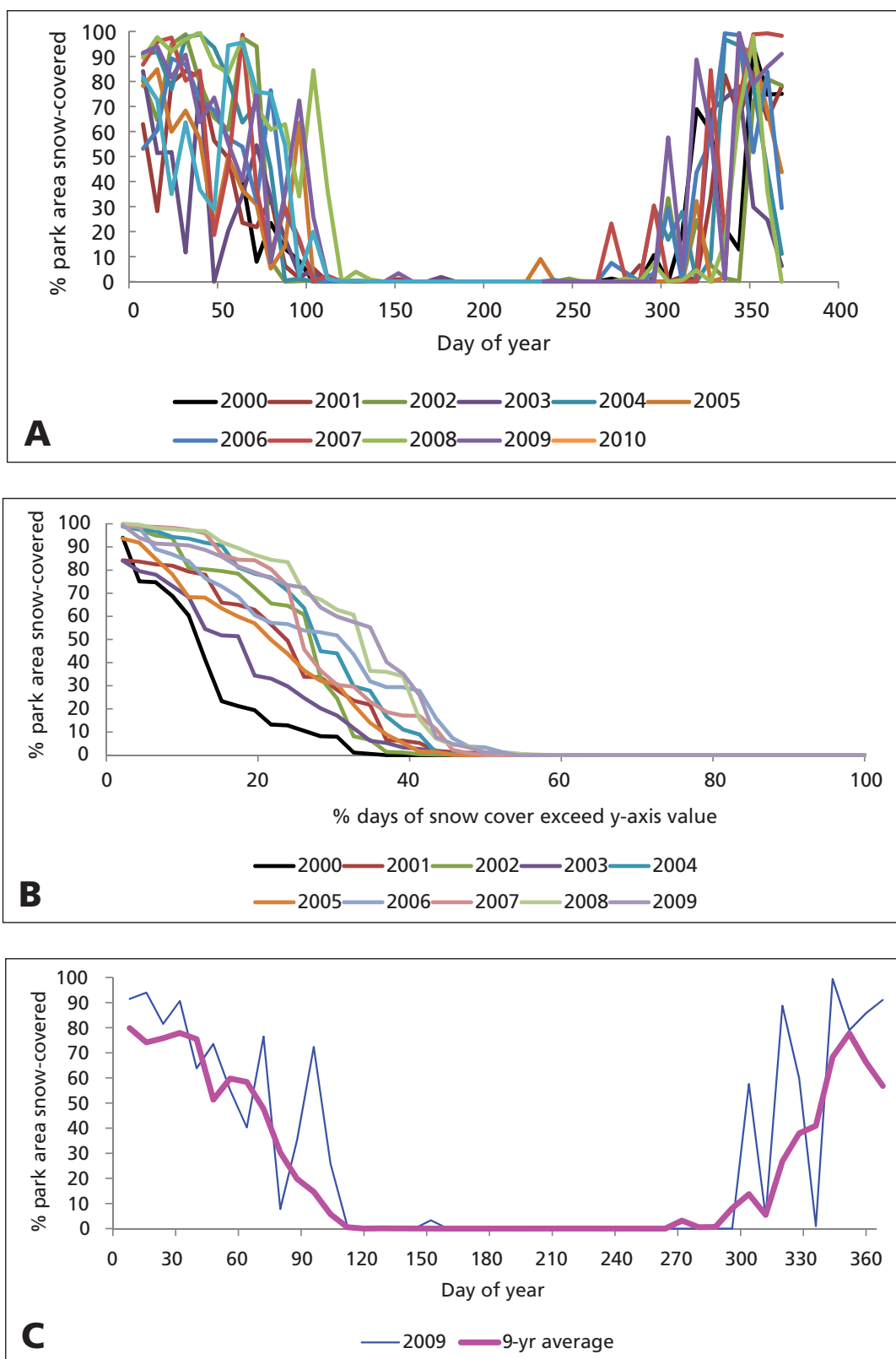


Figure 3.2-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Black Canyon of the Gunnison NP.

Table 3.2-3. Timing and duration of snow cover, Black Canyon of the Gunnison NP.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	4/13/2000	10/14/2000	104	288	184	181
2001	4/22/2001	10/7/2001	112	280	168	197
2002	3/30/2002	10/24/2002	88	296	208	157
2003	4/8/2003	11/10/2003	96	312	216	149
2004	3/31/2004	10/17/2004	88	288	200	165
2005	4/17/2005	8/15/2005	104	224	120	245
2006	4/18/2006	9/25/2006	104	264	160	205
2007	4/19/2007	9/26/2007	104	264	160	205
2008	5/5/2008	10/20/2008	120	288	168	197
2009	4/28/2009	10/29/2009	112	296	184	181
<i>correlation</i>			0.44	-0.18	-0.32	0.32
<i>slope</i>			1.50	-1.45	-2.96	2.96
<i>p-val slope</i>			0.20	0.62	0.37	0.37
<i>intercept</i>			-2910	3196	6105	-5740
<i>p-val intercept</i>			0.22	0.59	0.36	0.38

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

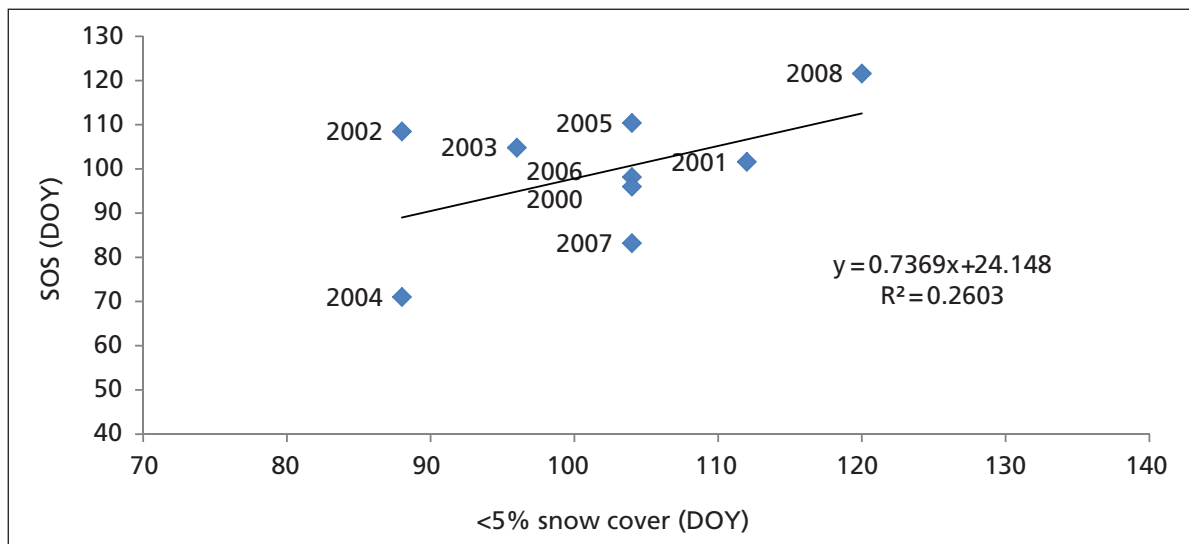


Figure 3.2-6. Relationship between snowmelt DOY and SOS, Black Canyon of the Gunnison NP.

3.3 Bryce Canyon National Park

3.3.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.3-1a). The strength of seasonal bi-modality in the 10-year time series is highly variable, most likely due to high variability in winter soil-moisture recharge and irregular monsoon precipitation. Bryce Canyon is regionally situated at mid- to high-elevation, and thus experiences orographically enhanced precipitation. However, its elevation is not high enough to ensure consistent winter snowpack, and the park is subject to inconsistent monsoon precipitation. This variability is apparent in the “jagged” nature of annual curves, which appear to be a cross between the consistent, smooth peaks typical of higher elevations and the even more-jagged, annual curves typical of lower elevations.

The influence of precipitation variability is dramatically illustrated by the year 2002 NDVI curve. Very low precipitation in winter 2001–2002, plus minimal precipitation in 2002 until DOY 225 (August 13), resulted in almost imperceptible spring growth (Figure 3.3-1a, b). However, after monsoon precipitation began, NDVI responded almost immediately but did not peak (142.7) until DOY 336 (December 3). The influence of precipitation variability on NDVI is further discussed in Section 3.3.3.

When annual curves are stacked (Figure 3.3-1b), a more direct year-to-year comparison of NDVI magnitude and timing is possible. The weak bi-modal signature becomes more apparent, as with years 2004 and 2005. The lack of monsoon precipitation in 2009, plus effects from the Bridge Fire (see Section 3.3.2), helps explain the lack of monsoon-season NDVI response that year. Annual NDVI curves show attributes of higher-elevation areas, which typically have relatively

uniform annual peak height and width, but also reflect the highly variable nature of monsoon events. These patterns indicate that the park generally receives the well-distributed, more abundant precipitation that is common at higher elevations on the Colorado Plateau, as well as monsoon precipitation that supports vegetation adapted to a bi-modal growing season. The significant dip in spring 2005 NDVI, and its potential cause, are discussed in Section 3.3.4.

Weather data from the park’s NWS Coop station were used to interpret NDVI variation (Figure 3.3-1c and 3.3-2b). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2004 had the maximum NDVI in the record (143.4) late in the year, at DOY 304 (October 31), which corresponded with the greatest monsoon precipitation in the 10-year record (Figure 3.3-1c). Year 2005 had the most extreme minimum (125.7) and the third-highest maximum NDVI (143.5) (Table 3.3-1). The two may be related to understory winter-kill (discussed later) and deep snow cover, which provided ample soil-moisture recharge for the subsequent growing season. Year 2007 exhibited the narrowest range in annual maximum and minimum NDVI (6.73), which may be explained by relatively low precipitation preceding the 2007 growing season and low precipitation until DOY 208 (July 27).

The record NDVI range in 2005 appears to have been related to winter conditions in 2004 and 2005 (Figure 3.3-2a, b). Winter 2004–2005 had the deepest snowpack since 1998 (Bruce Fields, personal comm.), which may have indirectly caused the depressed NDVI signal in early spring 2005 and, subsequently, the good growing conditions supported by adequate soil-moisture recharge that ultimately resulted in near-record NDVI levels for 2005.

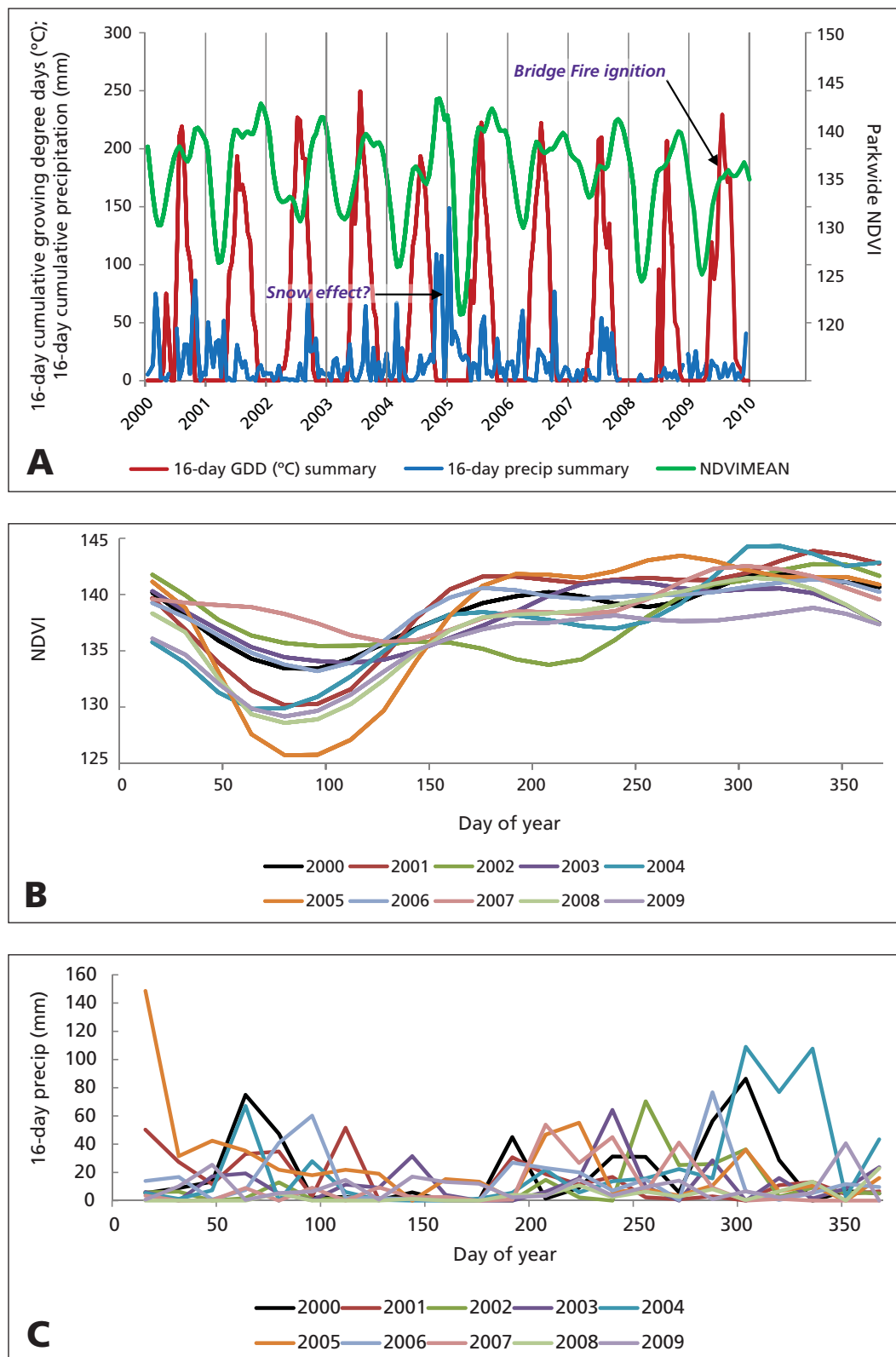


Figure 3.3-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Bryce Canyon NP.

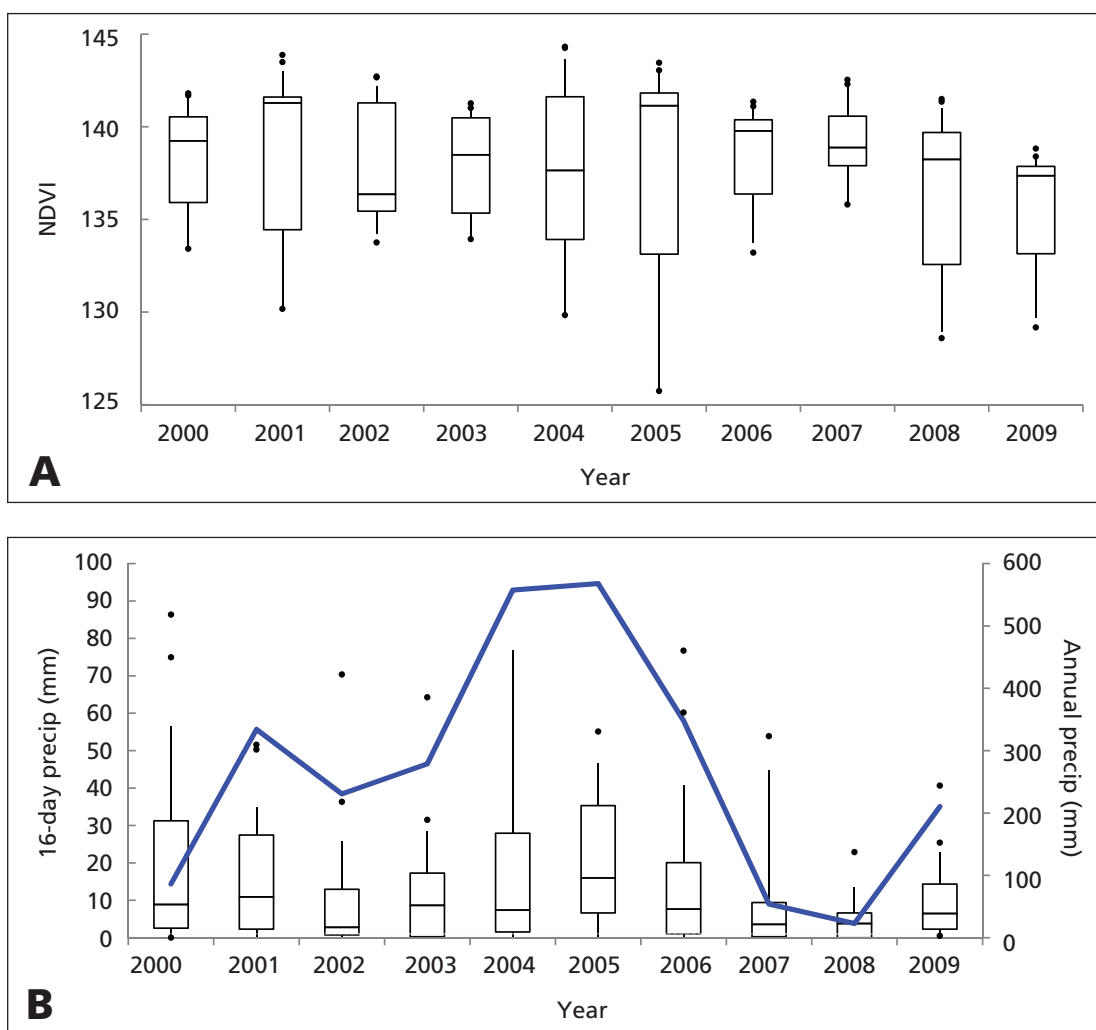


Figure 3.3-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Bryce Canyon NP.

Table 3.3-1. Annual descriptive statistics for parkwide average NDVI, Bryce Canyon NP.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	138.5	139.2	141.8	133.4	8.39	3184
2001	138.8	141.3	143.9	130.2	13.70	3193
2002	137.9	136.4	142.7	133.7	8.95	3172
2003	138.1	138.5	141.3	133.9	7.33	3176
2004	137.4	137.6	144.3	129.8	14.49	3159
2005	137.7	141.1	143.5	125.7	17.72	3166
2006	138.6	139.8	141.3	133.2	8.15	3188
2007	139.1	138.9	142.5	135.8	6.73	3199
2008	136.6	138.2	141.5	128.6	12.91	3142
2009	135.6	137.4	138.8	129.2	9.66	3119

3.3.2 Recent NDVI conditions

The 2009 NDVI curve was below the historical average at every period (Figure 3.3-3a) and was 1.6% below average for the year. Although 2009 cumulative precipitation was 39.1% below average for the year, the depressed NDVI may also have been due in part to the Bridge Fire, which started outside the park on DOY 165 (June 14) and eventually consumed approximately 600 ha (approximately 4%) of the park. Although evaluating the spread of the fire relative to NDVI through time is beyond the scope of this report, it is likely that below-normal precipitation was the primary factor. That, coupled with the Bridge Fire, is sufficient to explain why 2009 exhibited the lowest late-season NDVI in the 10-year record (Figure 3.3-1b).

The magnitude of the Bridge Fire's effect on vegetation may be put in perspective by comparing NDVI for 2008 and 2009. In 2008, conditions were drier than in 2009, and a low-intensity prescribed fire (Puma Fire) conducted on September 8–15 did not have nearly the dramatic effect on NDVI that the 2009 Bridge Fire had.

The spatial distribution of below-average NDVI in 2009 was widespread, indicating that it was primarily driven by below-normal precipitation. Notable exceptions to this were the areas burned in the Bridge and Puma fires. Interestingly, the anomaly map indicates burn severity in addition to burn extent (Figure 3.3-3c). Lighter shades of red represent areas of lighter burn intensity. Above-average NDVI was limited to a small area in the extreme southern end of the park, below the rim. NDVI in the main amphitheater was below average in 2009. On DOY 304 (October 31), most areas of Bryce Canyon NP were between -6.9 and -1.5 NDVI units, or -13.2 and -2.8%, of the long-term average.

3.3.3 Phenology

Over the nine-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 123, 60, 161, and 75 days, respectively. The most productive year, based on I-NDVI, was 2006, while the least productive was 2002 (Table 3.3-2). Year 2006 did not have a noticeably early SOS, but did have the latest EOS (DOY 467; April 12). SOS in 2002 was the latest on record (DOY 240) (August 28) due to minimal winter soil-moisture recharge coupled with a relatively dry spring. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. Years 2006 and 2002 certainly fit this pattern, with the longest (344 days) and shortest (183 days) growing seasons, respectively.

There were no statistically significant linear trends (p -value < 0.1) in the phenology metrics observed at the parkwide scale for the period of analysis (Table 3.3-2). This was not surprising, considering the enormous variability in precipitation and vegetation response. Year 2002 was notable for its late SOS, which did not occur until well into the monsoon, while the EOS and LOS contribution to annual productivity in 2006 were also clearly apparent (Figure 3.3-4). A longer observation period may show trends over time, but given the variability in precipitation and vegetation response observed thus far, it may take longer to observe trends, if they occur, at Bryce Canyon than at other parks.

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends, or only weak trends (Table 3.3-2, Figure 3.3-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

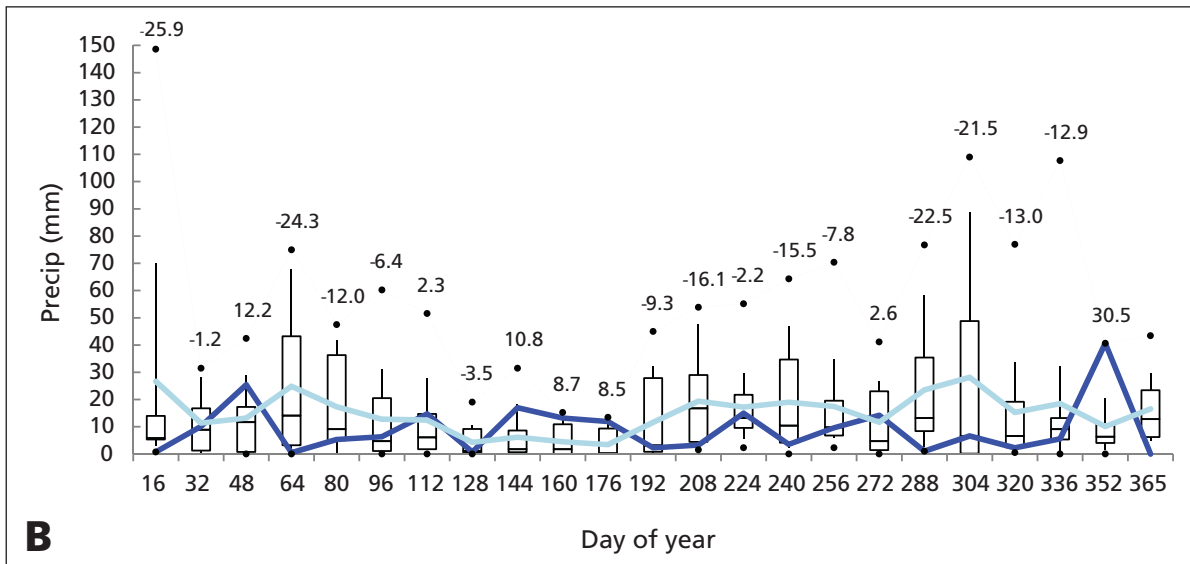
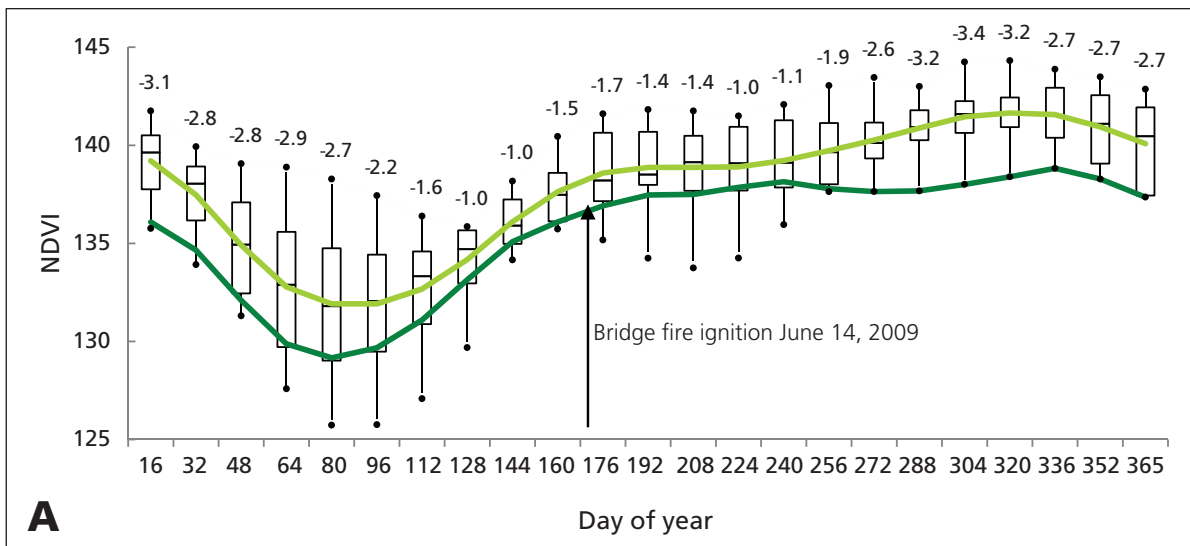


Figure 3.3-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Bryce Canyon NP. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period.

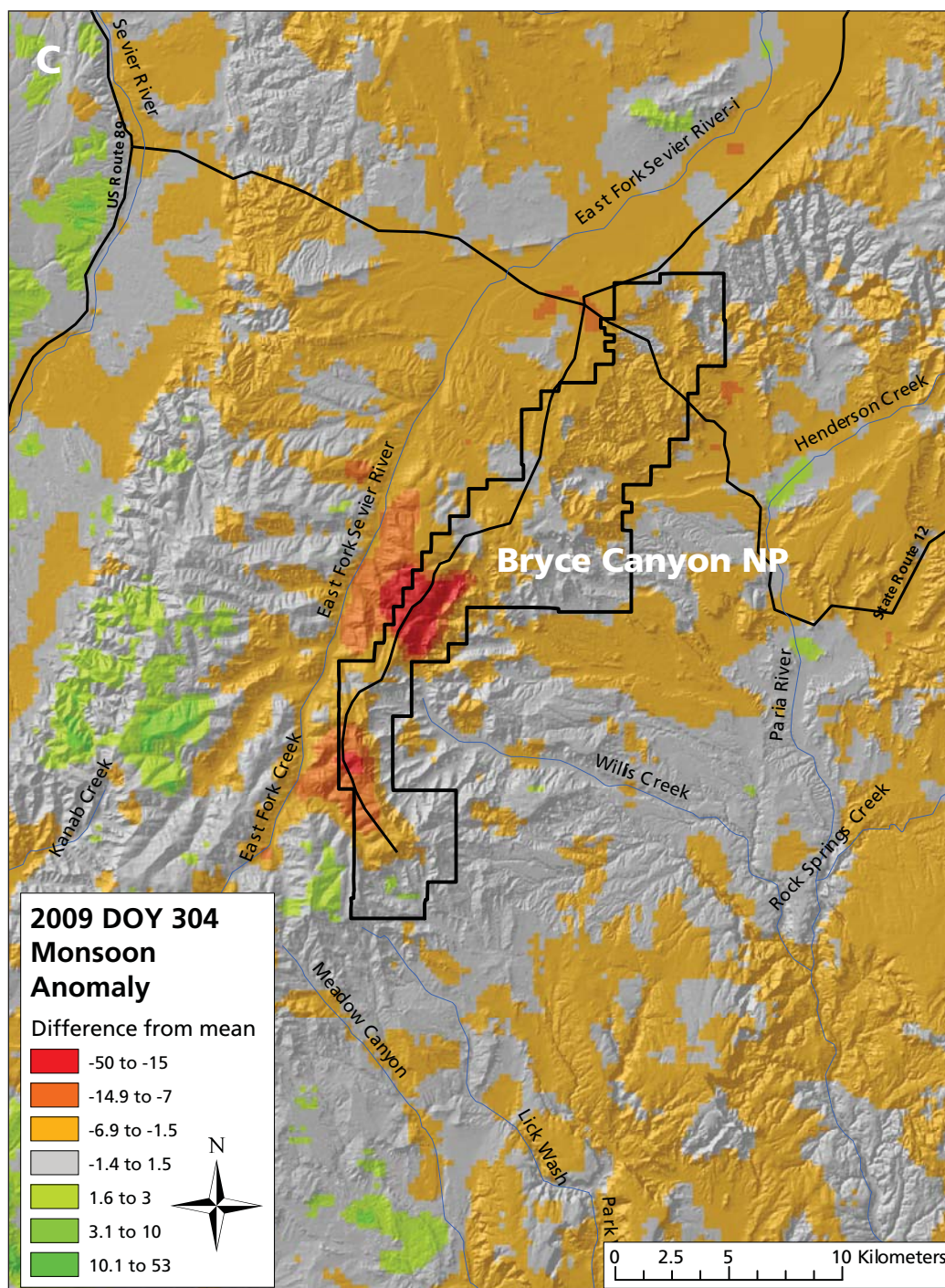


Figure 3.3-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Bryce Canyon NP. The dark red anomaly in the center of the park represents the area where the Bridge Fire occurred.

Table 3.3-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Bryce Canyon NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	127	333	421	294	2911	10.02
2001	123	276	435	312	3082	11.71
2002	240	334	424	183	1816	8.85
2003	155	280	407	252	2489	9.34
2004	117	338	424	307	2908	16.70
2005	128	262	422	293	2796	13.93
2006	123	264	467	344	3341	6.76
2007	170	320	419	249	2495	10.40
2008	123	293	414	292	2750	12.64
<i>correlation</i>	-0.16	-0.27	0.07	0.16	0.10	0.11
<i>slope</i>	-2.28	-3.06	0.46	2.79	15.87	0.12
<i>p-val slope</i>	0.69	0.48	0.85	0.67	0.80	0.78
<i>intercept</i>	4718.61	6434.77	-498.50	-5319.64	-29064.80	-221.28
<i>p-val intercept</i>	0.68	0.46	0.92	0.69	0.82	0.79

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude.

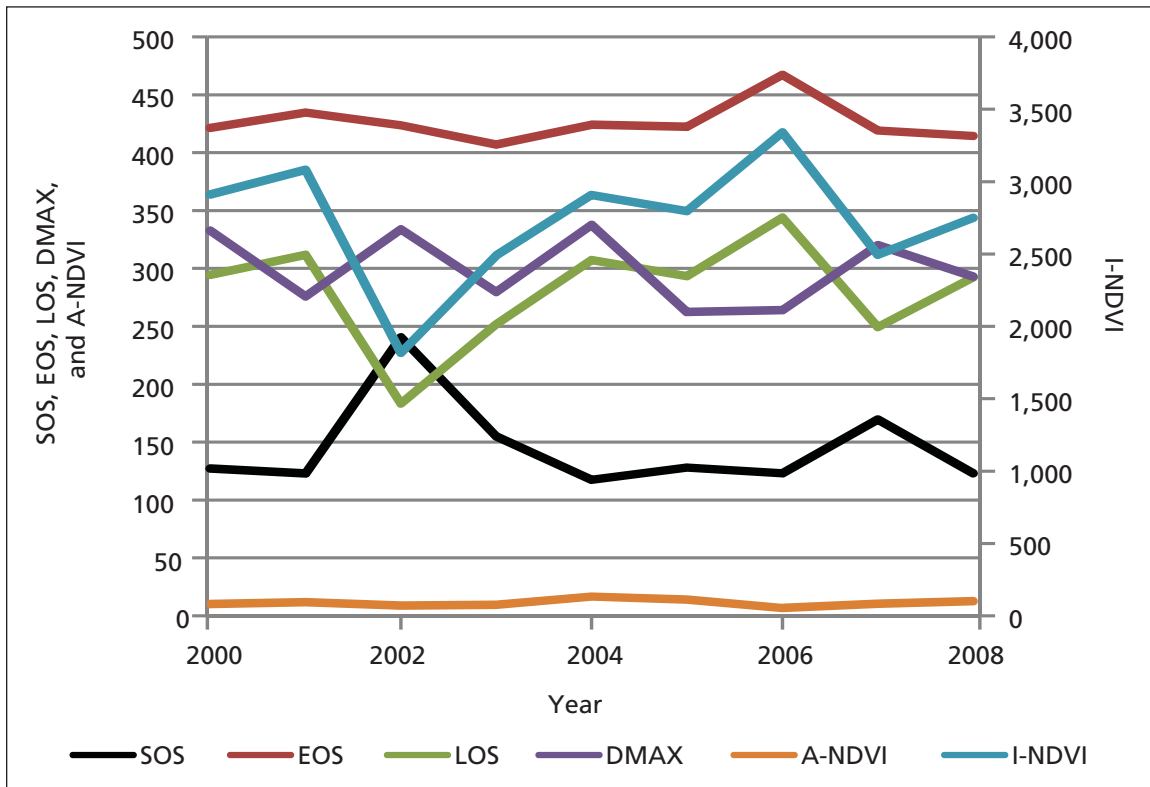


Figure 3.3-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Bryce Canyon NP. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.3.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Bryce Canyon (Figure 3.3-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is exceedingly unlikely (e.g., between DOYs 150 and 250). However, interpretation of what appear to be spurious results (five instances in the 10-year record) at this time of year is complicated in higher-elevation areas, where summer storms may drop significant amounts of hail that could be interpreted as snow by the processing algorithm. Cumulative exceedance frequency curves indicate that years 2001, 2004, 2008, and 2009 had the most extensive and persistent snow cover (Figure 3.3-5b). Years 2001 and 2004 had the two highest early season peak NDVI values and were two of the four most productive years in the record (Tables 3.3-1, 3.3-2).

Although water content cannot be directly inferred from snow cover, they are related—as indicated by productive growth years that follow winters with more persistent snow-cover extent that likely recharges soil with more moisture than in years with less persistent snow cover. Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. The inverse relationship between these two variables seen in 2002 (Figure 3.3-6) is largely a product of spurious conditions that caused the SOS not to register until well into the monsoon season (DOY 240; August 28). When 2002 is removed from the regression relationship, the slope becomes virtually flat, with $R^2 = 0.0002$. Stronger relationships might occur at finer spatial scales if the breaks were masked from analysis where snowmelt/SOS coupling is likely confounded by steep aspects

and lack of vegetation. However, air and soil temperatures are also important to SOS, and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Bryce Canyon NP, defined here as less than 5.5% coverage, was between DOYs 116 (April 26) and 267 (Sept 24). A statistically significant trend for snowmelt, or DOY when snow cover falls below 5.5%, was observed. The trend was in the positive direction and appeared to be a result of late snowmelt in 2008 (Table 3.3-3).

The dramatic dip in early 2005 NDVI may reflect freeze-kill from winter 2004–2005 that damaged understory vegetation (specifically, greenleaf manzanita). This indicates either that the cause of the 2004–2005 minimum was short-lived and vegetation recovered or, more likely, that the extreme minimum in 2004 was an artifact of the masking and smoothing performed during image processing prior to analysis. Support for the latter conclusion is provided via personal communication with park staff (Bruce Fields), who indicated that nothing unusual in terms of disturbance occurred in fall 2004 or winter 2004–2005.

Although the winter-kill scenario is speculative, the snow-cover analysis shows that during the period centered on January 11, 2005, Bryce Canyon NP was only 22% snow-covered, at a time when average minimum temperature was -18°C . The lack of insulating snow cover and low minimum temperatures may have conspired to kill evergreen shrubs. However, similar patterns were not apparent during the following (2005–2006) winter (centered on December 29, 2005), when both low snow cover (17%) and low temperatures (-26°C) occurred simultaneously. Other factors, such as freezing rain, may have contributed to making winter 2004–2005 exceptionally hard on evergreen understory vegetation.

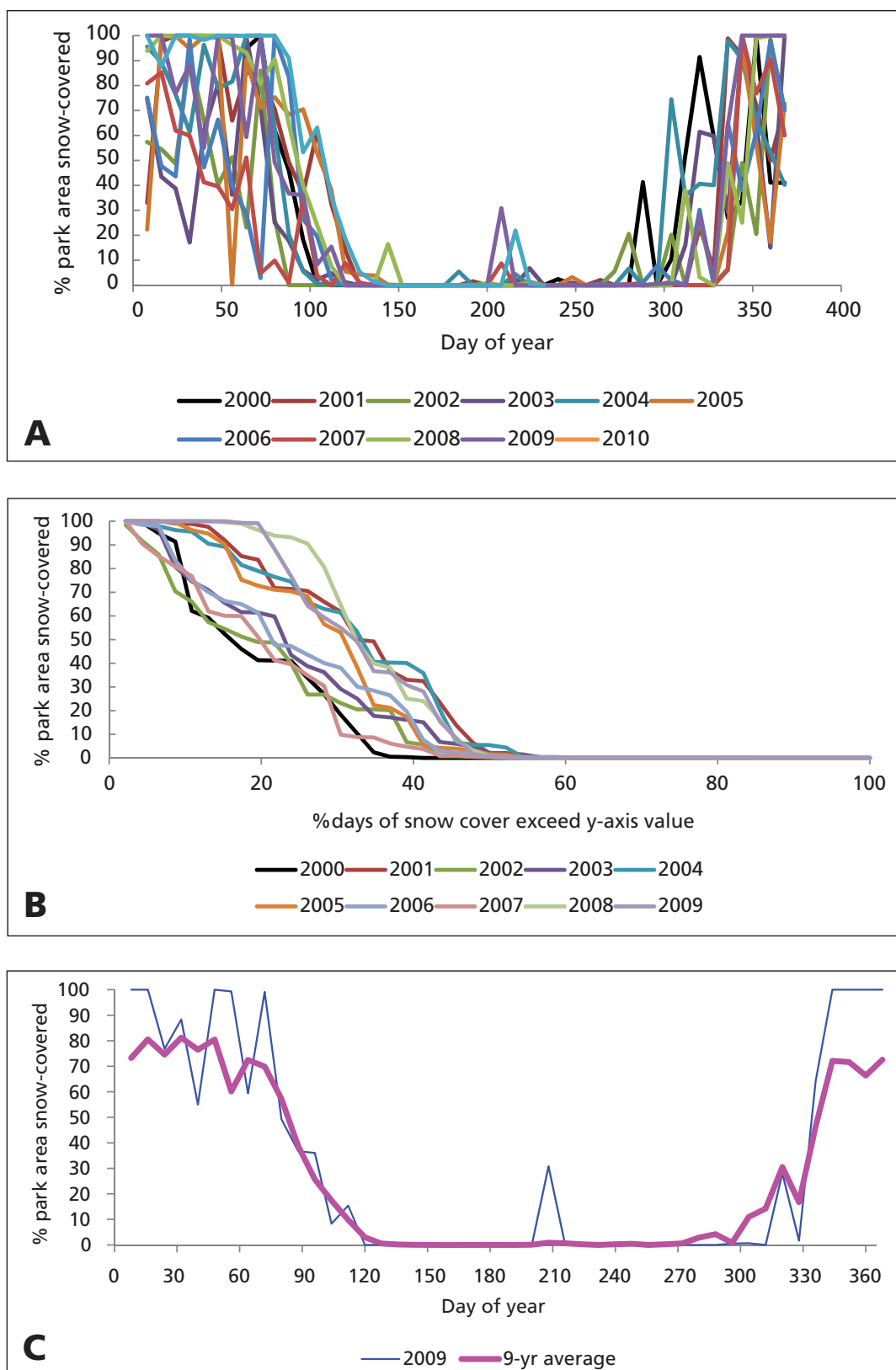


Figure 3.3-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Bryce Canyon NP.

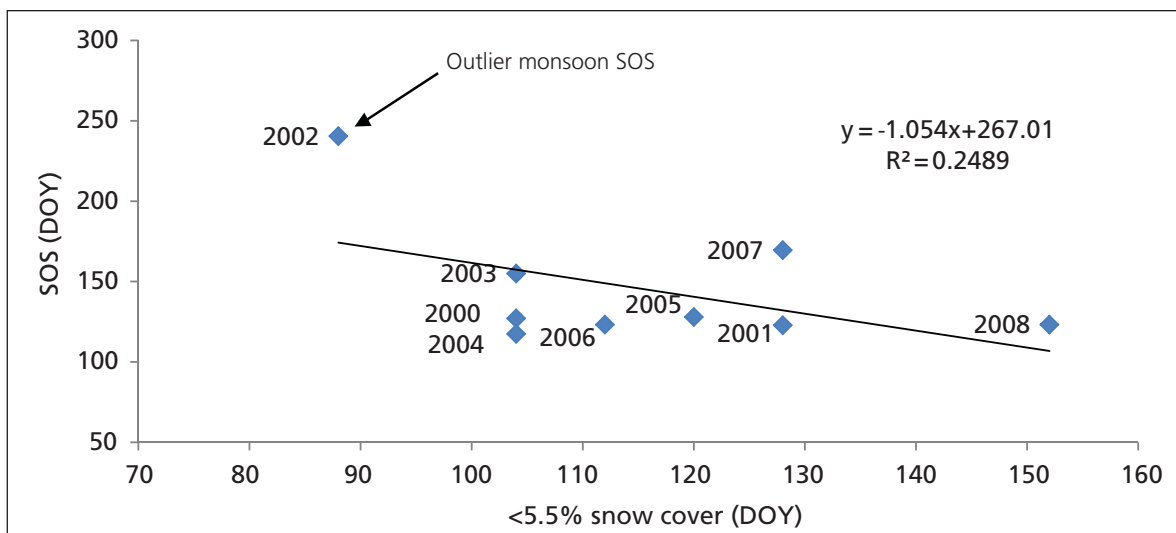


Figure 3.3-6. Relationship between snowmelt DOY and SOS, Bryce Canyon NP.

Table 3.3-3. Timing and duration of snow cover, Bryce Canyon NP.

Year	Snow off	Snow on	DOY <5.5% cover	DOY >5.5% cover	Days snow-free	Days snow-covered
2000	4/13/2000	10/6/2000	104	280	176	189
2001	5/8/2001	11/8/2001	128	312	184	181
2002	3/30/2002	9/22/2002	88	264	176	189
2003	4/16/2003	8/6/2003	104	216	112	253
2004	4/16/2004	10/1/2004	104	272	168	197
2005	5/3/2005	11/27/2005	120	328	208	157
2006	4/26/2006	10/19/2006	112	288	176	189
2007	5/13/2007	7/24/2007	128	200	72	293
2008	6/6/2008	11/5/2008	152	304	152	213
2009	5/6/2009	7/25/2009	120	200	80	285
<i>correlation</i>			0.57	-0.33	-0.55	0.55
<i>slope</i>			3.35	-4.99	-8.34	8.34
<i>p-val slope</i>			0.09	0.36	0.10	0.10
<i>intercept</i>			-6590	10277	16867	-16502
<i>p-val intercept</i>			0.09	0.35	0.10	0.11

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

3.4 Canyonlands National Park

3.4.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrated a high degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.4-1a). Vegetation condition in Canyonlands NP is strongly influenced by winter soil-moisture recharge and monsoon weather patterns, as indicated by a prominent bi-modal annual distribution in the NDVI curves that corresponds with timing, magnitude, and consistency of winter and monsoon-season precipitation patterns that charge soil moisture for plant growth with warmer spring temperatures.

The stacked annual curves illustrate differences in the magnitude and timing of significant growth periods between years (Figure 3.4-1b and c). The high productivity and strongly bi-modal signature of 2005 and 2007 contrasts with the lower productivity and much weaker bi-modal signature of 2000, when monsoon precipitation was insufficient to support vigorous late-season growth (Figure 3.4-1a). The opposite occurred in 2002, when a much stronger monsoon peak followed a relatively weak spring growth season. Years 2005 and 2007 illustrate the strong interaction of precipitation timing and vegetation functional types adapted to spring or monsoon precipitation. In 2005, monsoon productivity was greater than spring productivity following a dry winter. In 2007, when a wet winter stimulated vigorous early season growth, the opposite occurred.

Although seasonal patterns are likely of most interest and import, given the strong monsoon coupling of precipitation and plant growth in the park, descriptive statistics for annual NDVI are provided for inter-annual comparison that may be informative for extreme years. Annual average NDVI differed by 1.2%, from the lowest in 2009 (116.6) to the highest (118.0) in 2005. The annual maximum NDVI differed by 2.3%, from the lowest (117.3) in year 2009 to the highest (120.1) in 2007 (Table 3.4-1).

Year 2009 had the narrowest range in NDVI, and the lowest median NDVI in the 10-year record (Table 3.4-1, Figure 3.4-1a.) This corresponds to the lowest cumulative annual precipitation observed at the station for the same period and, perhaps more importantly, corresponds to one of the lowest cumulative winter soil-moisture recharge

periods in the 10-year record (Figures 3.4-1a and 3.4-2b). Winter soil-moisture recharge is critically important to early season native vegetation on the Colorado Plateau, because it is generally the most reliable (Comstock and Ehleringer 1992). The strong response to monsoon precipitation timing and magnitude is apparent in years like 2002, when 45.5 mm of precipitation fell at the Neck weather station at Island in the Sky in the 16 days preceding August 13, an optimal time for soil-moisture recharge for late season-adapted vegetation (Figure 3.4-1a).

Weather data from the NWS Coop station (Neck at Island in the Sky) were used to interpret NDVI variation (Figure 3.4-2b). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. It is likely that frontal winter precipitation recorded at the station is more representative of broader areas than summer convective precipitation associated with monsoon storms.

3.4.2 Recent NDVI conditions

The 2009 NDVI curve was lower than the historical average during every 16-day interval after DOY 80 (March 21) (Figure 3.4-3a) and was 0.52% below average for the year, corresponding with a cumulative precipitation for 2009 of 36.2% below average. The early season NDVI curve for 2009 followed the long-term average, with what appeared to be normal winter soil-moisture recharge (Figure 3.4-3a), but then fell below average, with little additional precipitation until DOY 144 (May 24) (Figure 3.4-3b). Precipitation was generally below long-term average after DOY 192 (July 11), which may explain the below-average NDVI for the remainder of the year.

The spatial distribution of below-average NDVI in 2009 was limited to a few areas along the Green River, one small area along Salt Creek, and the extreme southeast portion of the park (Figure 3.4-3c). The areas along the Green River should be evaluated for possible defoliation of tamarisk by beetles. Island in the Sky and the southern portion of the Needles District were the largest isolated areas of above-average NDVI. On DOY 304 (October 31), most areas of Canyonlands NP were within ± 1.5 NDVI units, or $\pm 2.8\%$, of the long-term average.

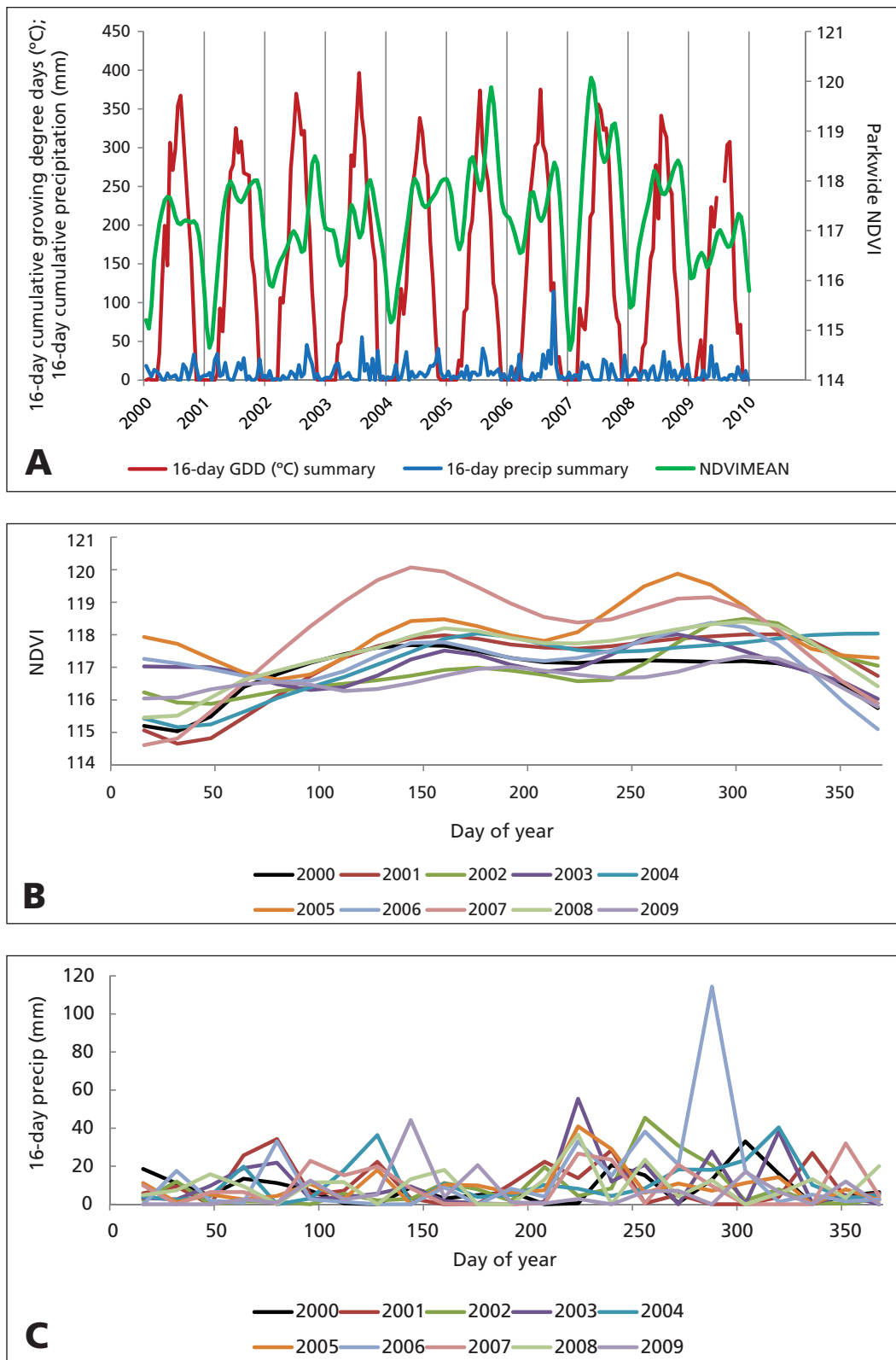


Figure 3.4-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Canyonlands NP.

Table 3.4-1. Descriptive statistics for parkwide average NDVI, Canyonlands NP.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	116.9	117.2	117.7	115.0	2.65	2688
2001	117.1	117.6	118.0	114.7	3.36	2694
2002	116.9	116.8	118.5	115.9	2.61	2690
2003	117.0	117.0	118.0	116.0	1.98	2692
2004	117.1	117.5	118.0	115.2	2.88	2694
2005	118.0	118.0	119.9	116.6	3.25	2714
2006	117.2	117.3	118.4	115.1	3.27	2696
2007	118.0	118.5	120.1	114.6	5.46	2714
2008	117.4	117.7	118.4	115.5	2.95	2701
2009	116.6	116.7	117.3	115.8	1.55	2682

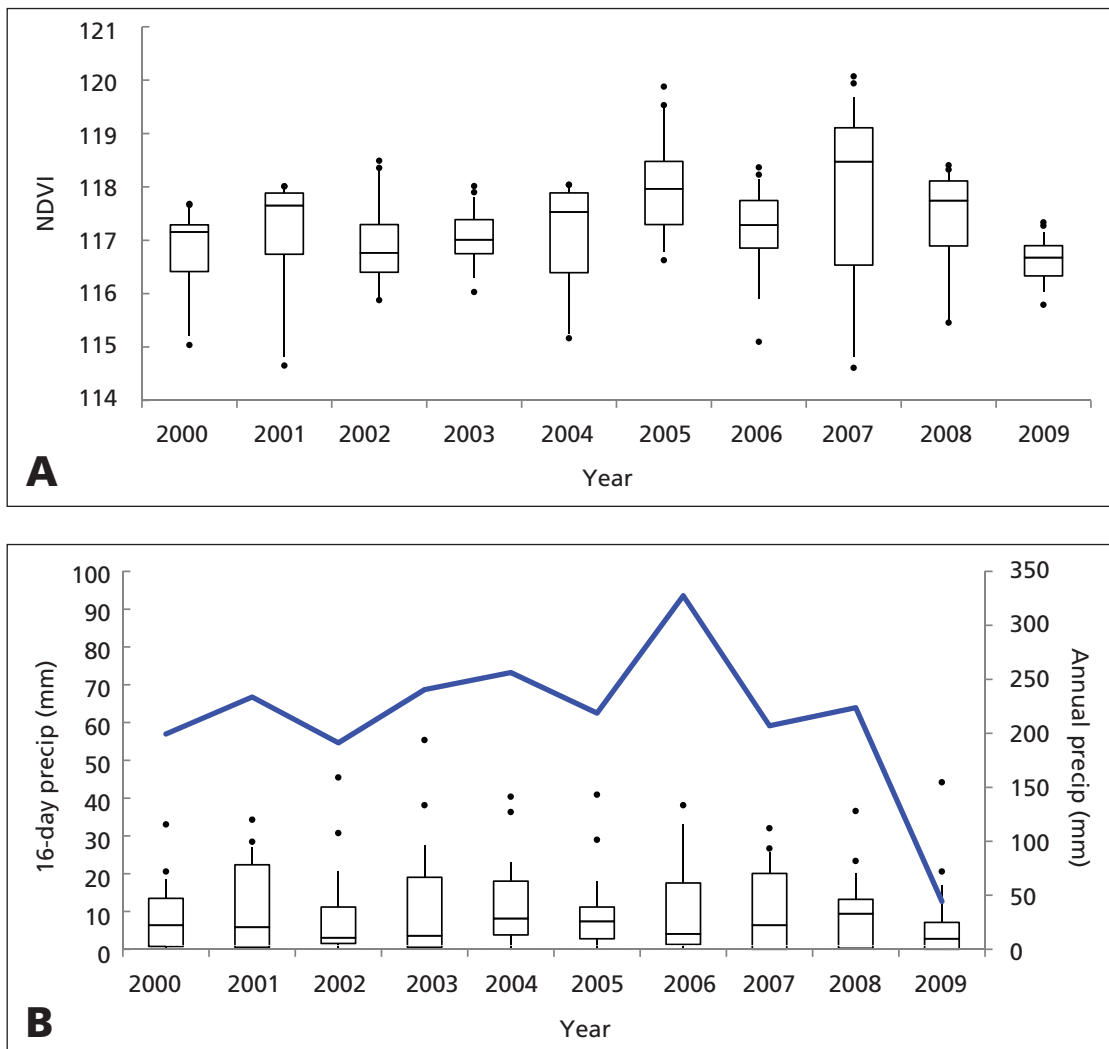


Figure 3.4-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Canyonlands NP.

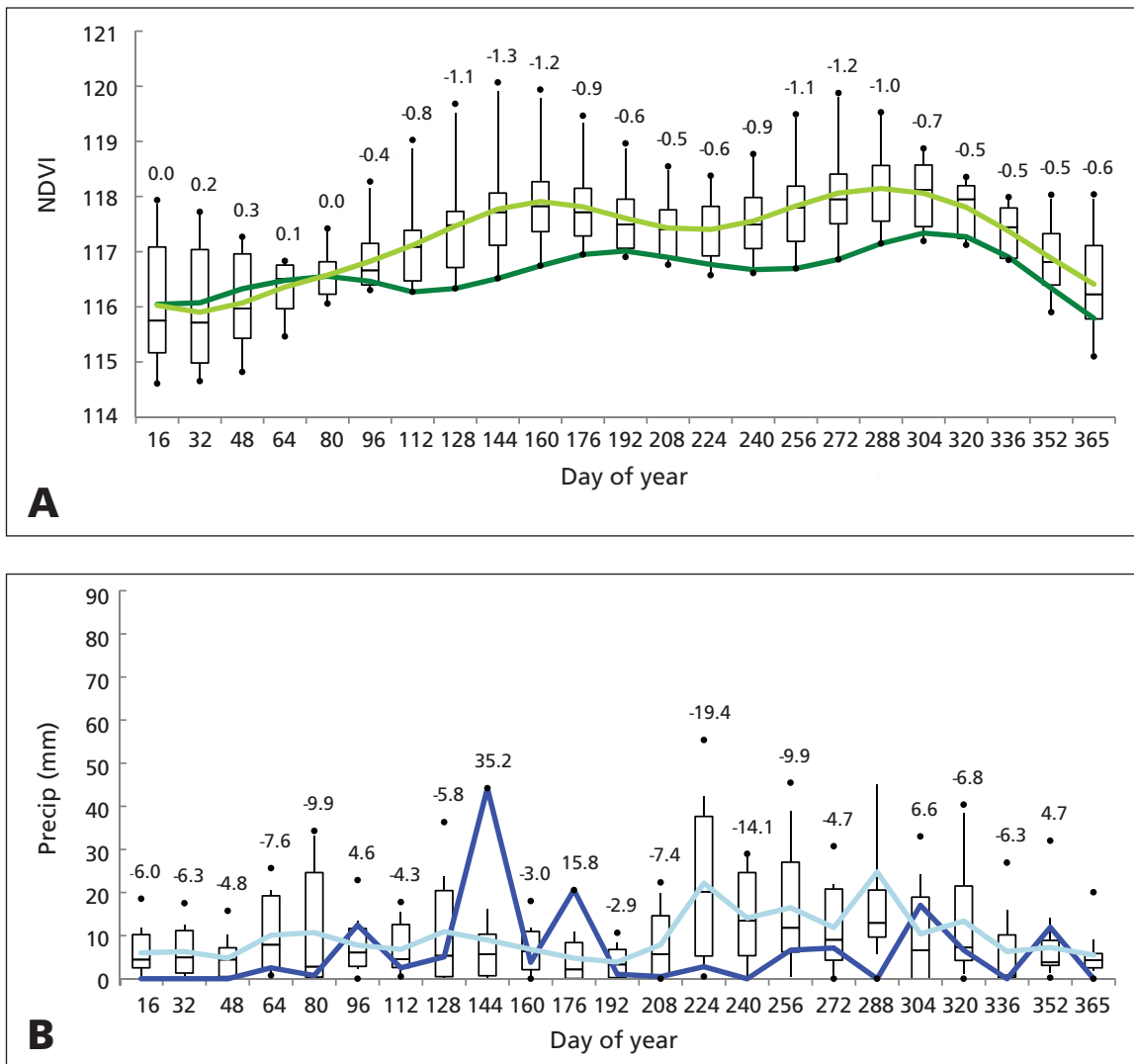


Figure 3.4-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Canyonlands NP. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

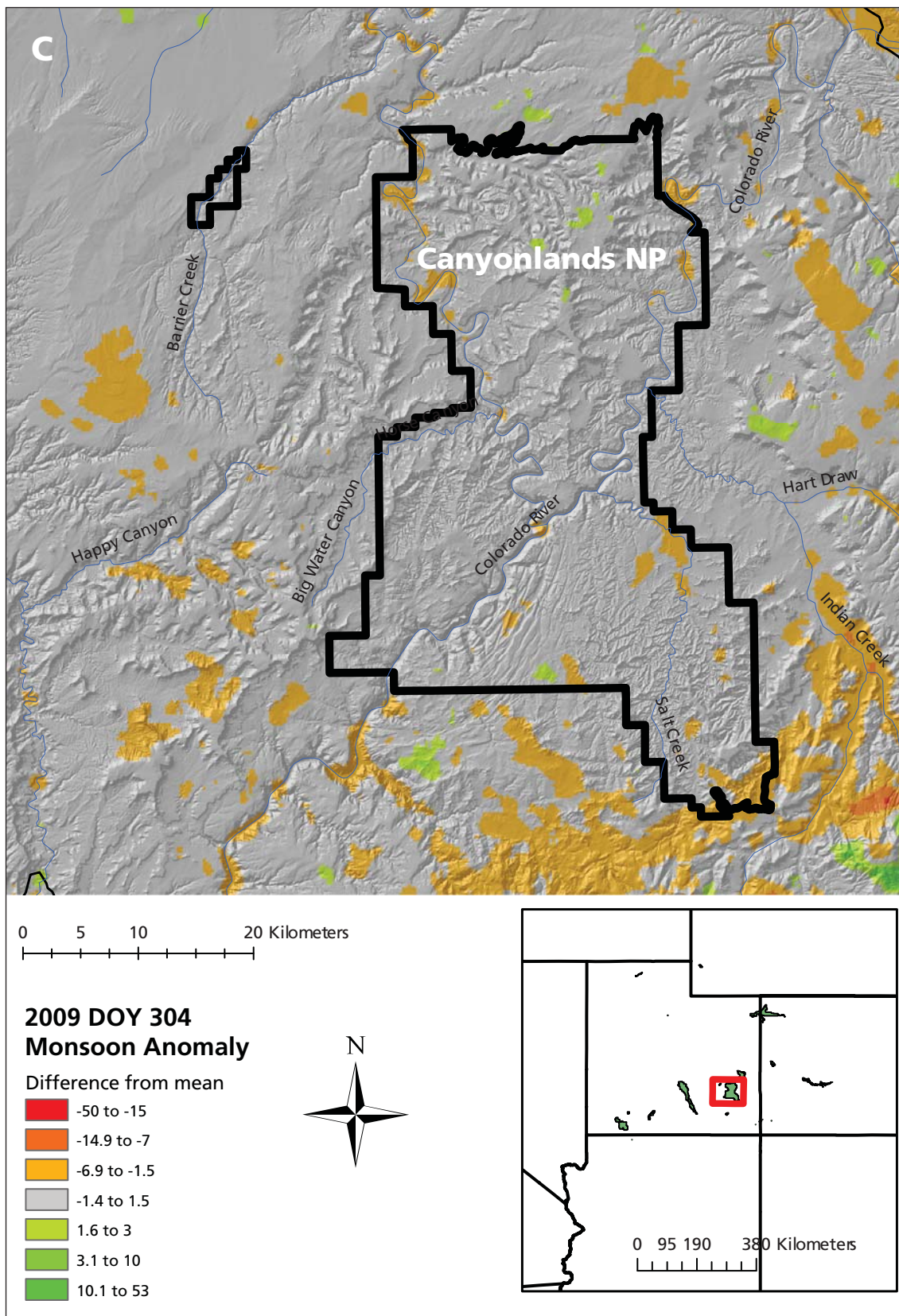


Figure 3.4-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Canyonlands NP.

3.4.3 Phenology

In most years, there are two distinct growing seasons at Canyonlands NP that represent the interaction of plant functional types (annual/perennial, early season/late season), phenology, and suitability of moisture for growth. The two seasons (spring and monsoon) are evaluated separately due to the distinct bi-modal nature of phenology at the park.

3.4.3.1 Spring

Over the 10-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 73, 37, 102, and 52 days, respectively. The most productive spring, based on I-NDVI, was 2009, while the least productive was 2003. The productivity rankings are counterintuitive, considering the relative position of curves for those years compared to other years in the time series (Figure 3.4-1a) and stacked series (Figure 3.4-1b); this is because length of growing season, rather than peak magnitude, is the primary determinant of annual productivity rankings. Year 2009 had the longest spring growing season (177 days), while 2003 had the shortest spring season (75 days)—102 days fewer than 2009. The most plausible explanation for the much longer growing season in 2009 is the early SOS date, in which 25% of the spring NDVI amplitude was achieved by DOY 48 (February 17). The remarkable early season growth is explained by the early accumulation of growing degree days. Although 2009 got off to an early start, it was temporarily hampered by a cool

weather spell that resulted in a dip in the NDVI signal near DOY 97 (April 7); at this time, when the GDD number would typically be steadily increasing, it dipped back to zero (Figure 3.4-1a). No spring phenology metrics exhibited a statistically significant linear trend (p-value <0.1) (Table 3.4-2, Figure 3.4-4a).

3.4.3.2 Monsoon

Over the nine-year historical record, the ranges of monsoon SOS, EOS, LOS, and DMAX were 46, 77, 60, and 86 days, respectively. The most productive monsoon season, based on I-NDVI, was 2002, while the least productive was 2008. The monsoon-season historical record does not include 2009 because the EOS for that year was expected to occur in early 2010, which was beyond the time period evaluated in this report. There were no significant linear trends in monsoon phenology observed for this period of record (Table 3.4-3; Figure 3.4-4b).

3.4.3.3 Summary

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends (Tables 3.4-2, 3.4-3; Figure 3.4-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

Table 3.4-2. Spring-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Canyonlands NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	51	132	195	143	1288	1.60
2001	66	143	197	131	1172	1.84
2002	72	169	214	142	1283	0.74
2003	121	161	196	75	819	0.88
2004	74	168	218	144	1288	1.71
2005	106	152	190	85	825	1.23
2006	110	152	189	79	821	0.88
2007	54	139	198	144	1304	3.52
2008	51	154	200	148	1292	1.55
2009	48	184	226	177	1516	0.62
<i>correlation</i>	-0.15	0.41	0.25	0.21	0.19	0.06
<i>slope</i>	-1.35	2.08	1.04	2.35	15.39	0.02
<i>p-val slope</i>	0.68	0.24	0.48	0.57	0.60	0.87
<i>intercept</i>	2776	-4014	-1883	-4588	-29698	-31
<i>p-val intercept</i>	0.67	0.26	0.52	0.58	0.62	0.88

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

Table 3.4-3. Monsoon-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Canyonlands NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	231	295	378	147	1284	1.30
2001	246	313	378	132	1175	1.28
2002	255	305	426	172	1527	2.08
2003	231	280	372	141	1288	1.98
2004	275	362	427	152	1295	0.99
2005	229	275	350	121	1068	2.60
2006	238	296	358	120	1173	2.42
2007	245	290	355	111	1062	2.20
2008	248	306	363	115	1060	1.51
<i>correlation</i>	0.10	-0.09	-0.45	-0.72	-0.65	0.40
<i>slope</i>	0.52	-0.83	-4.73	-5.20	-36.05	0.08
<i>p-val slope</i>	0.68	0.79	0.48	0.83	0.80	0.43
<i>intercept</i>	-803	1964	9854	10564	73459	-163
<i>p-val intercept</i>	0.67	0.82	0.53	0.82	0.78	0.44

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

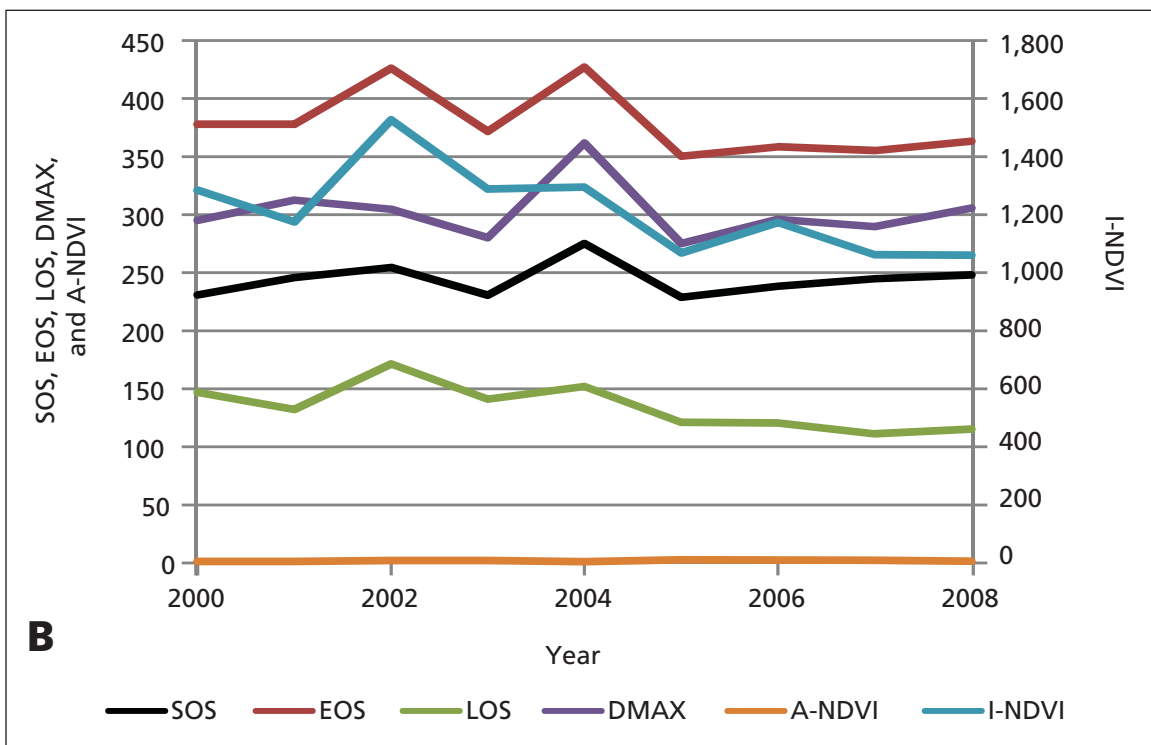
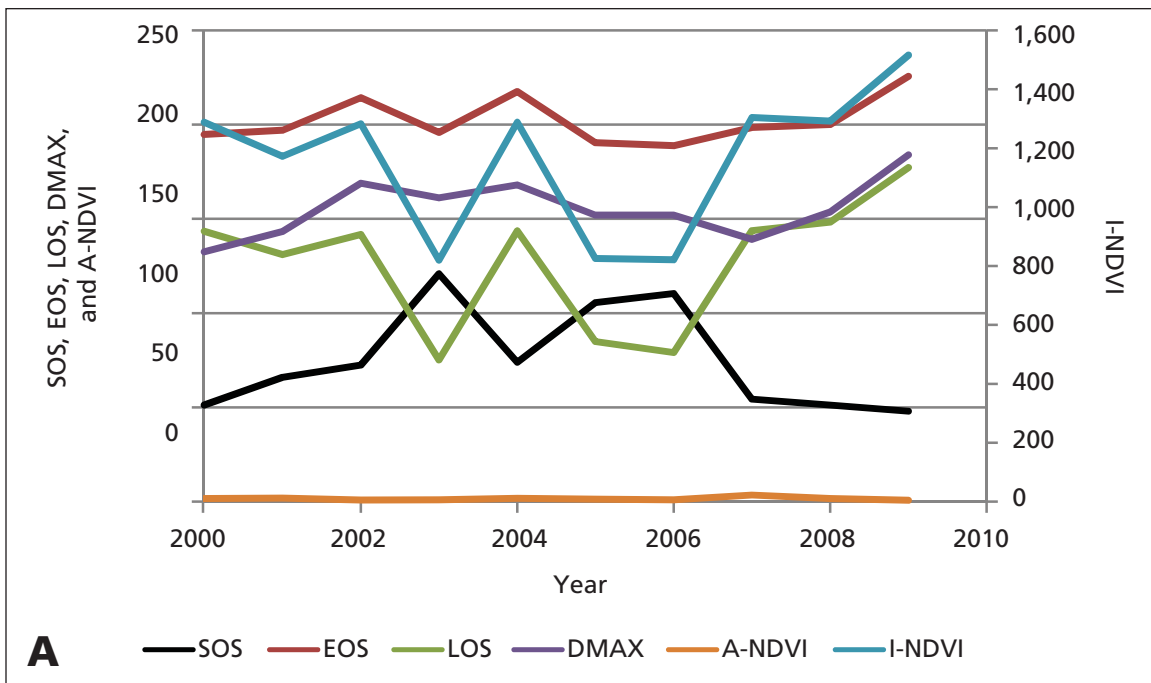


Figure 3.4-4. Annual (a) spring and (b) monsoon phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI and A-NDVI, Canyonlands NP. For both figures, metrics were computed with TimeSat for a bi-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.4.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Canyonlands NP (Figure 3.4-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also a small amount of noise in the snow-cover extent data, represented by spikes during times of year when snow cover is exceedingly unlikely (e.g., at DOY 224; August 12). The cumulative exceedance frequency curves show that 2009 exhibited the most snow cover for the longest duration in the record, followed by 2007 (Figure 3.4-5b). On average, Canyonlands NP has less than 0.3% snow cover by DOY 84 (March 25) and greater than 0.3% snow cover by DOY 260 (September 17). The 10-year average snow-free period in the park, defined here as less than 0.3% coverage, was 177 days (Table 3.4-4).

Statistically significant linear trends (p -value < 0.1) in the snow-cover extent metrics were observed at the parkwide scale for the period of analysis (Table 3.4.4) for first snowfall (10 days earlier per year), days snow-free (decreased by 10

days), and days snow-covered (increased by 10 days). These trends are statistically significant but likely not physically plausible, and may be the result of a step-change of low-snow years between 2000 and 2004 and higher snow years between 2005 and 2009.

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. A very weak positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.01$; Figure 3.4-6) for the eight years of record when snowmelt date and spring SOS could be determined. The relationship may be weak because temperature has more of an effect on spring SOS than snow cover in this park. In a semi-arid environment like Canyonlands NP, snow cover and temperature are not tightly coupled in all years, as might be the case at higher elevations that typically receive more snow when temperatures are low. The snow extent/SOS relationship is further complicated by the high variability in annual snow-cover extent.

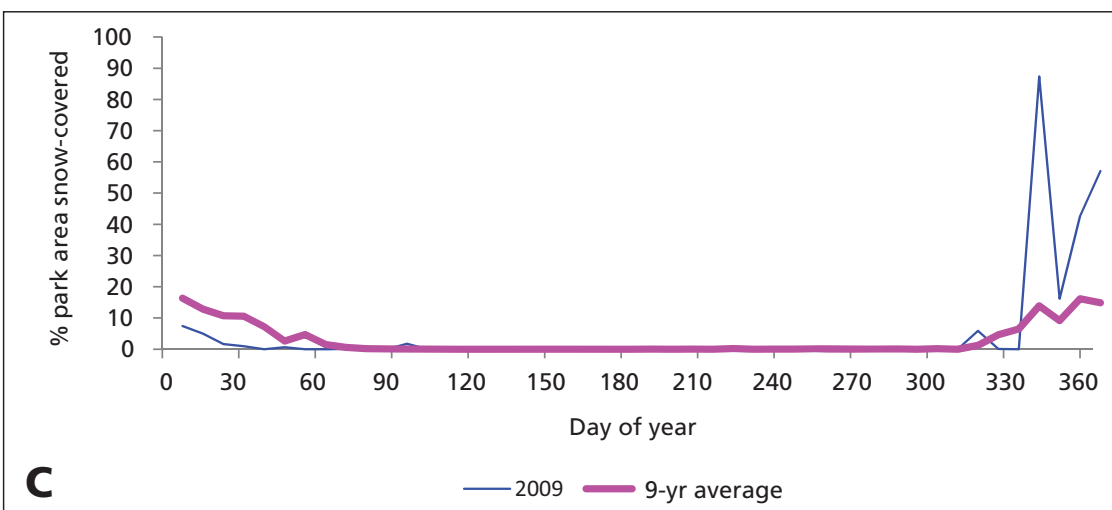
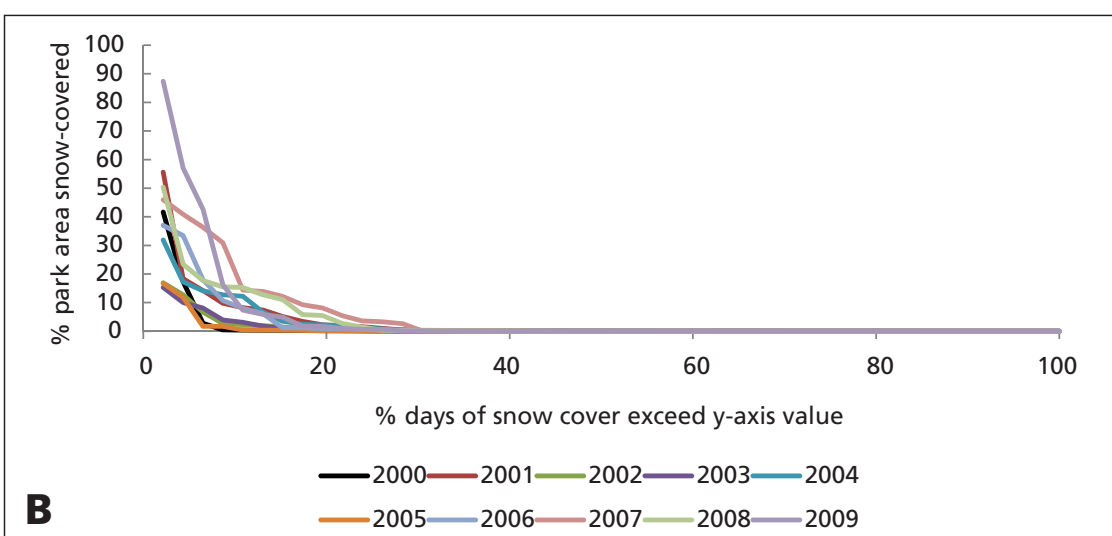
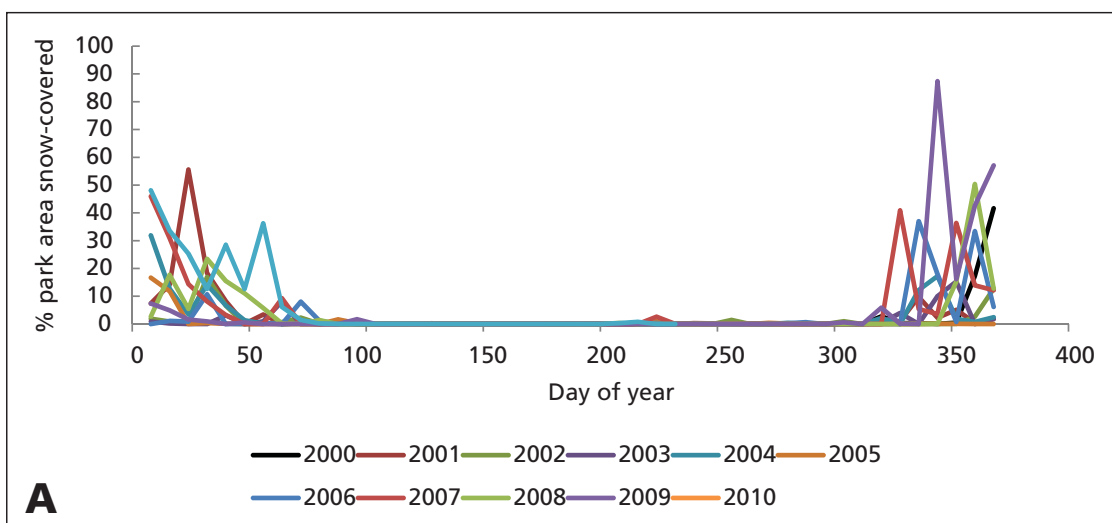


Figure 3.4-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Canyonlands NP.

Table 3.4-4. Timing and duration of snow cover, Canyonlands NP.

Year	Snow off	Snow on	DOY <0.3% cover	DOY >0.3% cover	Days snow-free	Days snow-covered
2000	4/5/2000	11/7/2000	96	312	216	149
2001	3/21/2001	11/16/2001	80	320	240	125
2002	3/22/2002	9/6/2002	80	248	168	197
2003	3/15/2003	11/10/2003	72	312	240	125
2004	2/28/2004	10/1/2004	56	272	216	149
2005	4/17/2005	8/7/2005	104	216	112	253
2006	4/2/2006	8/8/2006	88	216	128	237
2007	3/18/2007	8/9/2007	72	216	144	221
2008	4/3/2008	7/24/2008	88	200	112	253
2009	4/20/2009	10/29/2009	104	296	192	173
<i>correlation</i>			0.22	-0.58	-0.60	0.60
<i>slope</i>			1.12	-9.02	-10.13	10.13
<i>p-val slope</i>			0.54	0.08	0.06	0.06
<i>intercept</i>			-2151	18338	20489	-20124
<i>p-val intercept</i>			0.55	0.08	0.06	0.07

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

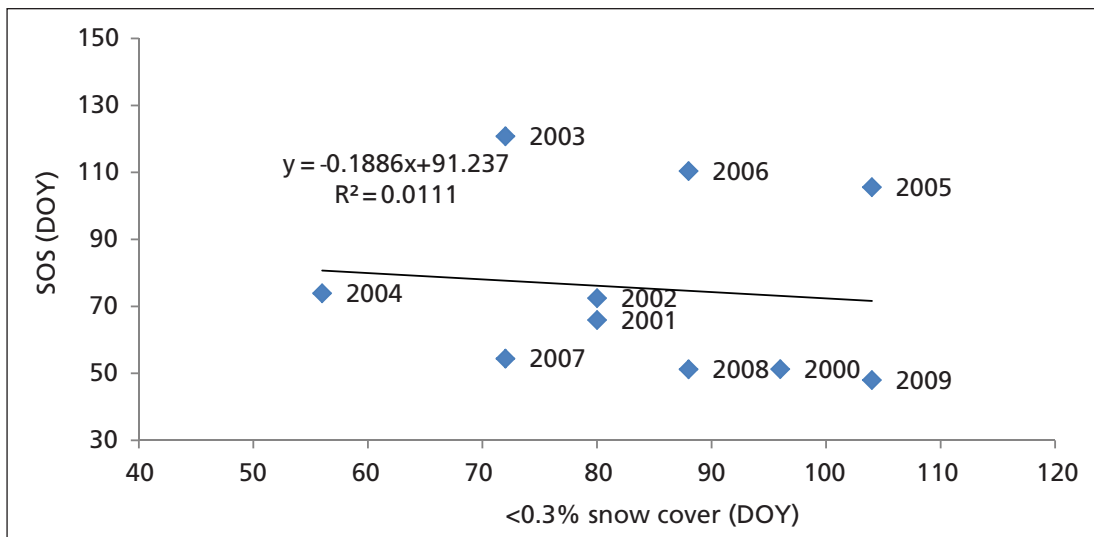


Figure 3.4-6. Relationship between snowmelt DOY and SOS, Canyonlands NP.

3.5 Capitol Reef National Park

3.5.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.5-1a). The strength of seasonal bi-modality in the 10-year time series is highly variable, most likely due to high variability in both winter soil-moisture recharge and monsoon precipitation. This variability in precipitation is apparent in the “jagged” nature of the annual curves, typical of lower elevations on the Colorado Plateau, where early and late season vegetation types respond strongly to the degree of seasonal wetting.

The influence of precipitation variability is dramatically illustrated by the year 2002 NDVI curve. Very low precipitation in winter 2001–2002, plus minimal precipitation in 2002 until DOY 208 (July 27), resulted in almost imperceptible spring growth (Figure 3.5-1a, b). However, after monsoon precipitation began, NDVI responded almost immediately (118.3) but did not peak until DOY 311 (November 7) (see Tables 3.5-1 and 3.5-2). The influence of precipitation variability is further discussed in Section 3.5.3.

When annual curves are stacked (Figure 3.5-1b), a more direct year-to-year comparison of NDVI magnitude and timing is possible. The bi-modal signature, when present, becomes more apparent, as with year 2005. The relationship between NDVI and precipitation is very strong at Capitol Reef NP, with almost every precipitation pulse answered soon after by an NDVI pulse. In other Colorado Plateau parks, precipitation pulses do not always translate to NDVI pulses when precipitation availability does not coincide with plant needs. This may indicate that Capitol Reef NP has a more even spatial distribution of vegetation functional types (early vs. late season) than other parks. The cause of the significant dip in spring 2001 NDVI is unknown, but was apparently not related to extended snow cover, as snow-cover extent dropped below 3% at DOY 80 (March 21), within five days of the 10-year average (see Table 3.5-3).

Weather data from the park’s NWS Coop station were used to interpret NDVI variation (Figures 3.5-1c and 3.5-2b). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally

tracks regional extremes. Year 2005 had the maximum NDVI in the record (120.3). It occurred late in the year, at DOY 275 (October 2), following what appeared to be the most consistent—if not most abundant—summer precipitation in the 10-year record (Figures 3.5-1a, c). Year 2001 had the most extreme minimum (114.5), perhaps due to 2000–2001 winter snow cover, but eventually reached the 10-year average maximum NDVI (118.7) (Table 3.5-1). Year 2000 exhibited the narrowest range in annual maximum and minimum NDVI (0.86), which may be explained by relatively low precipitation preceding the 2000 growing season and low precipitation until DOY 239 (August 27) (Figure 3.5-1a).

The record NDVI range in 2005 was related more to consistent warm-season precipitation—when GDD was above zero, stimulating record-setting productivity (maximum NDVI = 120.3, Table 3.5-1)—than to winter conditions that depressed NDVI, as in early 2001 (Figure 3.5-1a, b). In general, years with higher cumulative annual precipitation had higher median NDVI, and years with lower cumulative annual precipitation had lower median NDVI (Figure 3.5-2a, b). However, the timing and consistency of precipitation plays a more important role in productivity than cumulative annual precipitation.

3.5.2 Recent NDVI conditions

The 2009 NDVI curve was below the historical average at every period (Figure 3.5-3a) and was 0.58% below average for the year. This corresponded with 2009 cumulative precipitation, which was 32.1% below average. The degree to which vegetation condition tracks precipitation was apparent between DOYs 144 and 192, when periods of above-average precipitation caused a pulse in productivity that almost achieved average conditions before falling off with generally below-average conditions for the remainder of the year (Figure 3.5-3a, b).

The spatial distribution of below-average NDVI in 2009 was limited to a few areas in the extreme northern portion of the park (Figure 3.5-3c). NDVI in higher-elevation areas east (Henry Mountains) and west (Boulder plateau) of the park was well below average in 2009. Isolated patches of above-average NDVI occurred in patchy distributions in other portions of the park. On DOY 304 (October 31), most areas of Capitol Reef NP were within ± 1.5 NDVI units, or $\pm 2.8\%$, of the long-term average.

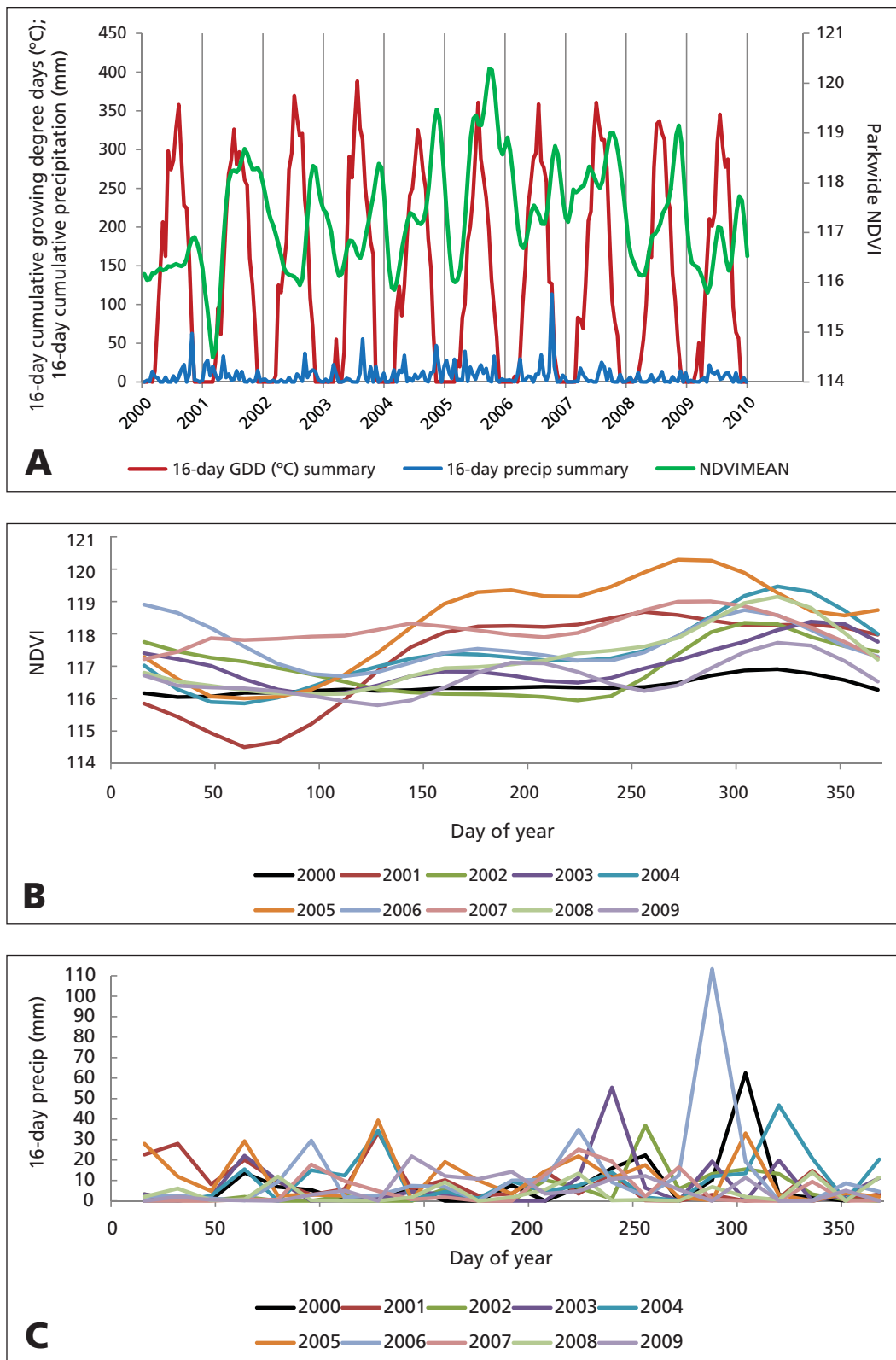


Figure 3.5-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Capitol Reef NP.

Table 3.5-1. Annual descriptive statistics for parkwide average NDVI, Capitol Reef NP.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	116.4	116.3	116.9	116.1	0.86	2677
2001	117.3	118.2	118.7	114.5	4.18	2697
2002	117.0	116.9	118.3	115.9	2.39	2690
2003	117.0	116.8	118.4	116.1	2.25	2692
2004	117.4	117.2	119.5	115.9	3.62	2701
2005	118.3	118.7	120.3	116.0	4.28	2722
2006	117.7	117.5	118.9	116.7	2.22	2706
2007	118.1	118.0	119.0	117.2	1.79	2716
2008	117.2	117.1	119.1	116.1	3.01	2697
2009	116.6	116.5	117.7	115.8	1.93	2682

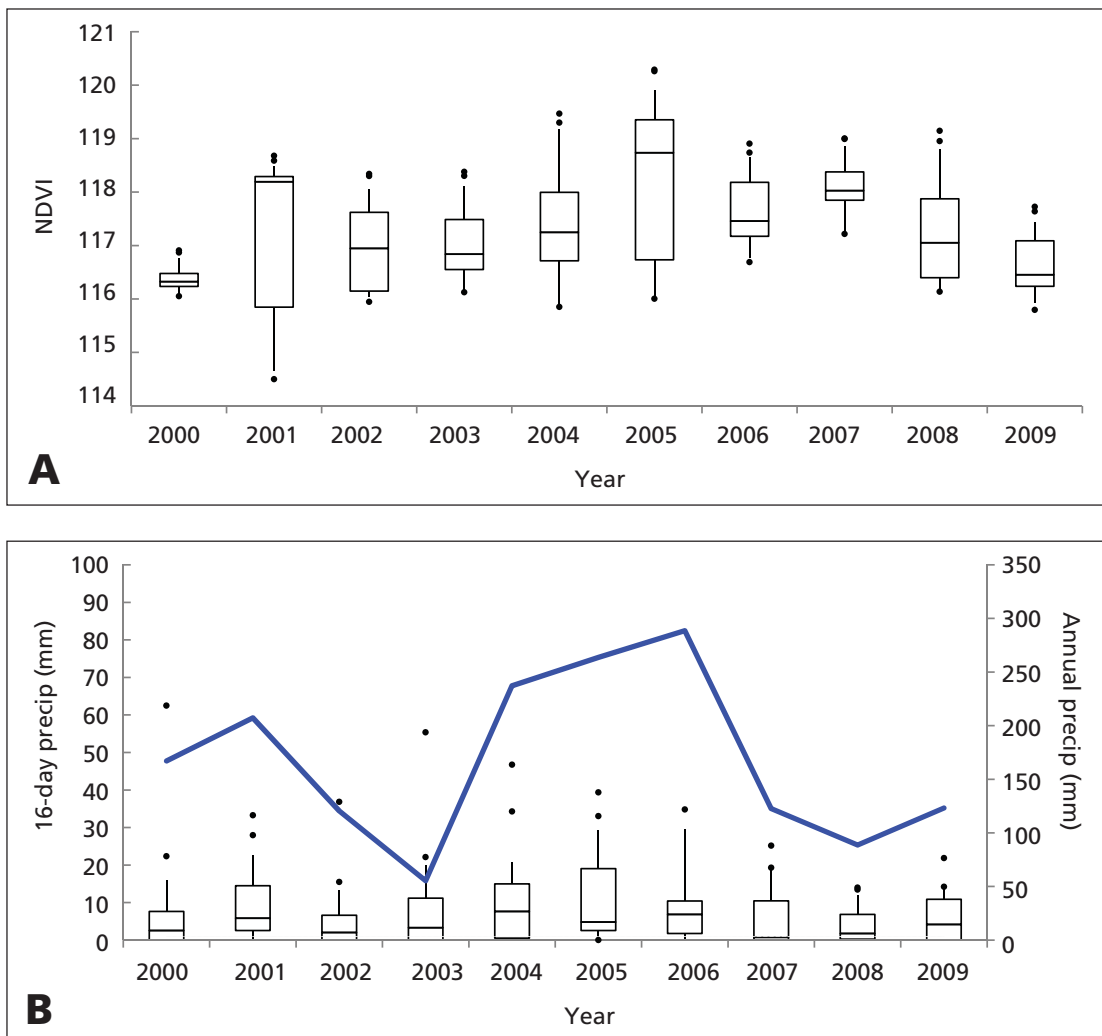


Figure 3.5-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Capitol Reef NP.

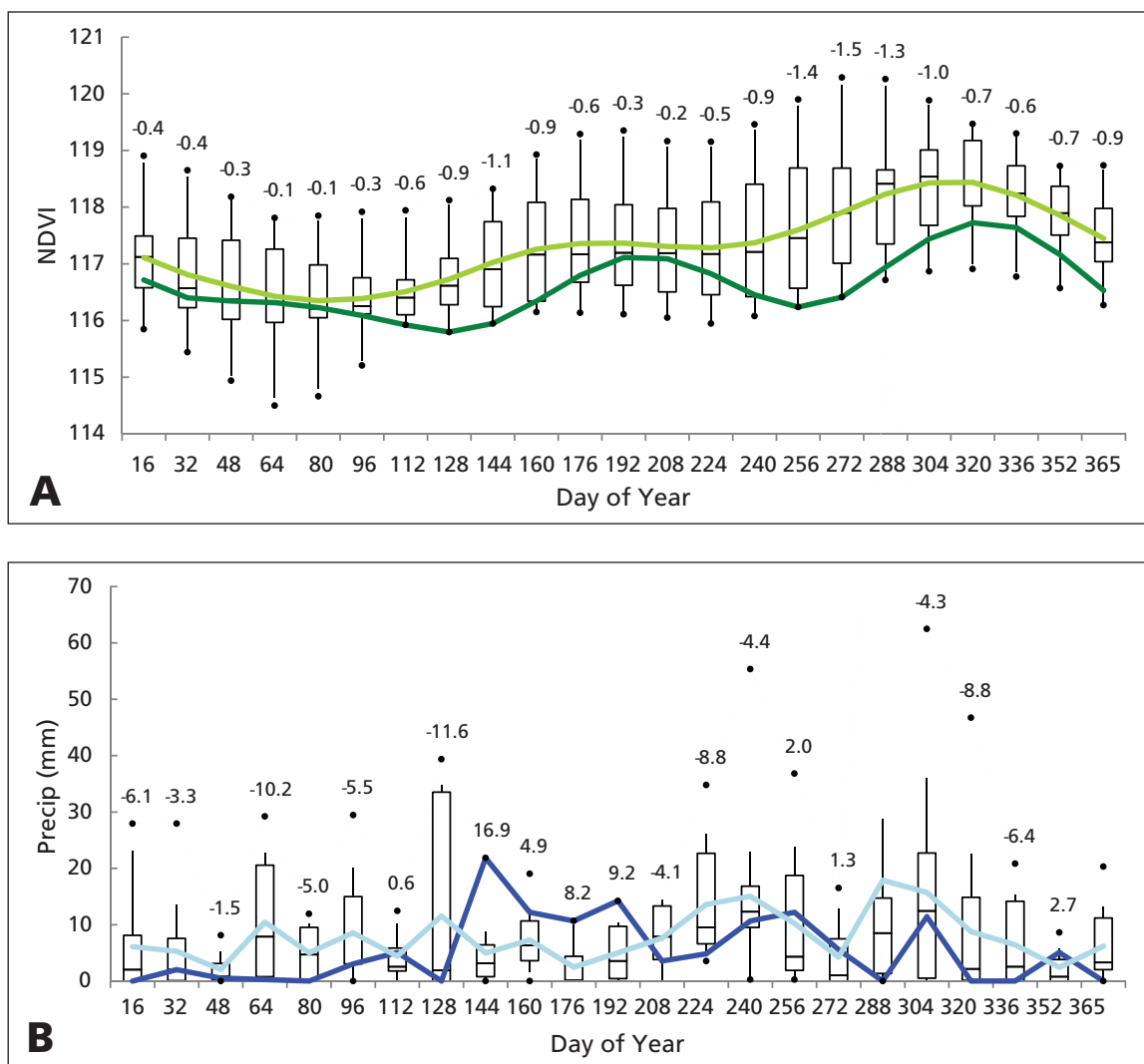


Figure 3.5-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Capitol Reef NP. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

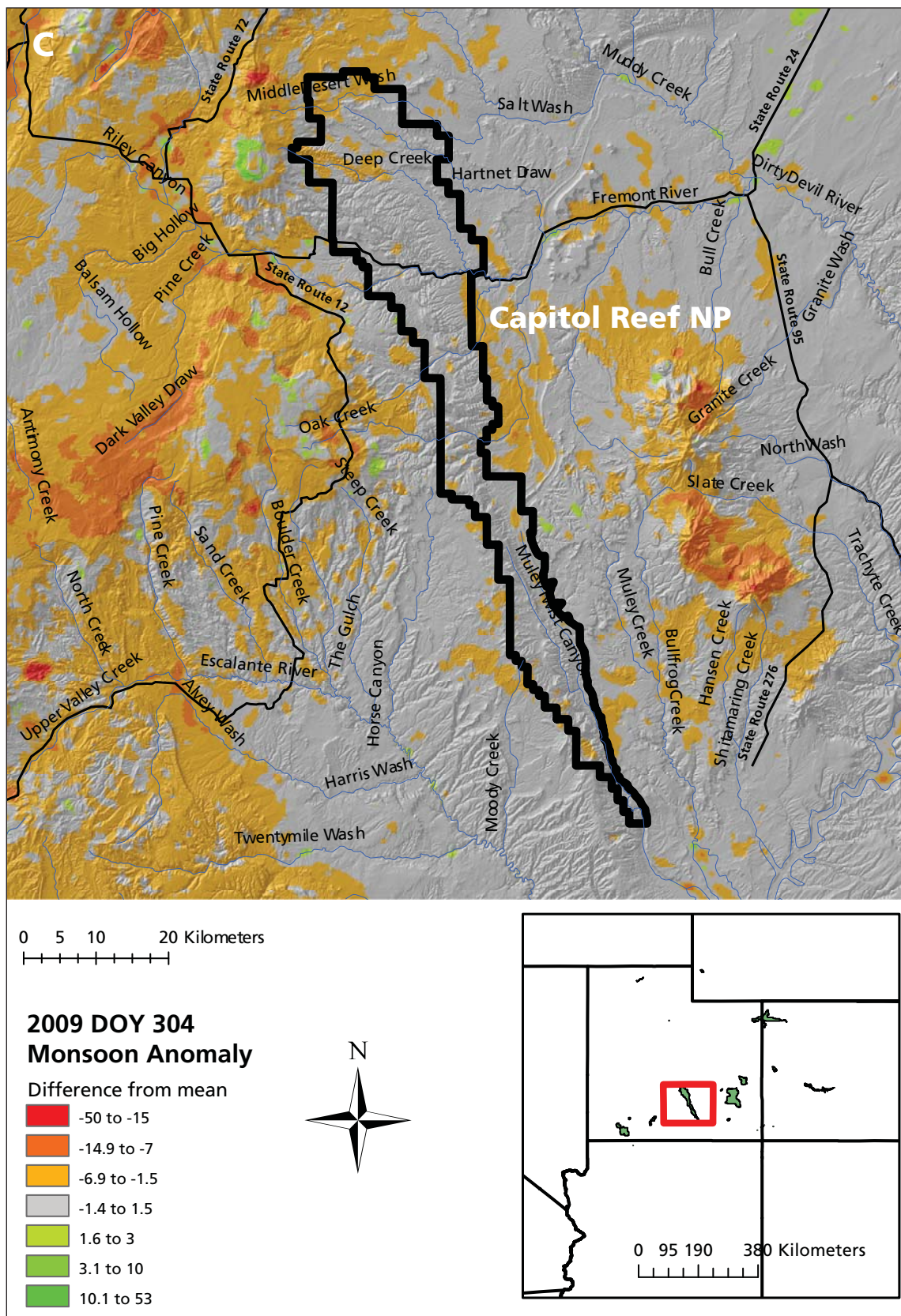


Figure 3.5-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Capitol Reef NP.

3.5.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 210, 119, 256, and 82 days, respectively. The most productive year, based on I-NDVI, was 2001, while the least productive was 2006 (Table 3.5-2). Productivity, defined as the integral under the NDVI curve, is a function not just of peak magnitude, but also of season length. The LOS was 368 days in 2001, but only 113 days in 2006 (Table 3.5-2). The LOS in 2001 was exceptionally long due to an EOS date of DOY 472 (April 17, 2002). This odd finding resulted from several factors, including (1) a long duration of snow cover in 2001, which may indicate that snowpack was deeper than normal, and (2) a lack of snowfall in early 2002, which would have “shut down” growth. Variation in precipitation can introduce much variability to annual productivity. Years like 2000, with almost no appreciable change in NDVI, are difficult to define in phenological terms because the phenology algorithm runs far into following years, searching for the change in amplitude that indicates EOS. Handling these issues may require that rules or heuristics be combined with algorithmic searches for changes in NDVI to determine meaningful phenology metrics in environments of low vegetation cover.

A statistically significant linear trend of -8 days per year EOS (p-value <0.1) was observed for the period of record (Table 3.5-2). According to this trend, EOS is occurring eight days earlier in each successive year. With only 10 years of observation and a high degree of variability known to exist in monsoon precipitation patterns that would determine EOS, it is not clear whether this trend is real (Figure 3.5-4). A longer observation period may show trends over time, but given the variability in precipitation and vegetation response observed thus far, it may take longer to observe trends, if they occur, at Capitol Reef NP than in other parks.

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends, or only weak trends (Table 3.5-2, Figure 3.5-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

Table 3.5-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Capitol Reef NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	145	325	408	263	2093	1.58
2001	104	256	472	368	2942	3.38
2002	253	311	429	176	1526	2.30
2003	243	338	396	154	1292	2.38
2004	115	322	394	280	2237	3.55
2005	118	275	432	314	2614	3.93
2006	242	304	354	113	1061	1.75
2007	43	290	382	340	2716	2.33
2008	157	317	387	230	1999	3.15
<i>correlation</i>	-0.18	-0.01	-0.62	-0.10	-0.05	0.20
<i>slope</i>	-4.73	-0.13	-7.84	-3.08	-11.03	0.06
<i>p-val slope</i>	0.65	0.97	0.07	0.80	0.91	0.61
<i>intercept</i>	9634	561	16112	6428	24164	-117
<i>p-val intercept</i>	0.64	0.94	0.07	0.80	0.90	0.62

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

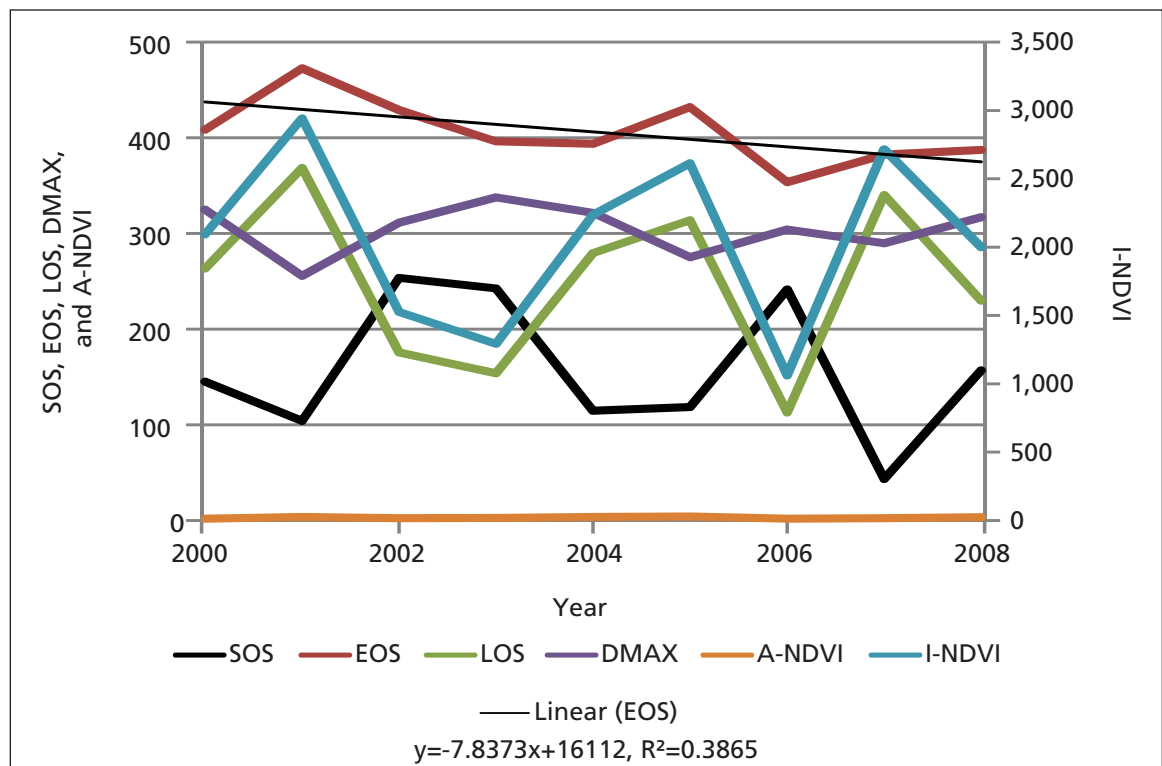


Figure 3.5-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Capitol Reef NP. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.5.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Capitol Reef NP (Figure 3.5-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is exceedingly unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2001, 2008, and 2009 had the most extensive and persistent snow cover (Figure 3.5-5b); however, early season NDVI was not noticeably higher in these years than in other years, as might be expected when more extensive snowpack is available to recharge soil moisture upon melting (Figure 3.5-1a). This is likely because the relationship between snow extent and water content of the snowpack is not direct. The relationship between extent and depth may be stronger at higher elevations, but based on data evaluated for this report, is less strong at mid- to lower elevations, like most of Capitol Reef NP.

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. At Capitol Reef NP, the inverse relationship between these two variables (Figure 3.5-6) is largely a product of spurious conditions in 2002, when SOS did not register until DOY 253 (September 10), well into the monsoon season. When 2002 is removed from the regression relationship, the slope becomes virtually flat, with $R^2 = 0.0002$. Stronger relationships might occur at finer spatial scales if the park were subdivided by elevation in the analysis. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Capitol Reef NP, defined here as less than 3% coverage, occurred between DOYs 75 (March 16) and 291 (October 18). No statistically significant trends in snow metrics were observed for the park (Table 3.5-3).

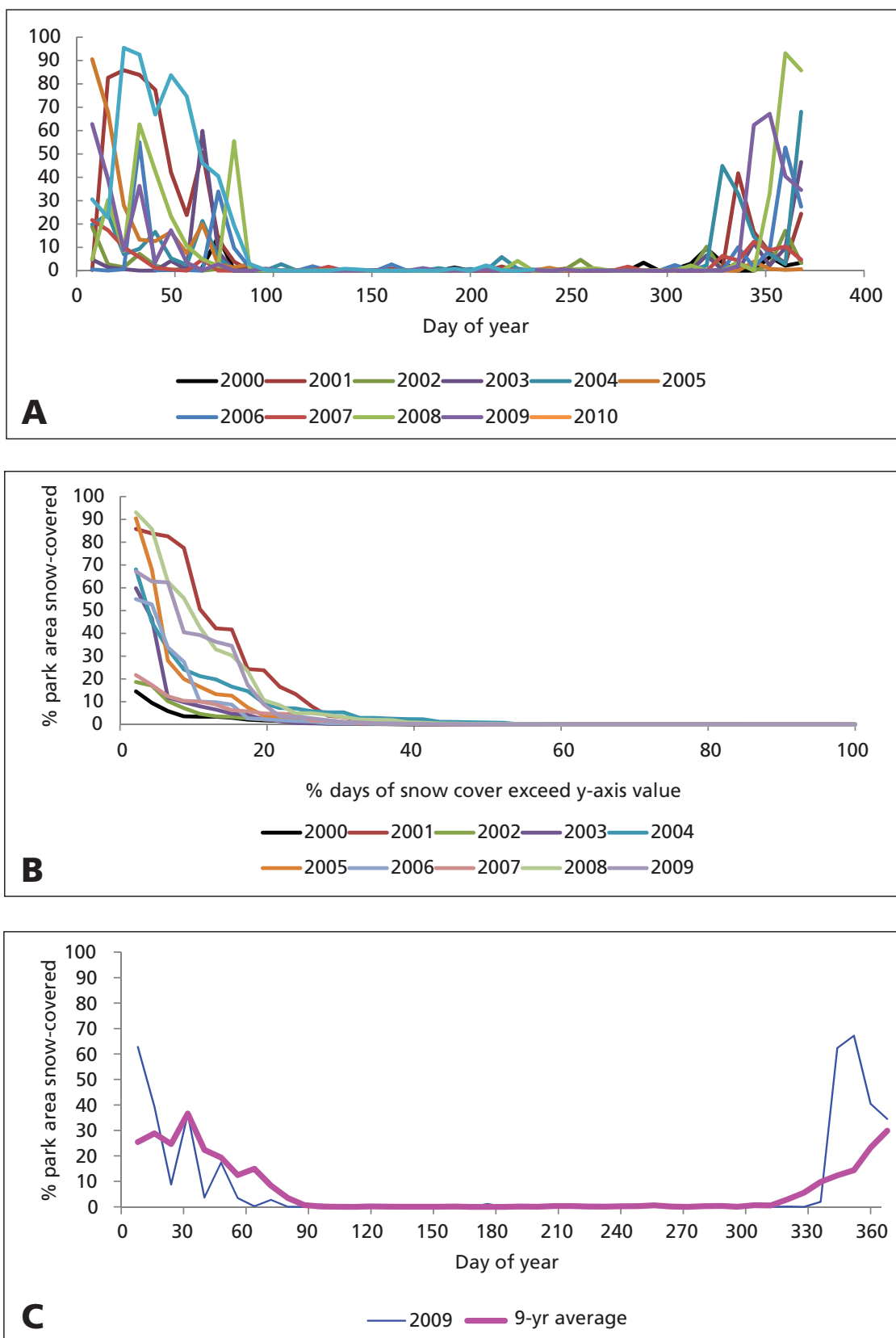


Figure 3.5-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Capitol Reef NP.

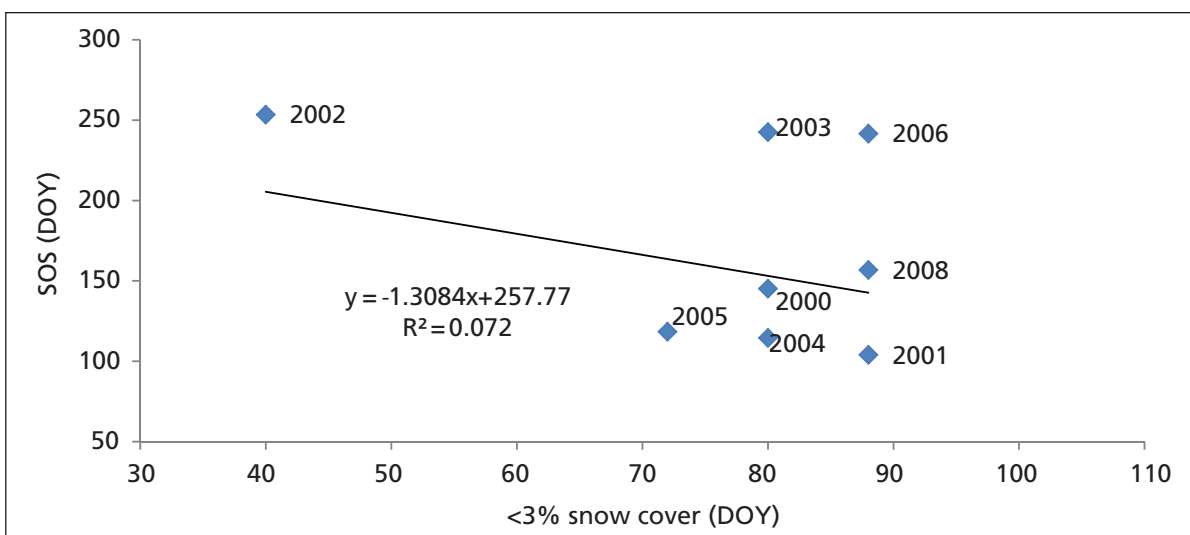


Figure 3.5-6. Relationship between snowmelt DOY and SOS, Capitol Reef NP.

Table 3.5-3. Timing and duration of snow cover, Capitol Reef NP.

Year	Snow off	Snow on	DOY <3% cover	DOY >3% cover	Days snow-free	Days snow-covered
2000	3/20/2000	10/6/2000	80	280	200	165
2001	3/29/2001	11/24/2001	88	328	240	125
2002	2/10/2002	9/6/2002	40	248	208	157
2003	3/23/2003	11/10/2003	80	312	232	133
2004	3/23/2004	7/29/2004	80	208	128	237
2005	3/16/2005	12/5/2005	72	336	264	101
2006	4/2/2006	11/28/2006	88	328	240	125
2007	3/18/2007	11/21/2007	72	320	248	117
2008	4/3/2008	8/9/2008	88	216	128	237
2009	3/11/2009	12/8/2009	64	336	272	93
<i>correlation</i>			0.04	0.09	0.08	-0.08
<i>slope</i>			0.19	1.55	1.36	-1.36
<i>p-val slope</i>			0.91	0.80	0.83	0.83
<i>intercept</i>			-314	-2819	-2505	2870
<i>p-val intercept</i>			0.93	0.82	0.84	0.82

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

3.6 Cedar Breaks National Monument

3.6.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.6-1a). In the 10-year time series, a strong uni-modal seasonal phenology was apparent. When annual curves are stacked (Figure 3.6-1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2005, are easily contrasted with less productive years, such as 2000. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to lower-elevation NCPN parks, the NDVI annual curves for Cedar Breaks National Monument (NM) are remarkably consistent, which may indicate that the park's precipitation is well-distributed, more abundant than elsewhere, and supports vegetation adapted to a single growing season.

Weather data from the Brian Head NWS Coop station were used to interpret NDVI variation (Figure 3.6-1a). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2002 had the narrowest range in annual maximum and minimum NDVI (14.9), while 2005 had the widest range (Table 3.6-1 and Figure 3.6.2). The large NDVI range in 2005 (109.5–147.6) may have been the result of the above-average precipitation in winter 2004–2005 and spring 2005 (Figure 3.6-1a). The minimum NDVI in 2005 may have been the result of snow-cover effects that suppressed vegetation response early in the year. In subsequent years, the depressed NDVI was not persistently low, indicating recovery by the following year.

Temperature effects on vegetation productivity at Cedar Breaks NM are intertwined with moisture effects. In year 2004, what appeared to be adequate moisture early in the year was counteracted by cooler temperatures, which may have limited productivity. A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

3.6.2 Recent NDVI conditions

The 2009 NDVI curve was close to the historical average until DOY 240 (August 28), when it began to fall, ending the year at 0.68% below the long-term average. Although weather data for 2009 were not complete, available data indicated that the precipitation deficit was 31.9% below the 10-year average (Figure 3.6-3a, b).

The spatial distribution of below-average NDVI in 2009 was limited to the steeper and higher-elevation portion of the breaks, whereas the lower-elevation areas and higher-elevation flat areas were close to normal (Figure 3.6-3c). The below-average NDVI in 2009 may have been influenced by pine beetles in some areas south and east of the park (darker orange colors); however, if beetle kill occurred in the middle of the analysis period, its influence would be minimized mathematically. Anomaly mapping with the focus on years other than 2009 may provide better spatial indication of beetle kill in the area. On DOY 304 (October 31), most areas of Cedar Breaks NM were within -6.9 to -1.5 NDVI units, or between -13.2 and -2.8%, of the long-term average. The park as a whole was only 0.68% below average in 2009.

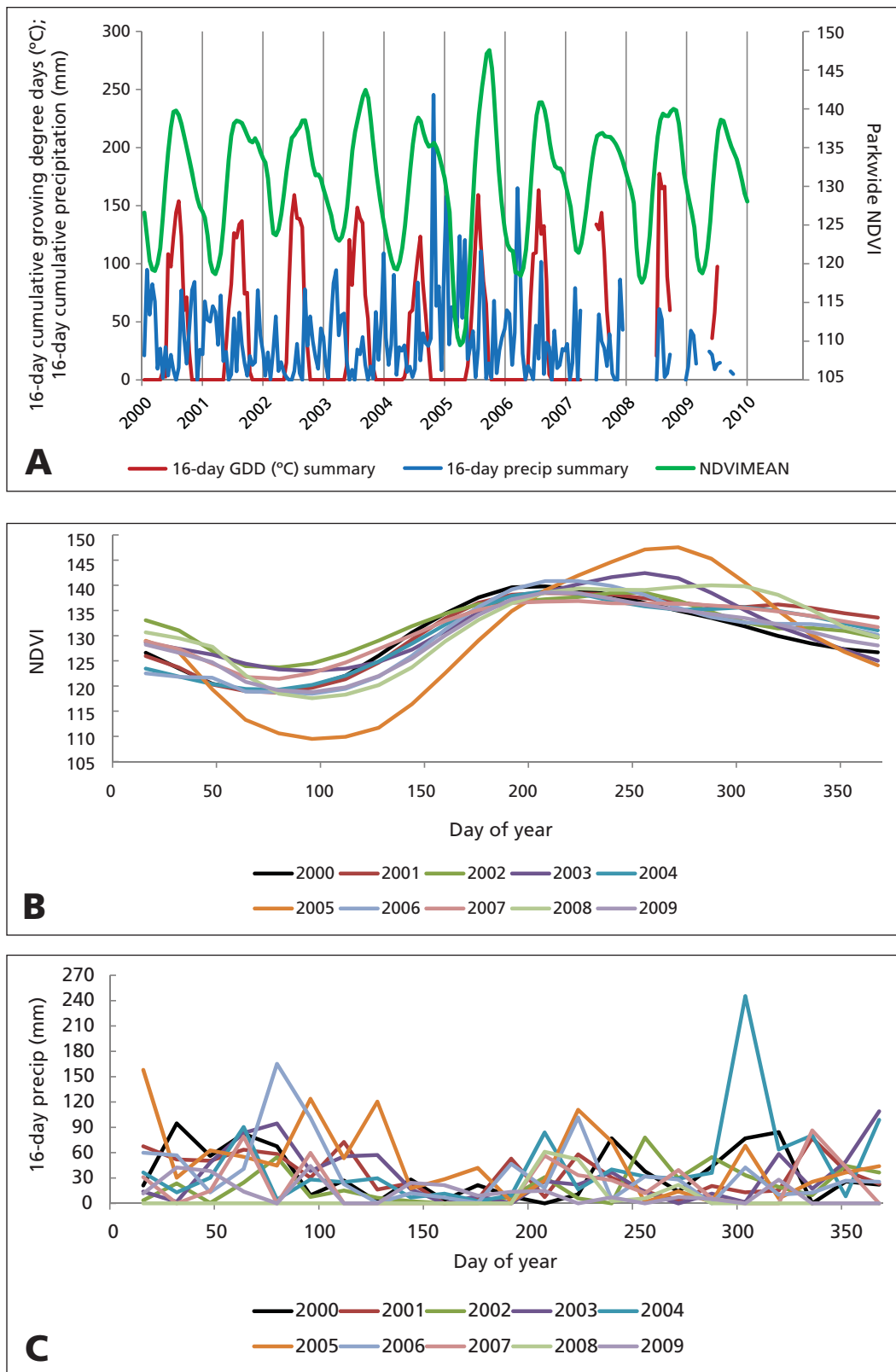


Figure 3.6-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Cedar Breaks NM.

Table 3.6-1. Annual descriptive statistics for parkwide average NDVI, Cedar Breaks NM.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	129.8	129.9	139.8	119.1	20.69	2985
2001	130.9	134.5	138.5	118.7	19.79	3011
2002	132.1	131.9	138.5	123.7	14.84	3037
2003	131.4	129.5	142.4	123.0	19.46	3022
2004	130.2	132.4	138.9	119.3	19.57	2994
2005	128.5	129.0	147.6	109.5	38.07	2955
2006	129.7	131.6	140.8	118.5	22.38	2983
2007	131.3	132.9	136.9	121.4	15.45	3021
2008	131.2	131.6	140.0	117.6	22.42	3017
2009	129.6	130.1	138.6	118.8	19.80	2980

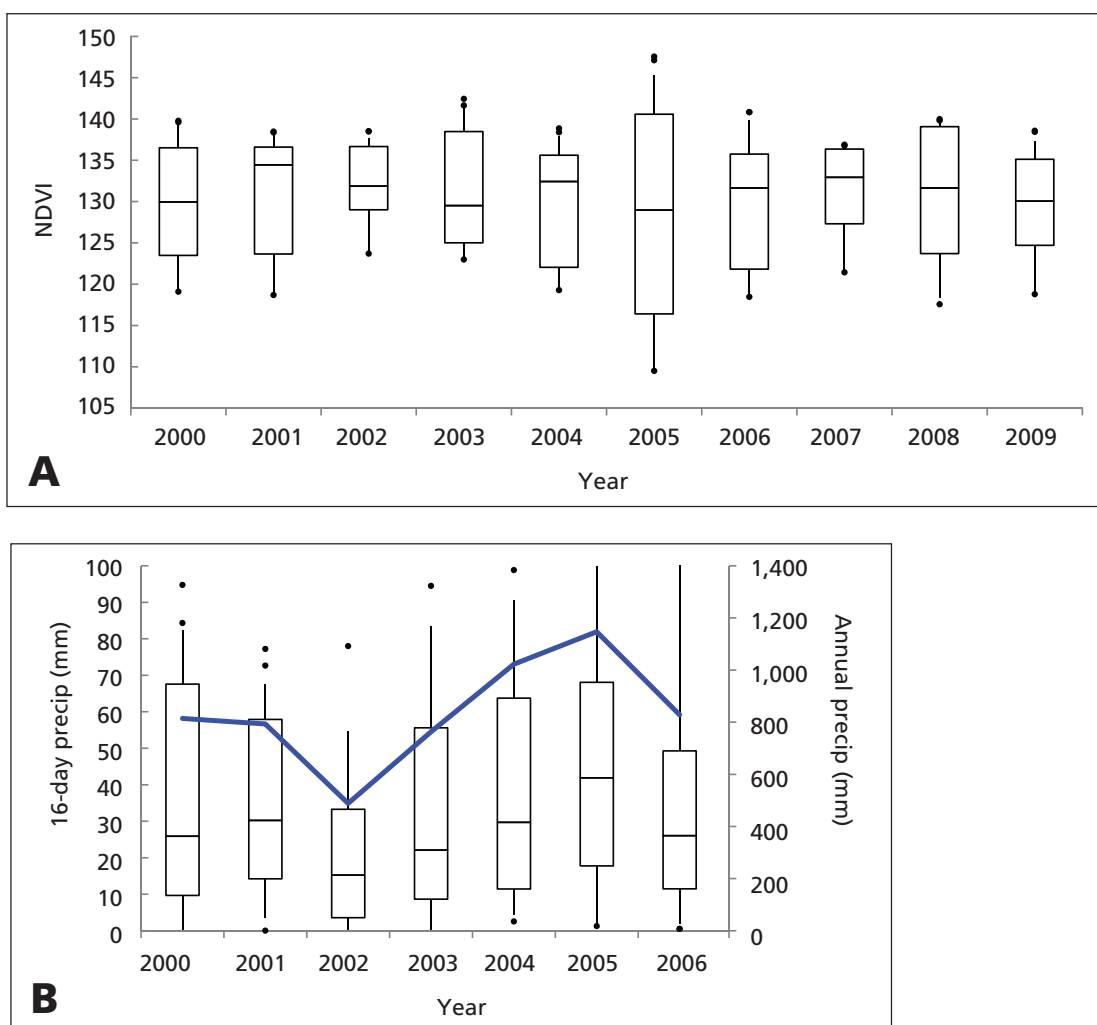


Figure 3.6-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Cedar Breaks NM. Station data were incomplete for years 2007–2009.

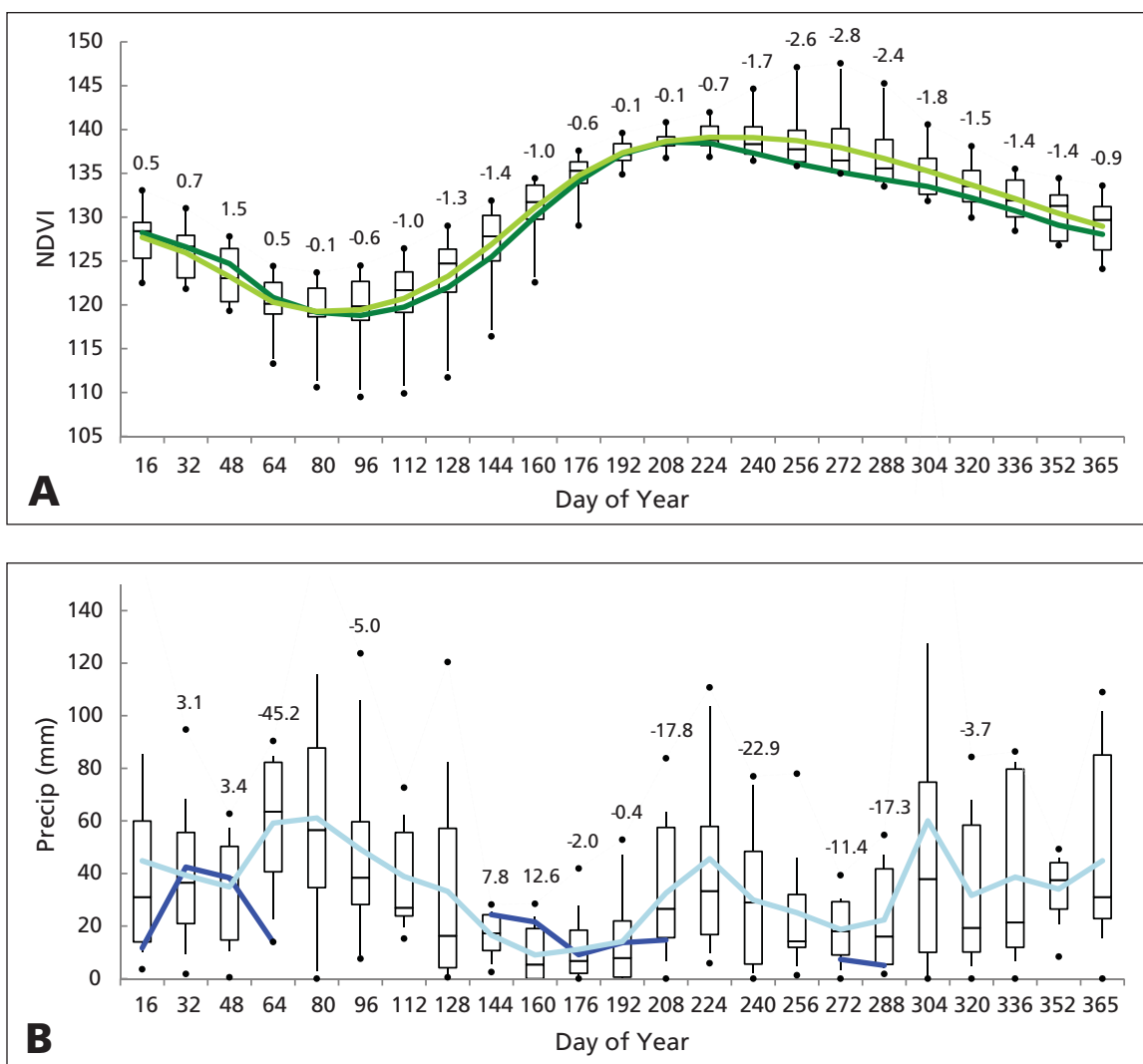


Figure 3.6-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Cedar Breaks NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

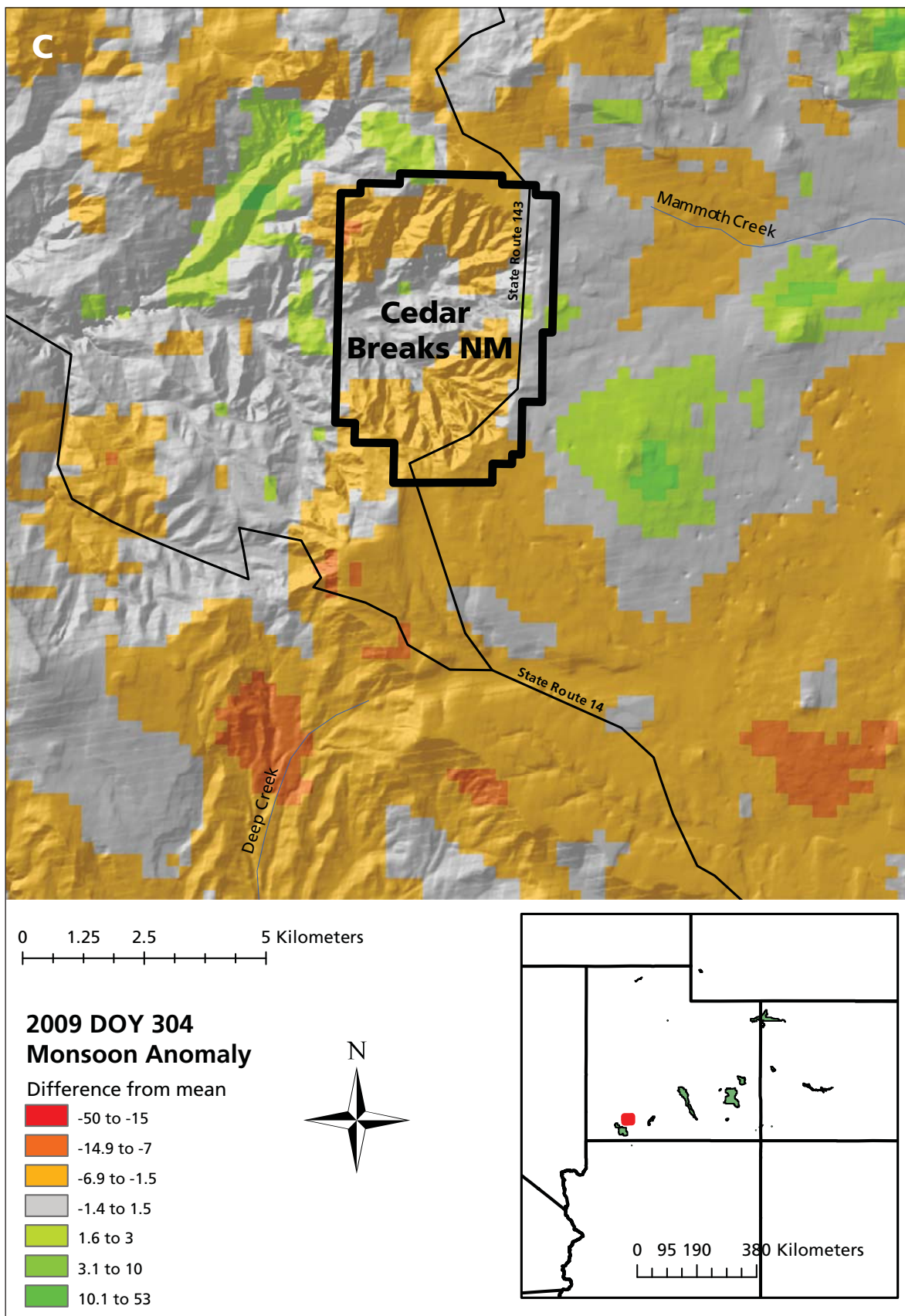


Figure 3.6-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Cedar Breaks NM.

3.6.3 Phenology

Over the nine-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 35, 75, 110, and 43 days, respectively. The most productive year, based on I-NDVI, was 2007, while the least productive was 2005 (Table 3.6-2); these years corresponded to the longest (317) and shortest (208) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. There were no statistically significant linear trends (p -value <0.1) in the phenology metrics observed at the parkwide scale for the period of analysis (Table 3.6-2; Figure 3.6-4).

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends, or only weak trends (Table 3.6-2, Figure 3.6-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

3.6.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Cedar Breaks NM (Figure 3.6-5a) is highly variable within and between years, due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cu-

mulative exceedance frequency curves indicate that years 2009, 2005, and 2004 had the most extensive and persistent snow cover (Figure 3.6-5b). In 2009, more park area was snow-covered for longer than in the past 10 years (Figure 3.6-5c).

Although water content cannot be directly inferred from snow cover, they are related. For example, years 2002 and 2004 had the two earliest snowmelt dates (DOYs 128 and 136, respectively; Table 3.6-3) and two of the most productive growing seasons (NDVI integrals 2656 and 2758, respectively) (Table 3.6-2). Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both. Coupling these data with NRCS Snotel and USGS streamflow data in the watershed could help answer that question. Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. However, snow cover is not the only factor driving SOS, as was shown in 2002, which had the earliest snowmelt date but ranked second in the record for SOS. A positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.30$) for the eight years of record (Figure 3.6-6). Stronger relationships may occur at finer spatial scales, where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Cedar Breaks NM, defined here as less than 5% coverage, occurred between DOYs 154 (June 3) and 264 (September 21). There were no statistically significant trends at the park scale in snow-cover metrics for the period of record (Table 3.6-3).

Table 3.6-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Cedar Breaks NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	121	216	396	275	2506	20.93
2001	123	251	415	292	2675	17.37
2002	117	227	407	290	2656	15.21
2003	146	249	368	222	2145	21.19
2004	124	259	424	300	2758	24.42
2005	150	256	358	208	2025	33.51
2006	136	221	405	269	2522	20.96
2007	115	258	434	317	2903	17.42
2008	141	259	416	276	2653	21.91
<i>correlation</i>	0.35	0.49	0.22	0.03	0.14	0.24
<i>slope</i>	1.66	3.13	2.01	0.35	14.73	0.46
<i>p-val slope</i>	0.36	0.19	0.57	0.95	0.72	0.54
<i>intercept</i>	-3203	-6025	-3627	-423	-26987	-910
<i>p-val intercept</i>	0.38	0.20	0.61	0.97	0.74	0.54

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

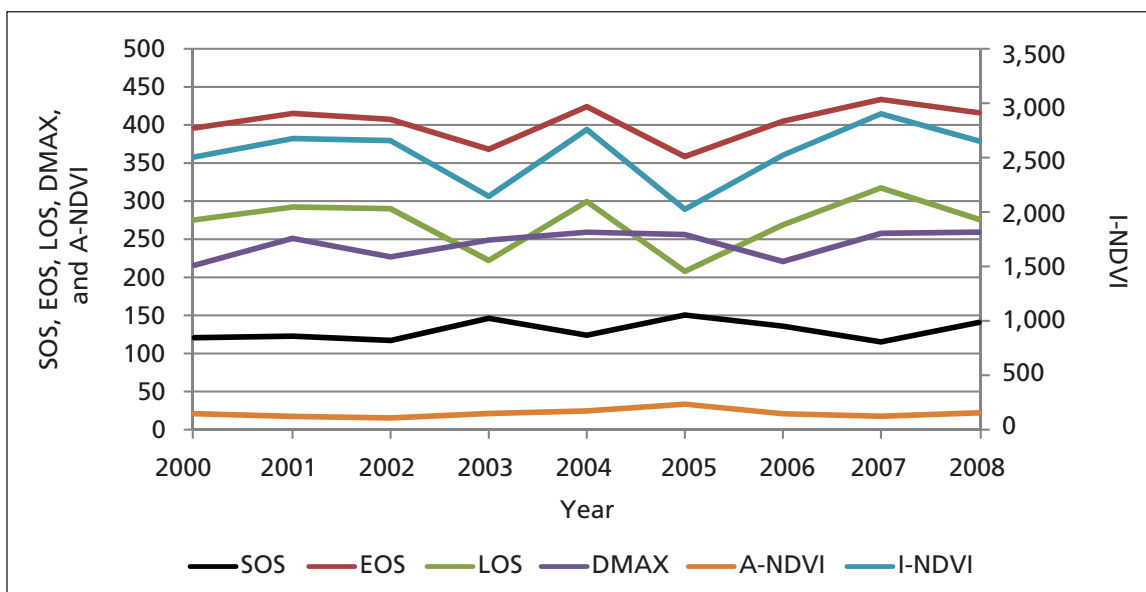


Figure 3.6-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Cedar Breaks NM. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

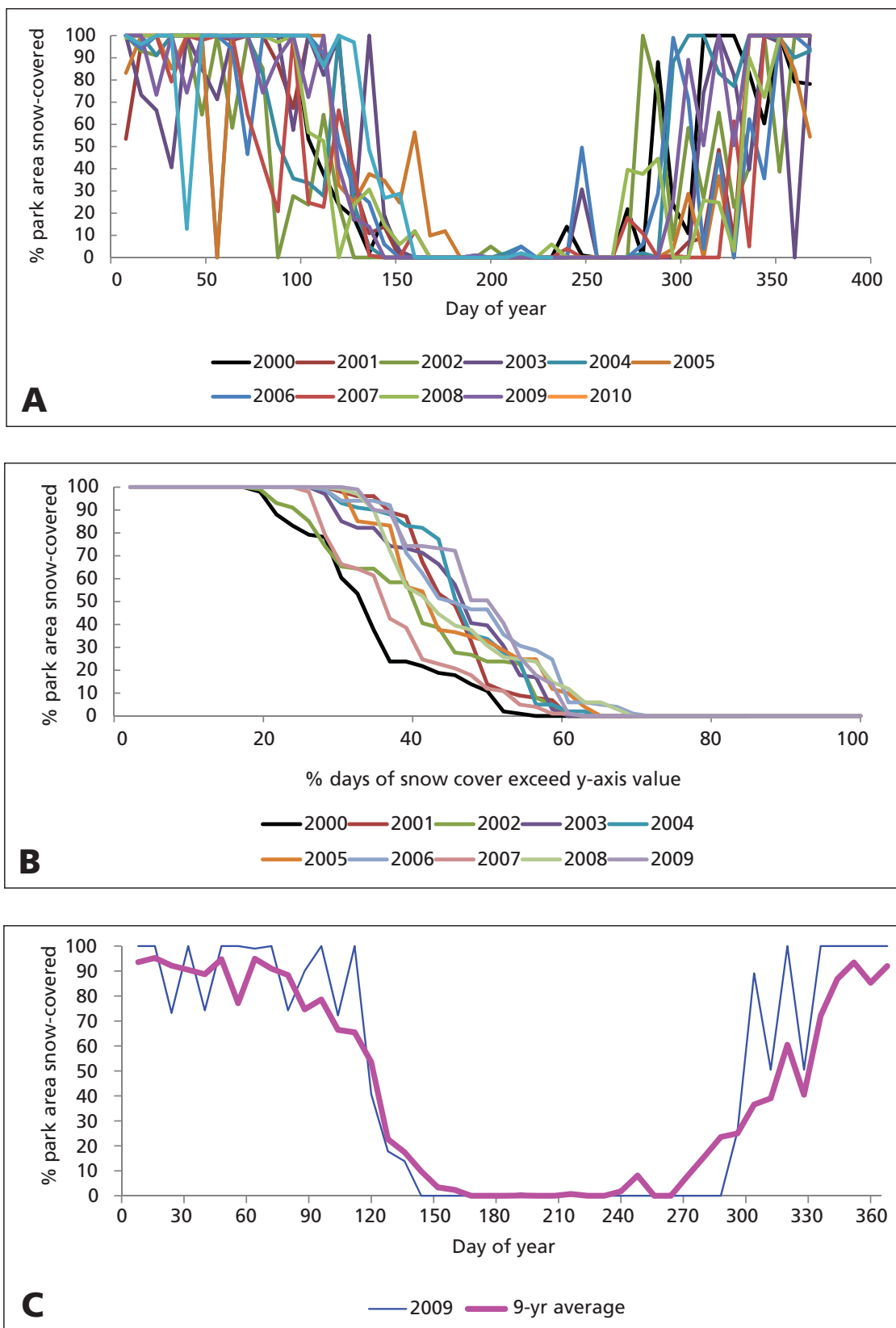


Figure 3.6-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Cedar Breaks NM.

Table 3.6-3. Timing and duration of snow cover, Cedar Breaks NM.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	5/31/2000	8/19/2000	152	232	80	285
2001	6/1/2001	10/23/2001	152	296	144	221
2002	5/9/2002	9/30/2002	128	272	144	221
2003	6/3/2003	8/30/2003	152	240	88	277
2004	5/18/2004	10/17/2004	136	288	152	213
2005	7/6/2005	10/26/2005	184	296	112	253
2006	6/5/2006	9/1/2006	152	240	88	277
2007	6/22/2007	9/26/2007	168	264	96	269
2008	6/22/2008	8/17/2008	168	224	56	309
2009	5/30/2009	10/21/2009	144	288	144	221
<i>correlation</i>			0.32	-0.02	-0.17	0.17
<i>slope</i>			1.75	-0.19	-1.94	1.94
<i>p-val slope</i>			0.36	0.95	0.63	0.63
<i>intercept</i>			-3345	653	3998	-3633
<i>p-val intercept</i>			0.38	0.92	0.62	0.65

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

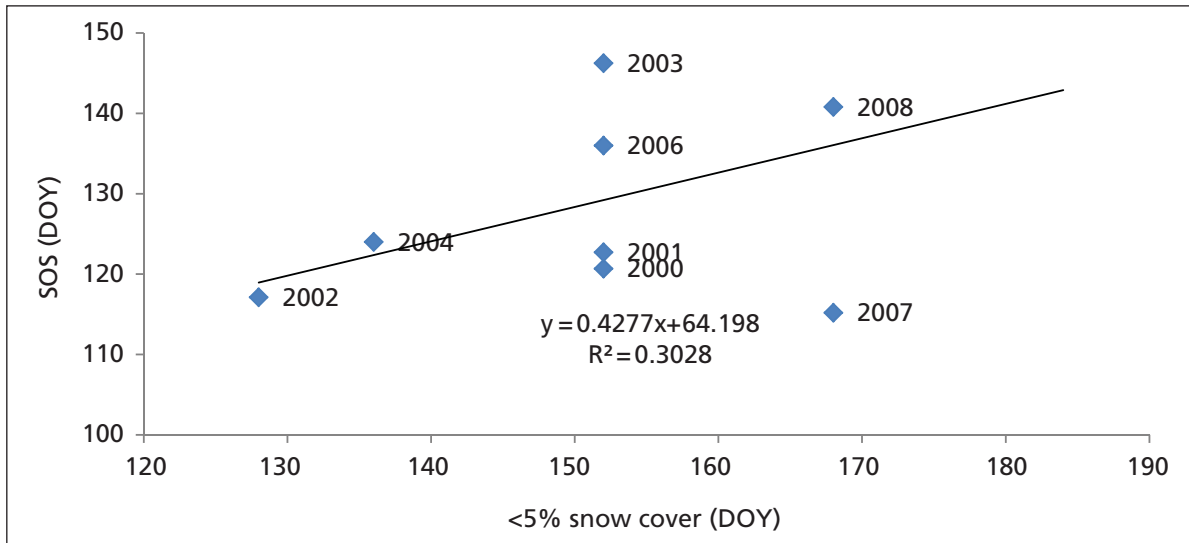


Figure 3.6-6. Relationship between snowmelt DOY and SOS, Cedar Breaks NM.

3.7 Colorado National Monument

3.7.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.7-1a). In the 10-year time series, a strong bi-modal seasonal phenology was apparent in most years, with the notable exceptions of 2005 and 2006, when only a single annual peak was observed. When annual curves are stacked (Figure 3.7-1b), a more direct year-to-year comparison is possible, in which where more productive years, such as 2005, are easily contrasted with less productive years, such as 2001. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to higher-elevation NCPN parks, the NDVI annual curves for Colorado NM are bi-modal and “jagged,” reflecting unevenly distributed and less abundant precipitation that supports vegetation adapted to multiple growing seasons in a single year.

Weather data from the park’s NWS Coop station were used to interpret NDVI variation (Figure 3.7-1a, c). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2001 had the narrowest range in annual maximum and minimum NDVI (2.1); 2008 had the widest range (7.3) (Table 3.7-1). The largest maximum NDVI (135.3) occurred in 2005. Years of higher cumulative precipitation generally had higher median NDVI (Figure 3.7-2a, b). However, it is clear that the strength of bi-modal NDVI response is partly explained by

differences in the temporal distribution of precipitation (Figure 3.7-1). A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

3.7.2 Recent NDVI conditions

The NDVI curve dropped below the historical average, in correspondence with a lagged response to below-average precipitation, twice in 2009. Below-average spring precipitation resulted in below-average NDVI between DOYs 80 and 176 (March 21–June 25). Below-average monsoon precipitation resulted in below-average NDVI between DOYs 256 and 365 (September 22–December 31). Annual average NDVI for 2009 was 0.88% below the 10-year average. Weather data for 2009 indicated that the precipitation deficit was 7.9% below the 10-year average (Figure 3.7-3a, b).

The spatial distribution of below-average NDVI in 2009 was limited to the central portion of the park, near Monument Mesa (Figure 3.7-3c). No Thorofare Canyon was the largest isolated area of above-average NDVI, although a small area in the northern portion of the monument was also above average. In general, the park’s “badlands” and surrounding rough country fared better in 2009 than more level areas. It may be instructive to investigate the relationships between soil, geology, and vegetation in this park, to better understand how changes in precipitation might impact different parts of the landscape. On DOY 304 (October 31), most areas of Colorado NM were within ± 1.5 NDVI units, or $\pm 2.8\%$, of the long-term average.

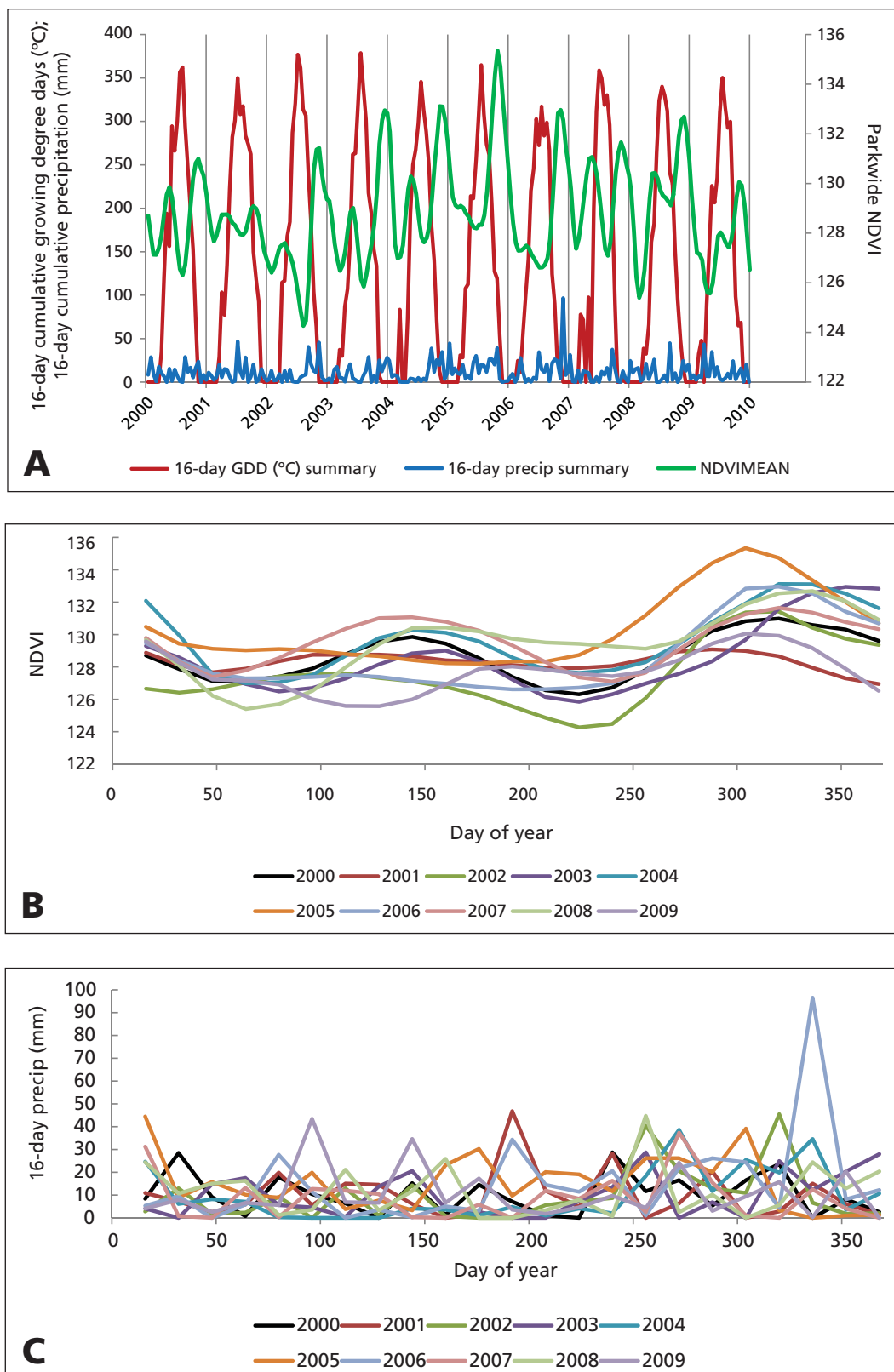


Figure 3.7-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Colorado NM.

Table 3.7-1. Annual descriptive statistics for parkwide average NDVI, Colorado NM.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	128.6	128.7	131.0	126.3	4.67	2959
2001	128.3	128.4	129.1	126.9	2.14	2951
2002	127.5	127.1	131.4	124.3	7.15	2933
2003	128.5	128.2	132.9	125.8	7.09	2955
2004	129.7	129.6	133.1	127.0	6.12	2982
2005	130.4	129.1	135.3	128.2	7.15	2998
2006	128.7	127.5	133.0	126.6	6.34	2959
2007	129.5	129.8	131.6	127.1	4.55	2979
2008	129.5	129.6	132.7	125.4	7.28	2977
2009	127.7	127.7	130.1	125.6	4.48	2937

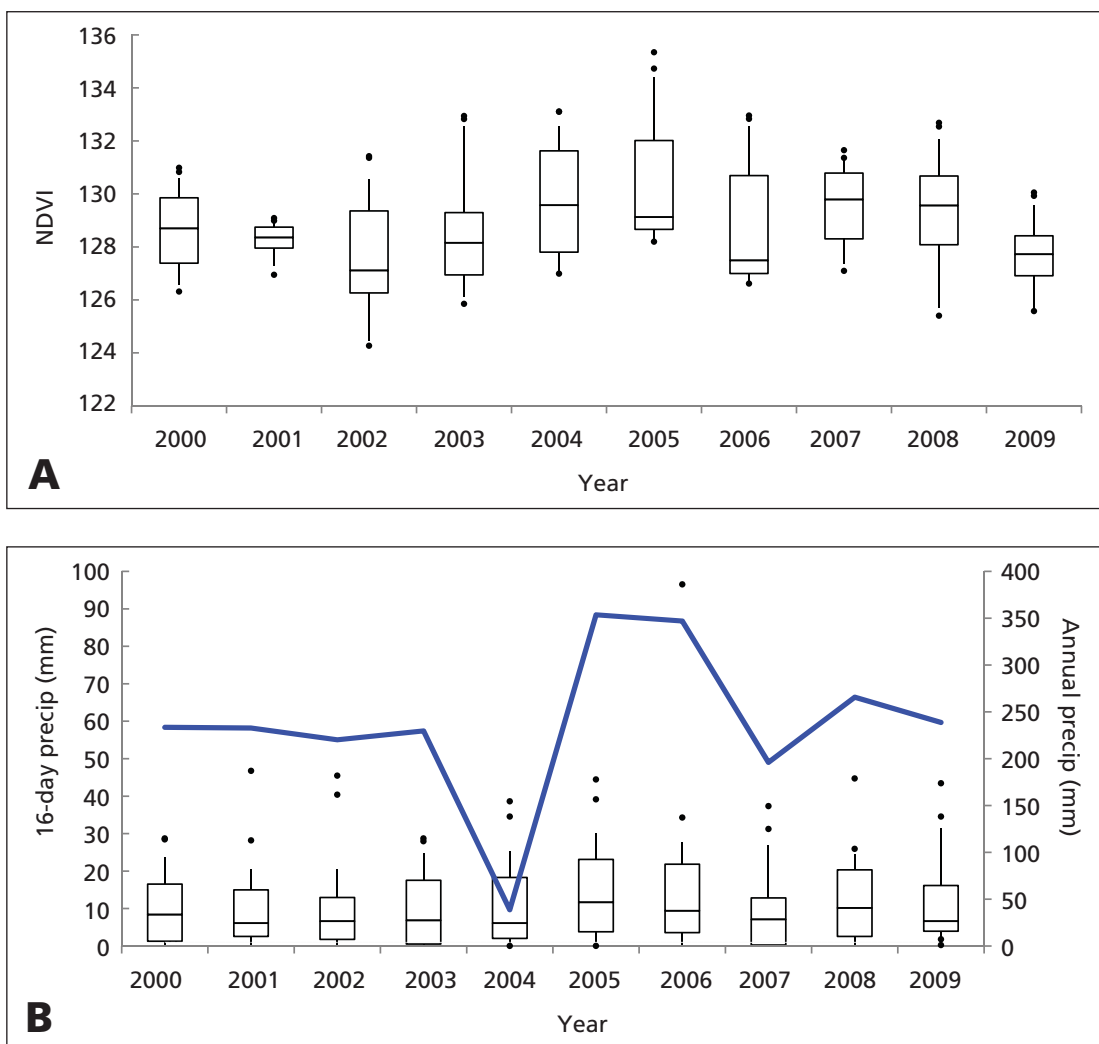


Figure 3.7-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Colorado NM. Due to missing weather station data for 2007, 2008, and 2009, box plots and cumulative precipitation do not reflect actual conditions.

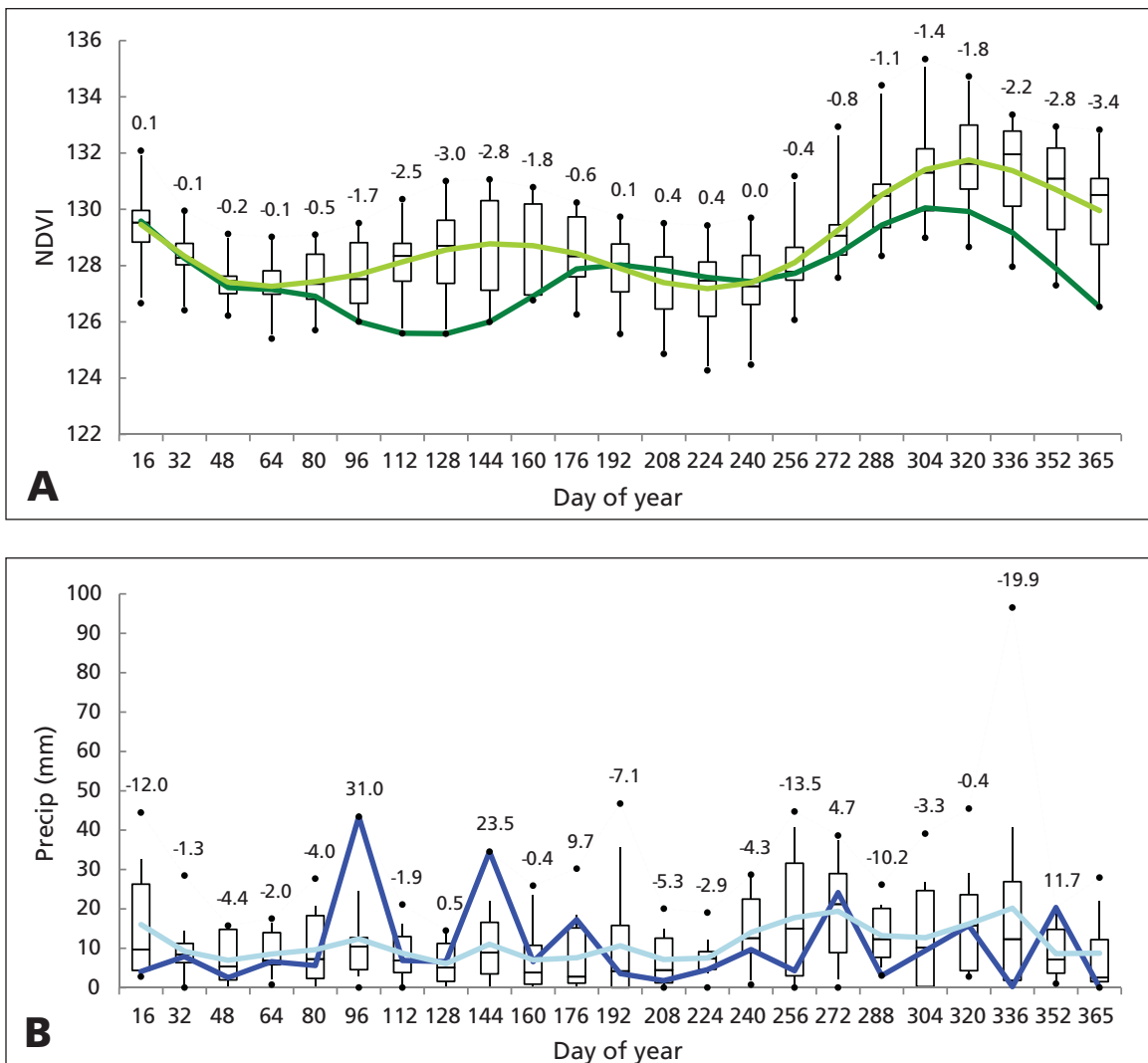


Figure 3.7-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Colorado NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

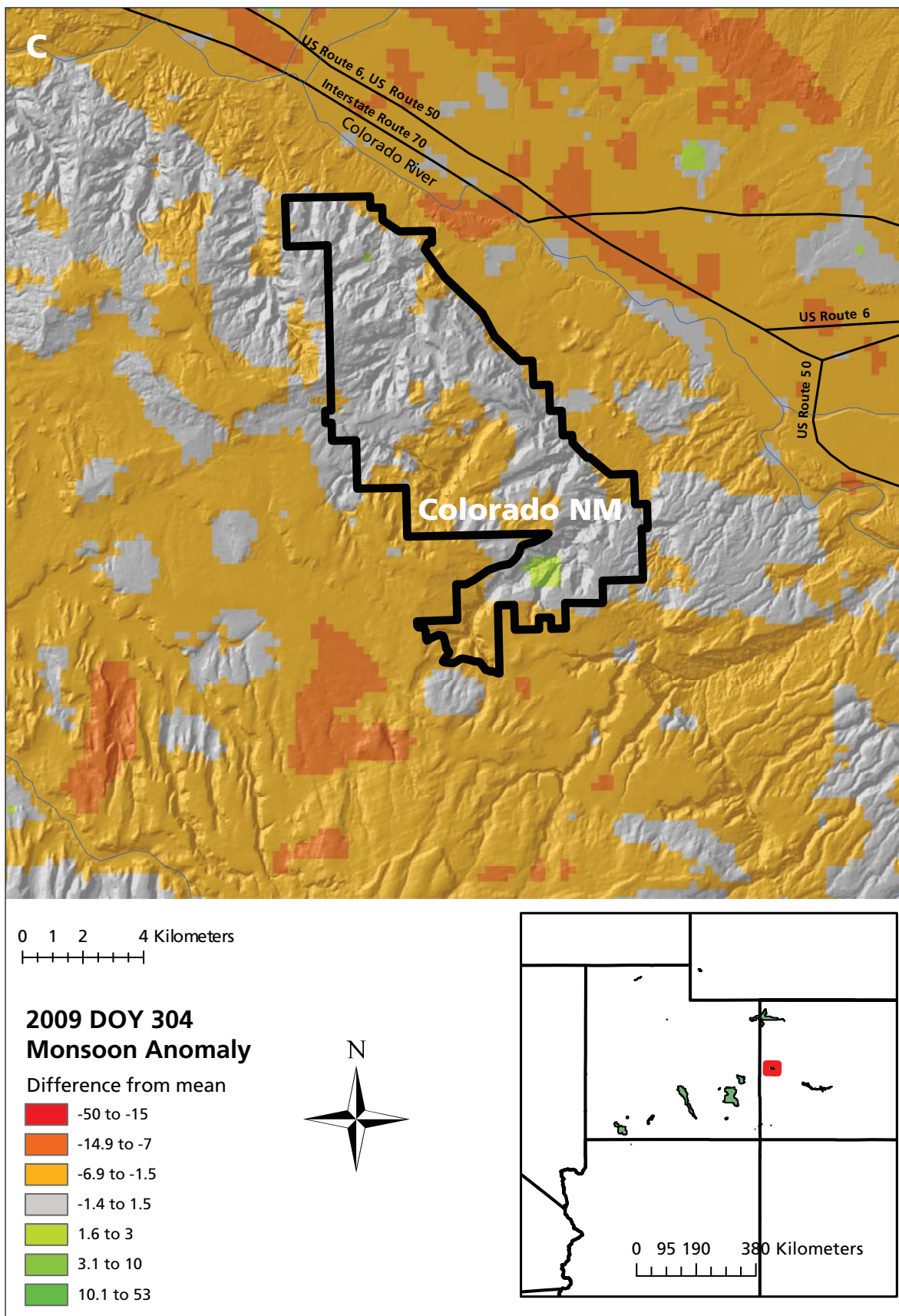


Figure 3.7-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Colorado NM.

3.7.3 Phenology

In most years, there are two distinct growing seasons at Colorado NM that represent the interaction of plant functional types (annual/perennial, early season/late season), phenology, and suitability of moisture for growth. The two seasons (spring and monsoon) are evaluated separately due to the distinct bi-modal nature of phenology observed in the park.

3.7.3.1 Spring

Over the 10-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 55, 30, 61, and 40 days, respectively. The most productive spring, based on I-NDVI, was 2002, while the least productive (with a clearly identifiable spring peak) was 2003 (Table 3.7-2); these years corresponded to the longest (170 days) and shortest (110 days) growing seasons, respectively. Because the Timesat software had difficulty defining two growing seasons for years 2005, 2006, and 2009, any of those years may be considered to have had less productive growing seasons than 2003. By visual inspection, it appears that 2006 was the least productive spring in the record (Figure 3.7-1a). In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. A statistically significant linear trend (p -value <0.1) for spring EOS was observed at the parkwide scale for the period of analysis (Table 3.7-2; Figure 3.7-4a). According to this trend, spring EOS is occurring 3.2 days later in each successive year. This trend should be considered with caution because it is based on a short (10-year) record with two years (2005 and 2006) of missing data, when spring season NDVI was insufficient to register a seasonal signal in the phenology.

3.7.3.2 Monsoon

Over the nine-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 42, 97, 80, and 58 days, respectively. The most productive monsoon season, based on I-NDVI, was 2004, while the least productive was 2001 (Table 3.7-3); these years corresponded to the longest (224 days) and shortest (124 days) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. The influence of precipitation variability on vegetation productivity is made apparent by the decoupling of seasonal productivity, in which productive spring seasons are not always followed by productive monsoon seasons and vice versa. Based on the results from the 10-year record, the monsoon season is always more productive than the spring season at Colorado NM. There were no statistically significant linear trends (p -value <0.1) in the monsoon-season phenology metrics observed at the parkwide scale for the period of analysis (Table 3.7-3; Figure 3.7-4b).

3.7.3.3 Summary

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends, or only weak trends (Table 3.7-3, Figure 3.7-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

Table 3.7-2. Spring-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Colorado NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	79	144	206	127	1282	3.11
2001	59	118	204	144	1412	0.97
2002	44	116	214	170	1645	2.20
2003	99	156	208	110	1148	2.72
2004	86	149	208	122	1159	2.99
2005	-	-	-	-	-	-
2006	-	-	-	-	-	-
2007	67	142	222	155	1424	3.77
2008	85	150	234	148	1418	3.17
2009	-	-	-	-	-	-
<i>correlation</i>	-0.56	-0.56	-0.56	-0.43	-0.47	-0.19
<i>slope</i>	-236.80	-241.35	-246.73	-9.97	-104.27	-0.10
<i>p-val slope</i>	0.49	0.24	0.01	0.78	0.96	0.17
<i>intercept</i>	473978	483138	493979	20087	209951	195
<i>p-val intercept</i>	0.49	0.25	0.02	0.79	0.94	0.17

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

Table 3.7-3. Monsoon-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Colorado NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	240	318	403	162	1551	3.90
2001	235	296	378	144	1409	1.90
2002	244	312	429	184	1674	6.03
2003	248	353	422	174	1685	6.56
2004	251	331	475	224	2084	5.11
2005	227	307	410	182	1709	7.50
2006	245	320	405	160	1561	5.99
2007	251	331	421	169	1679	5.31
2008	269	336	459	192	1815	5.27
<i>correlation</i>	0.56	0.40	0.45	0.31	0.40	0.47
<i>slope</i>	2.4	2.5	4.9	2.6	27.7	0.3
<i>p-val slope</i>	0.11	0.29	0.22	0.42	0.28	0.20
<i>intercept</i>	-4569	-4690	-9416	-5005	-53892	-549
<i>p-val intercept</i>	0.13	0.32	0.24	0.43	0.30	0.21

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

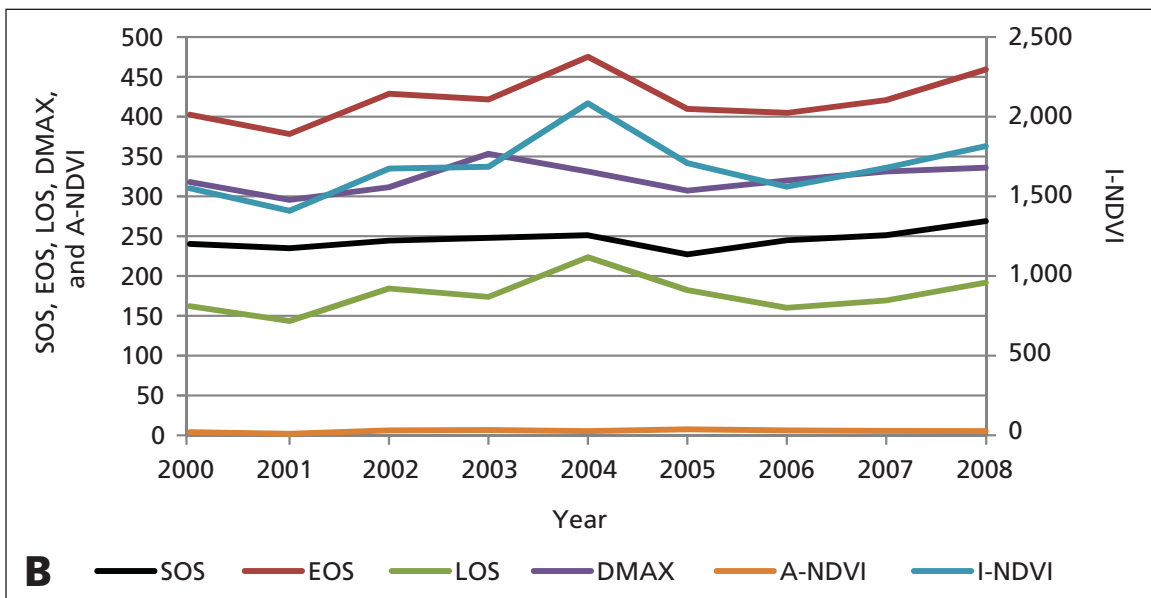
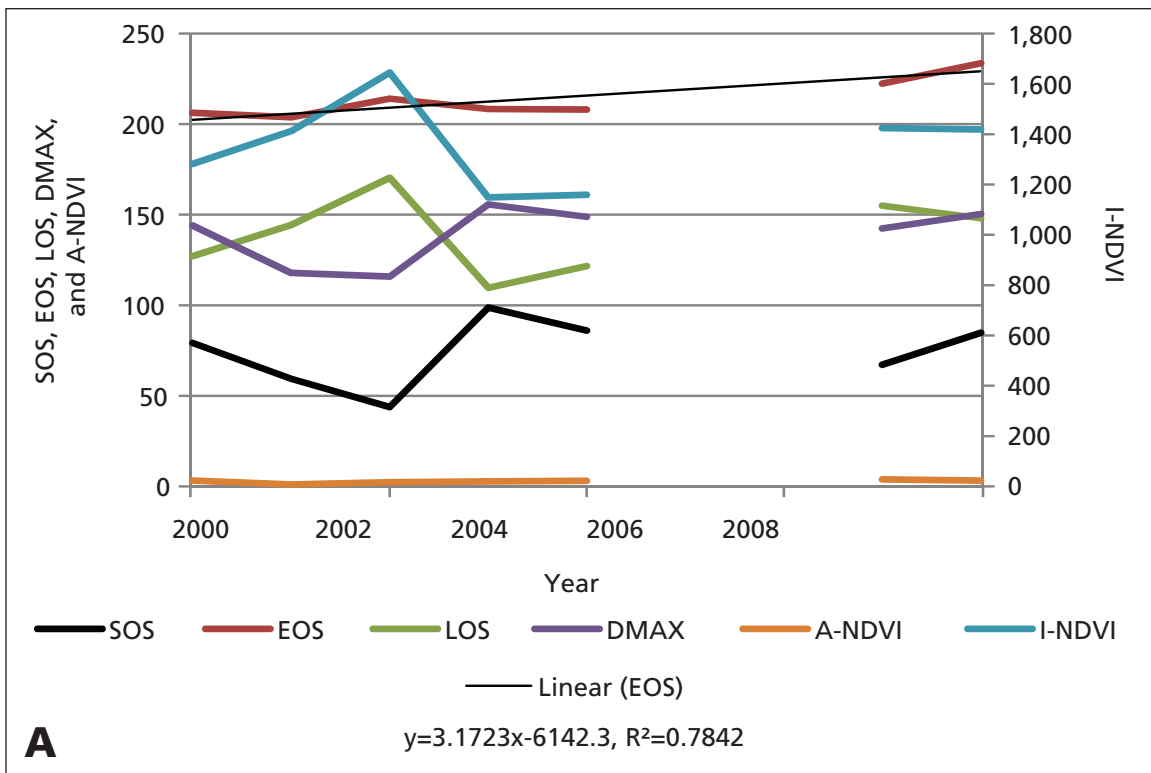


Figure 3.7-4 Annual (a) spring and (b) monsoon phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Colorado NM. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.7.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Colorado NM (Figure 3.7-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is unlikely (e.g., between DOYs 130 and 250). Cumulative exceedance frequency curves indicate that years 2004, 2008, and 2007 had the most extensive and persistent snow cover (Figure 3.7-5b), and that in 2009, less park area was snow-covered less frequently in the spring, but more of the park was snow-covered more of the time in late fall than in the past 10 years (Figure 3.7-5c).

The relationship between snow-covered extent and water content available for plant growth when snow melts is generally stronger at higher elevations. At Colorado NM, the relationship is highly variable. In some years (e.g., 2001, 2005), late snow cover corresponded with low spring productivity. In other years, early snowmelt resulted in high productivity (2002), or low productivity (2003) (Tables 3.7-4, 3.7-2). Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both.

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. However, based on seven years of data, the parkwide relationship at Colorado NM appears inverse, such that spring SOS increased by about 0.5 days for each day of earlier snowmelt. Although earlier snowmelt could result in an earlier SOS, snow cover is not the only factor driving SOS, as is shown by the negative relationship, at the parkwide scale, between snowmelt DOY and SOS ($R^2 = 0.15$) for the seven years of record (Figure 3.7-6). Stronger relationships may occur at finer spatial scales, where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in the park, defined here as less than 5% coverage, was between DOYs 92 (April 2) and 310 (November 6). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.7-4).

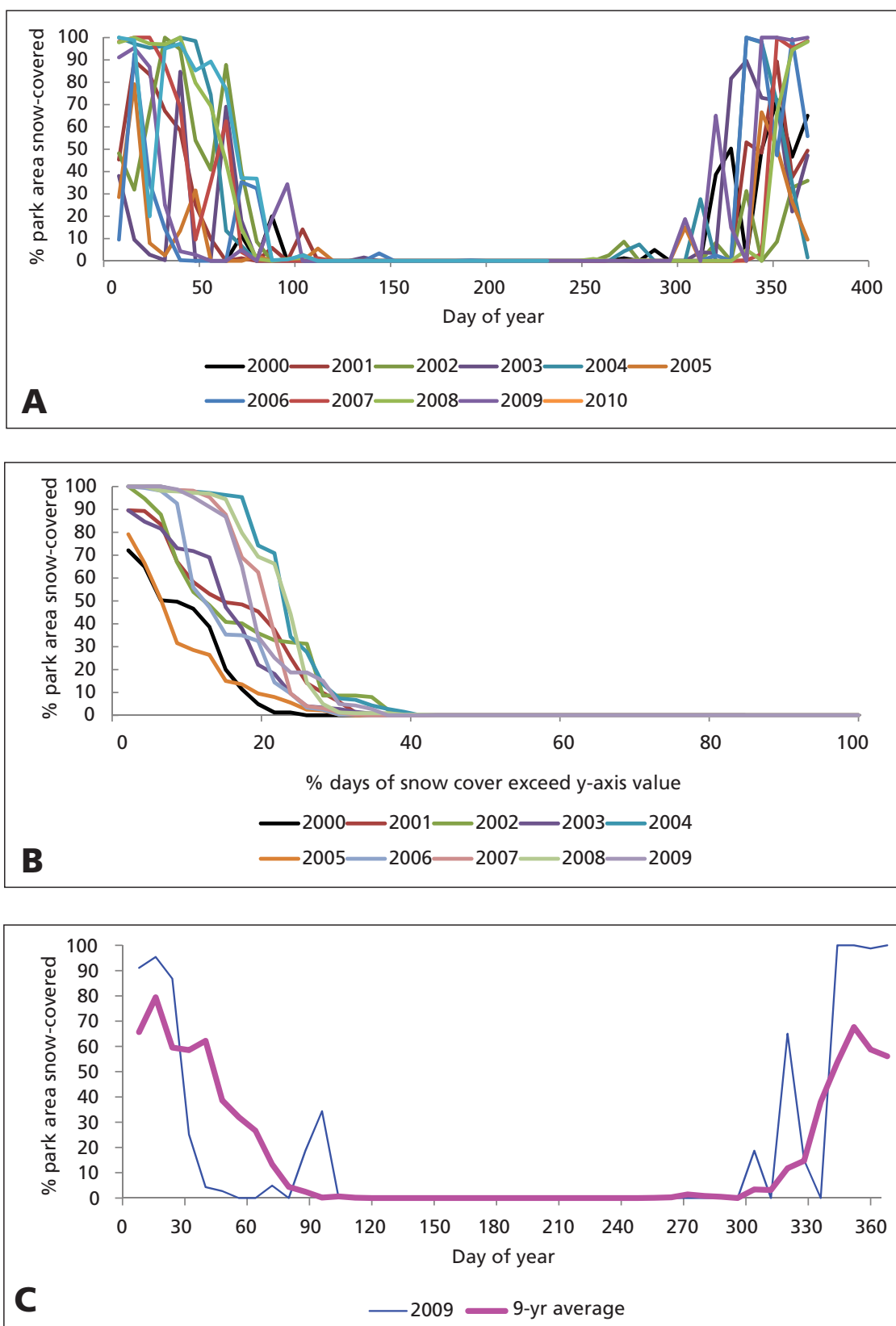


Figure 3.7-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Colorado NM.

Table 3.7-4. Timing and duration of snow cover, Colorado NM.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	4/5/2000	11/7/2000	96	312	216	149
2001	4/22/2001	11/24/2001	112	328	216	149
2002	3/30/2002	9/22/2002	88	264	176	189
2003	3/23/2003	11/18/2003	80	320	240	125
2004	3/23/2004	10/1/2004	80	272	192	173
2005	5/3/2005	10/26/2005	120	296	176	189
2006	4/2/2006	11/28/2006	88	328	240	125
2007	3/18/2007	12/15/2007	72	344	272	93
2008	3/26/2008	12/15/2008	80	344	264	101
2009	4/20/2009	10/29/2009	104	296	192	173
<i>correlation</i>			-0.20	0.27	0.31	-0.31
<i>slope</i>			-1.02	2.52	3.54	-3.54
<i>p-val slope</i>			0.59	0.44	0.39	0.39
<i>intercept</i>			2133	-4743	-6876	7241
<i>p-val intercept</i>			0.57	0.47	0.40	0.38

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

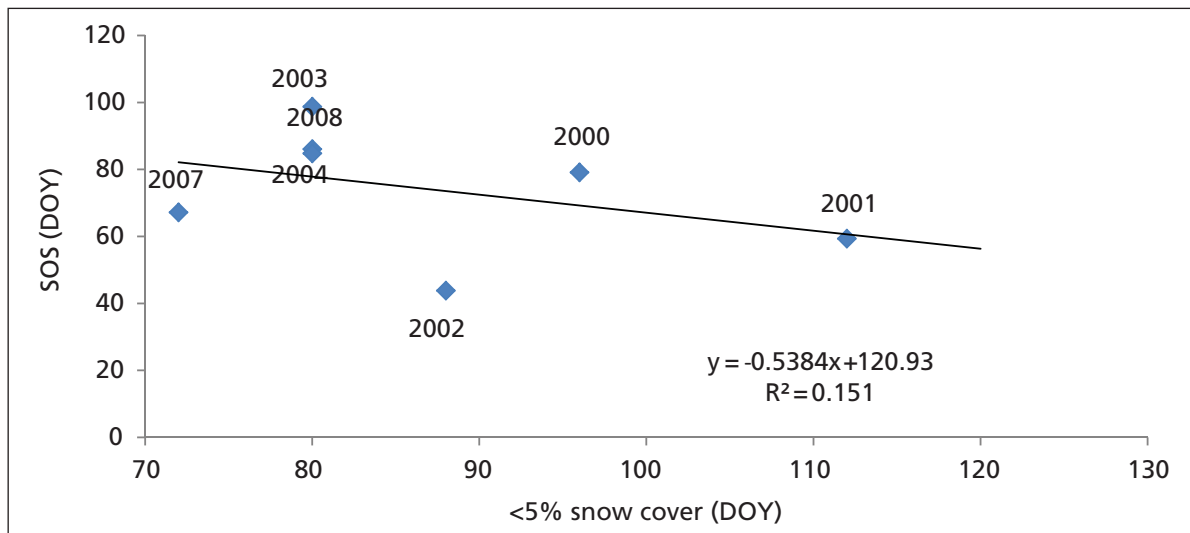


Figure 3.7-6. Relationship between snowmelt DOY and SOS, Colorado NM.

3.8 Curecanti National Recreation Area

3.8.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.8-1a). In the 10-year time series, a strong uni-modal seasonal phenology was apparent in most years. A weak bi-modal NDVI signature was apparent in 2002, 2003, 2005, and 2006. When annual curves are stacked (Figure 3.8-1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2008 and 2009, are easily contrasted with less productive years, such as 2002. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to lower-elevation NCPN parks, the NDVI annual curves for Curecanti National Recreation Area (NRA) are remarkably consistent, which may indicate that the park's precipitation is well-distributed, more abundant than elsewhere, and supports vegetation adapted to a single growing season.

Weather data from the park's NWS Coop station were used to interpret NDVI variation (Figure 3.8-1a). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2002 had the narrowest range in annual maximum and minimum NDVI (18.3), while 2004 had the widest (34.5) (Table 3.8-1). The wide range in 2004 may have been related to extent and depth of snow cover in winter 2003–2004, but other years with similar snow-cover extent and duration did not have the pronounced dip in NDVI observed on DOY 19 (January 19) of 2004. The minimum NDVI in 2004 may have resulted from lack of snow-cover insulation, which may have suppressed vegetation response early in the year. This theory is supported by the cumulative exceedance frequency curve for 2003 (Figure 3.8-5b), which indicated that less of the park area was snow-covered in that year than any other except 2001. Lack of snow cover, coupled with extreme cold, can damage roots (Peng et al. 2010). Data for year 2001 were incomplete, starting shortly after the satellite was launched in March 2000. Nevertheless, the years after 2004 showed no indication of unusually low winter NDVI, indicating that if growth was

stunted by severe winter conditions, recovery occurred by the following year.

Temperature effects on vegetation productivity at Curecanti NRA are intertwined with moisture effects. Based on peak amplitude, if not cumulative productivity (discussed later), low spring precipitation, coupled with below-normal temperatures, may have slightly limited peak productivity in 2004 (Figure 3.8-1a). A better understanding of the relationship between temperature, moisture, snow cover, and NDVI will help improve understanding of potential impacts to vegetation caused by weather and climate.

Differences in mean annual NDVI were minimal for the 10-year period of record in spite of wide variation in cumulative annual precipitation (Figure 3.8-2a, b). This highlights the importance of precipitation timing and indicates that even in the lowest precipitation years, precipitation generally may be high enough to support the vegetation adapted to the climate at Curecanti NRA.

3.8.2 Recent NDVI conditions

The seasonal curve for NDVI fluctuated around the 10-year average in 2009, but its relative position above or below average generally followed periods of precipitation that were above or below average. The 2009 annual NDVI was 0.28% below the 10-year average, corresponding to a precipitation deficit of 11.2% below the 10-year average (Figure 3.8-3a, b).

The spatial distribution of below-average NDVI in 2009 was patchy, but northern aspects and the extreme western portion of the park generally had the largest areas below average (Figure 3.8-3c). It is interesting to note that the reservoirs also exhibited below-average NDVI in the 2009 anomaly map. This may either be a result of reservoir turnover or differences in phytoplankton concentration at this time of year. Although NDVI may not be the optimum index for assessing changes in water quality, either possibility suggested above could be investigated using available data collected by the Curecanti NRA hydrology program (however, that is beyond the scope of this report). On DOY 304 (October 31), most areas of Curecanti NRA were within ± 1.5 NDVI units, or $\pm 2.8\%$, of the long-term average. Future analysis can be made for the reservoirs themselves, only the land surrounding the reservoirs, or, as was done here, with both reservoirs and land considered together.

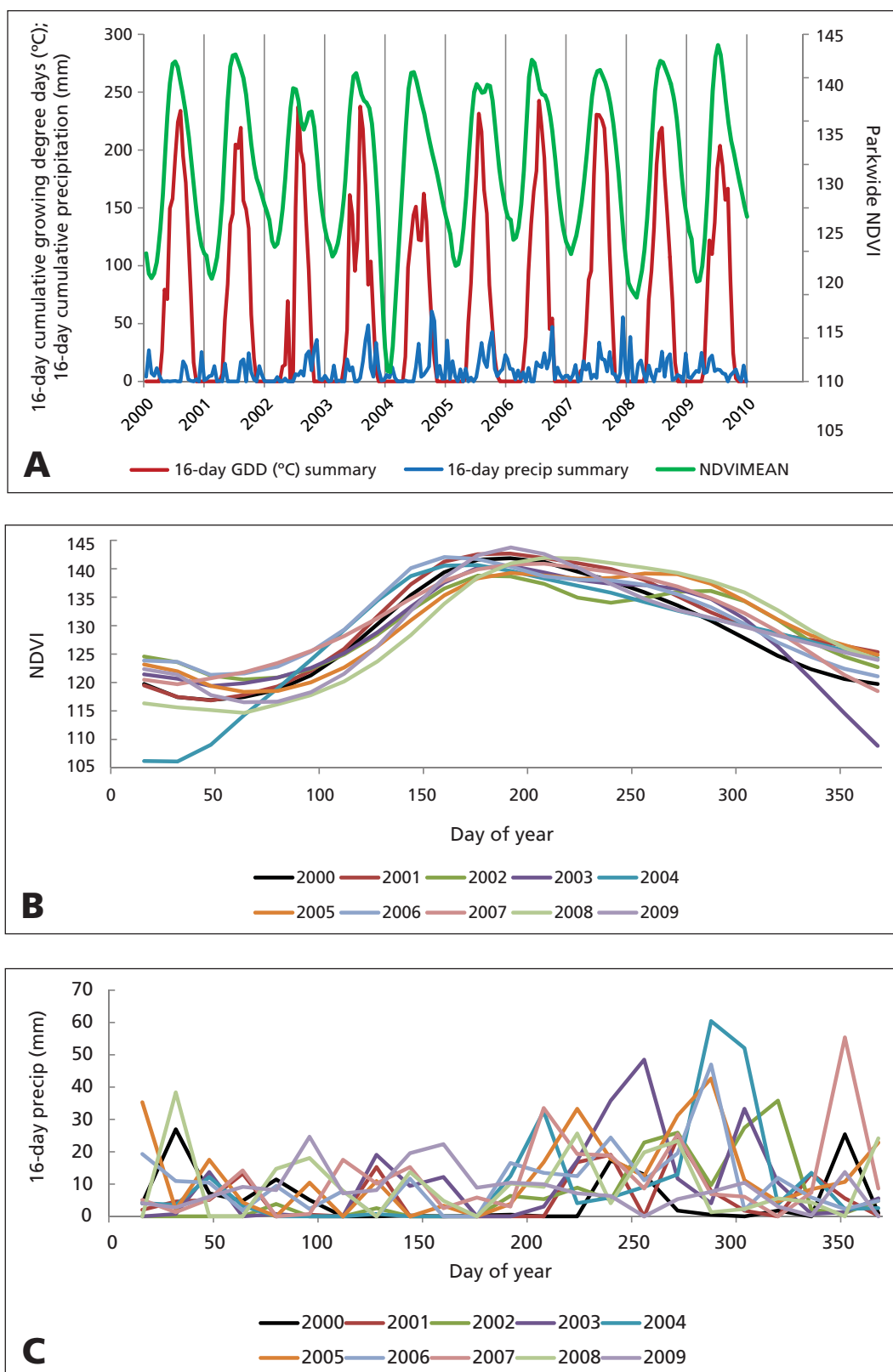


Figure 3.8-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Curecanti NRA.

Table 3.8-1. Annual descriptive statistics for parkwide average NDVI, Curecanti NRA.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	128.7	127.8	141.9	116.9	24.94	2959
2001	130.5	130.0	142.7	116.8	25.82	3000
2002	129.8	131.0	138.8	120.5	18.26	2986
2003	128.5	128.8	140.5	108.9	31.64	2955
2004	128.1	130.0	140.6	106.1	34.54	2947
2005	130.0	130.9	139.3	118.3	20.92	2990
2006	131.0	130.3	142.0	121.1	20.95	3013
2007	130.5	131.3	140.9	118.5	22.39	3001
2008	129.2	129.1	141.9	114.7	27.27	2971
2009	129.2	128.3	143.7	116.5	27.23	2971

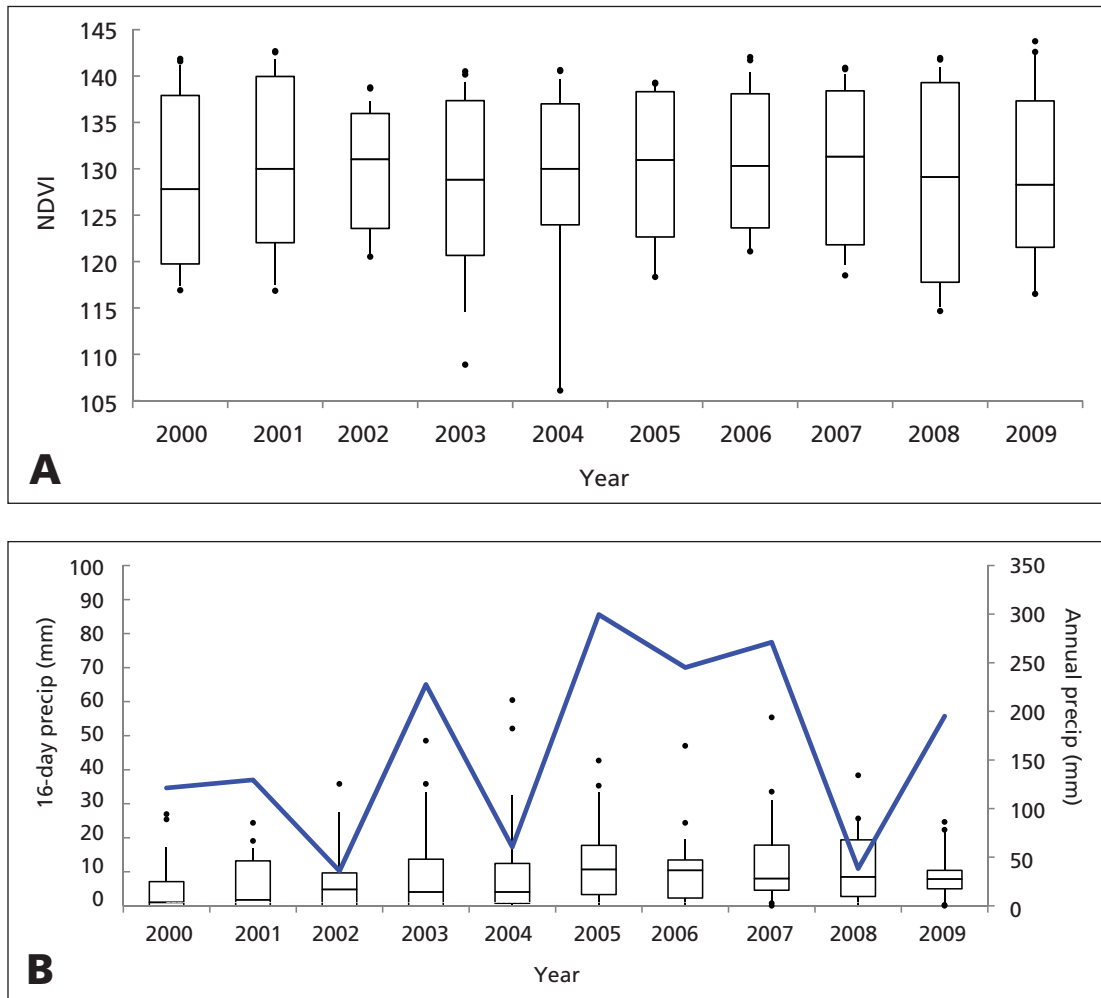


Figure 3.8-2. (a) CURE Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Curecanti NRA. Due to missing weather station data for 2007, 2008, and 2009, box plots and cumulative precipitation do not reflect actual conditions.

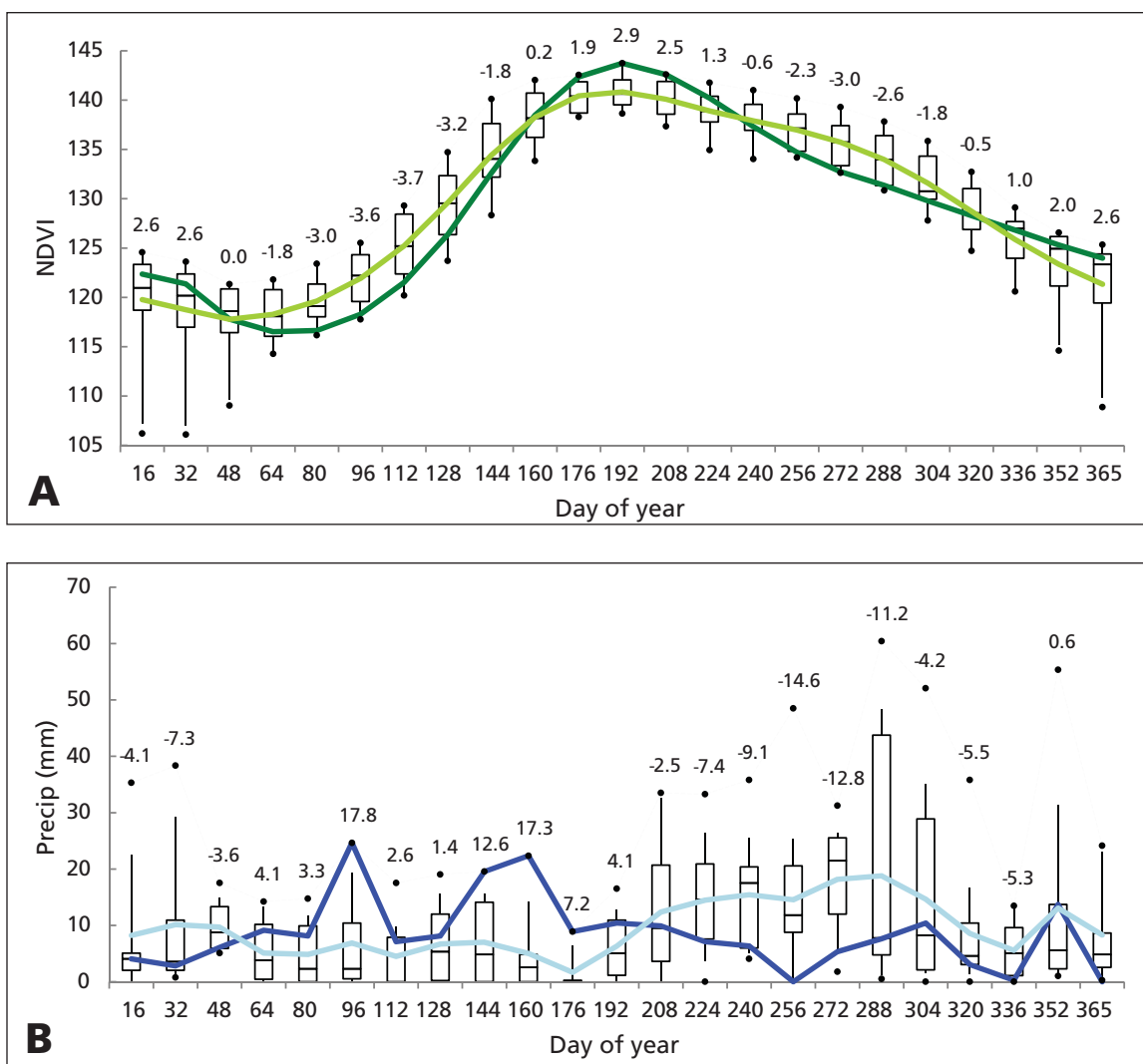


Figure 3.8-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Curecanti NRA. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

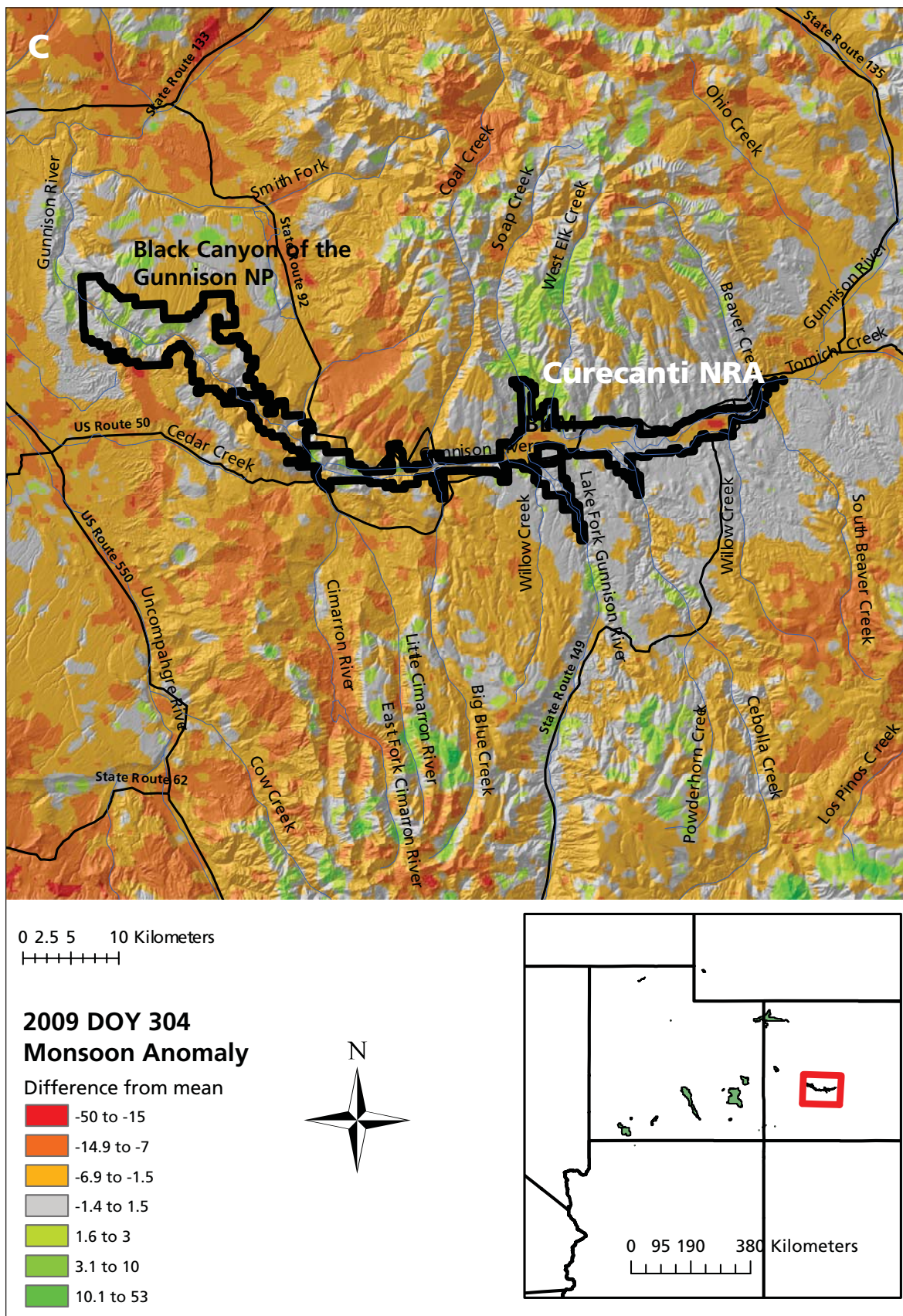


Figure 3.8-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Curecanti NRA.

3.8.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 52, 53, 81, and 53 days, respectively. The most productive year, based on I-NDVI, was 2004, while the least productive was 2000 (Table 3.8-2); these years corresponded to the longest (308) and shortest (207) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. There were no statistically significant linear trends (p-value <0.1) in the phenology metrics observed at the parkwide scale for the period of analysis (Table 3.8-2; Figure 3.8-4).

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends (Table 3.8-2, Figure 3.8-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

3.8.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Curecanti NRA (Figure 3.8-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2009, 2008, and 2004 had the most extensive and persistent snow cover (Figure 3.8-5b) and that in 2009, more park area was snow-covered for longer than in the past 10 years (Figure 3.8-5c).

Statistically significant linear trends (p-value ≤ 0.1) in the snow-cover extent metrics were observed at the parkwide scale for the period of analysis (Table 3.8.3) for days snow-free (increased by 6 days), and days snow-covered (decreased by 6 days per year). These trends are statistically significant, but may not be physically plausible and may be the result of quasi-periodic fluctuations in climate that cycle at irregular intervals of between two and seven years.

Although water content cannot be directly inferred from snow cover, they are related. For example, years 2004 and 2007 had the two earliest snowmelt dates (DOYs 96 and 88, respectively; Table 3.8-3) and two of the most productive growing seasons (NDVI integrals 2748 and 2518, respectively; Table 3.8-2). Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both. Coupling these data with NRCS Snotel and USGS streamflow data in the watershed could help answer that question. Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. A positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.19$) for the nine years of record (Figure 3.8-6). Stronger relationships may occur at finer spatial scales, where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Curecanti NRA, defined here as less than 5% coverage, occurred between DOYs 113 (April 23) and 297 (October 24). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.8-3).

Table 3.8-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Curecanti NRA.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	103	199	330	227	2129	25.03
2001	101	200	359	257	2409	23.95
2002	112	226	353	240	2253	18.67
2003	110	224	351	241	2244	27.56
2004	67	181	374	308	2748	28.41
2005	115	229	358	242	2269	19.35
2006	101	192	330	229	2156	21.31
2007	94	218	352	259	2518	23.32
2008	118	234	382	264	2398	26.23
<i>correlation</i>	<i>0.06</i>	<i>0.32</i>	<i>0.39</i>	<i>0.24</i>	<i>0.29</i>	<i>0.00</i>
<i>slope</i>	<i>0.35</i>	<i>2.17</i>	<i>2.49</i>	<i>2.17</i>	<i>20.57</i>	<i>0.00</i>
<i>p-val slope</i>	<i>0.87</i>	<i>0.41</i>	<i>0.30</i>	<i>0.53</i>	<i>0.45</i>	<i>1.00</i>
<i>intercept</i>	<i>-601</i>	<i>-4128</i>	<i>-4642</i>	<i>-4087</i>	<i>-38868</i>	<i>24</i>
<i>p-val intercept</i>	<i>0.89</i>	<i>0.43</i>	<i>0.33</i>	<i>0.55</i>	<i>0.48</i>	<i>0.98</i>

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

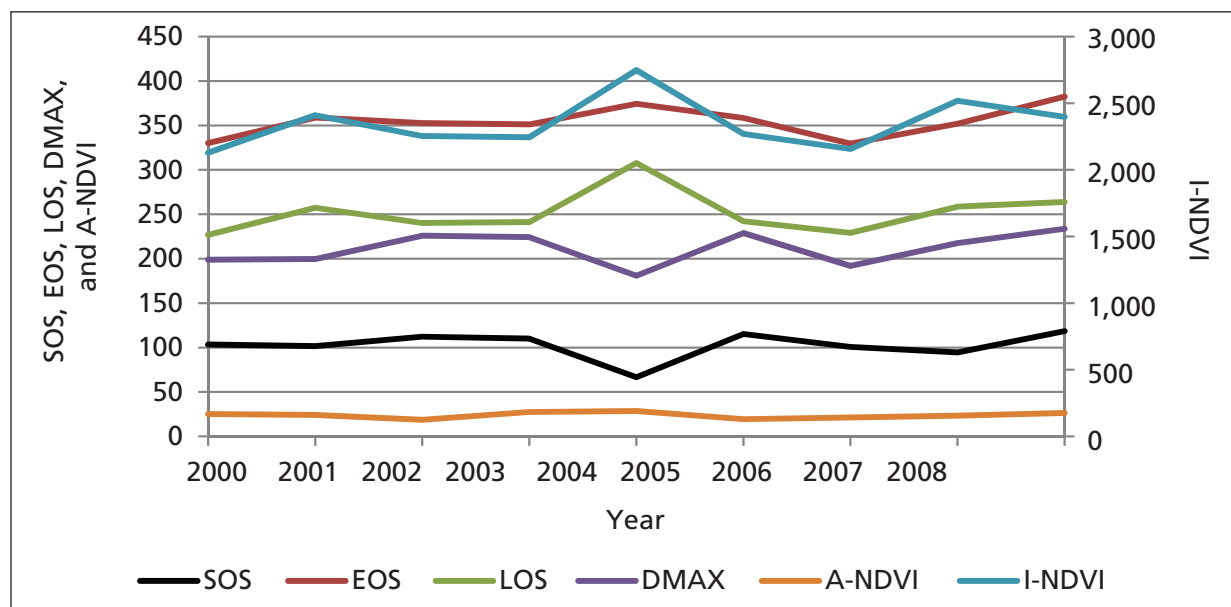


Figure 3.8-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Curecanti NRA. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

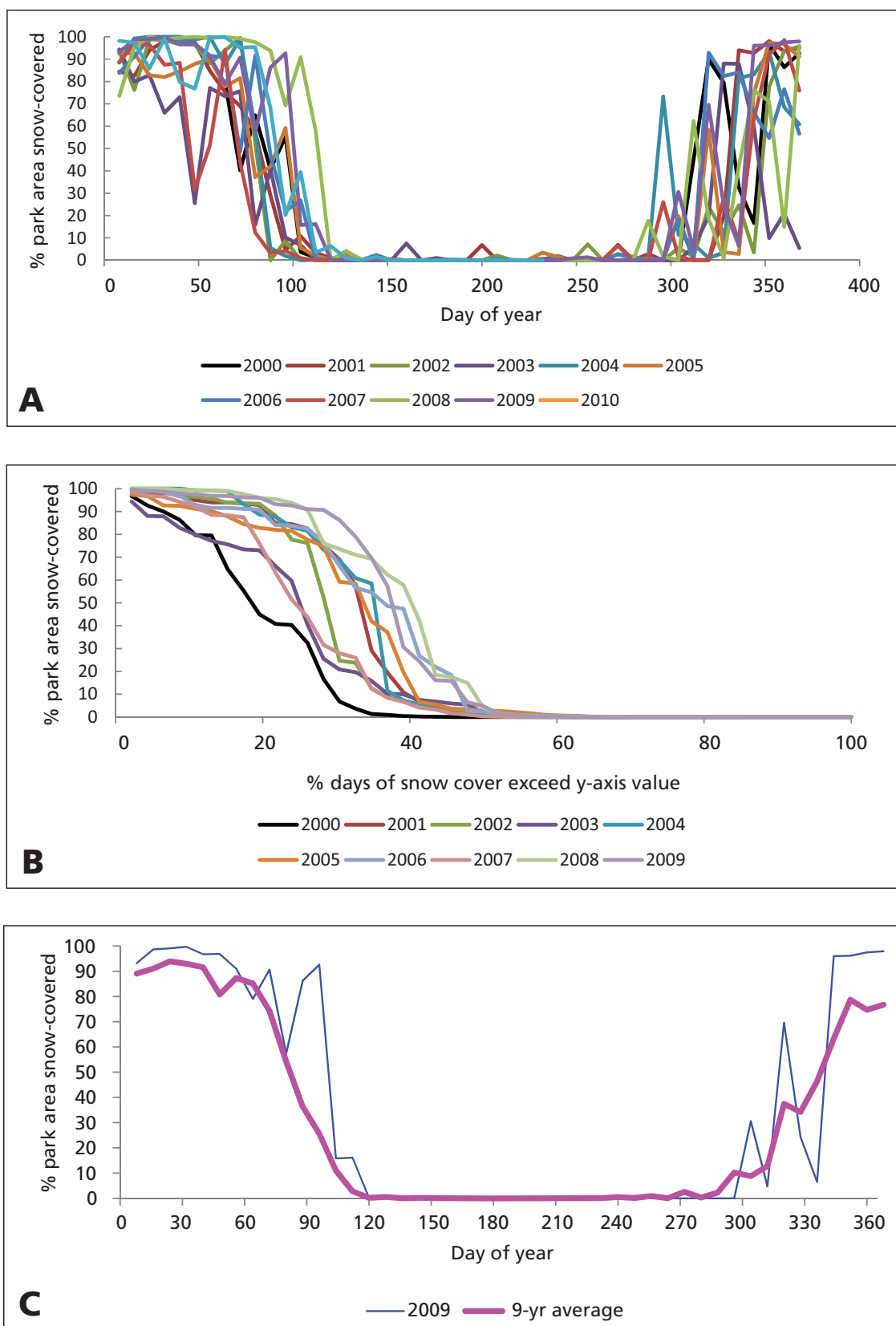


Figure 3.8-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Curecanti NRA.

Table 3.8-3. Timing and duration of snow cover, Curecanti NRA.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	4/13/2000	9/20/2000	104	264	160	205
2001	4/22/2001	7/11/2001	112	192	80	285
2002	4/15/2002	9/6/2002	104	248	144	221
2003	6/19/2003	11/2/2003	168	304	136	229
2004	4/8/2004	10/17/2004	96	288	192	173
2005	4/25/2005	9/24/2005	112	264	152	213
2006	4/26/2006	10/27/2006	112	296	184	181
2007	4/3/2007	9/26/2007	88	264	176	189
2008	5/5/2008	10/12/2008	120	280	160	205
2009	5/6/2009	10/29/2009	120	296	176	189
<i>correlation</i>			-0.03	0.53	0.55	-0.55
<i>slope</i>			-0.19	5.67	5.87	-5.87
<i>p-val slope</i>			0.94	0.12	0.10	0.10
<i>intercept</i>			502	-11101	-11604	11969
<i>p-val intercept</i>			0.92	0.13	0.10	0.09

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

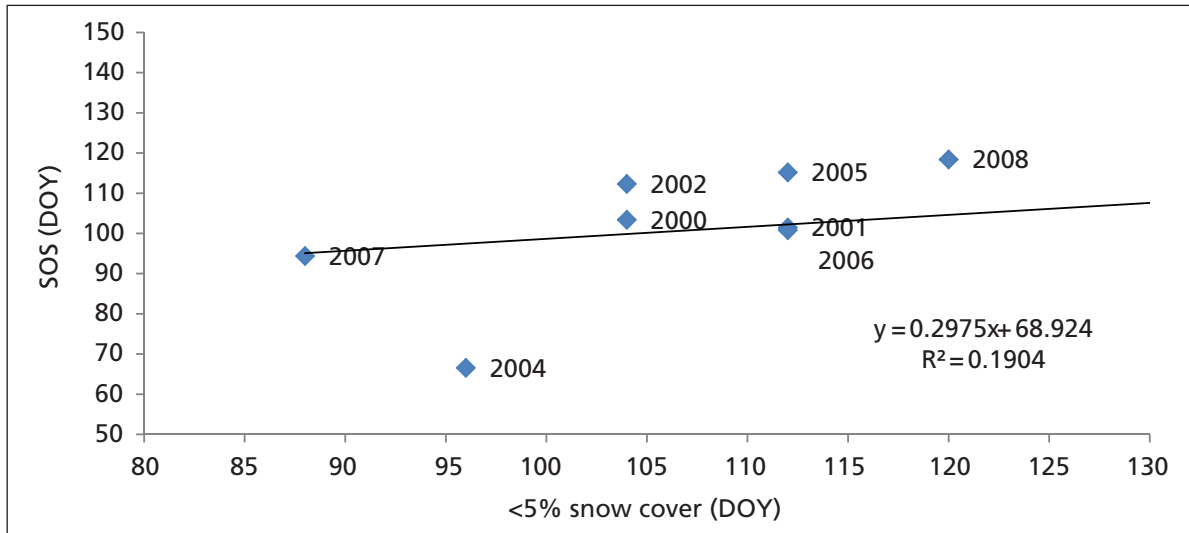


Figure 3.8-6. Relationship between snowmelt DOY and SOS, Curecanti NRA.

3.9 Dinosaur National Monument

3.9.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.9.1a). In the 10-year time series, a strong bi-modal seasonal phenology was apparent in most years, the notable exception being year 2003, when bi-modal seasonality was present but weakly expressed in the second season. Patterns in vegetation productivity followed the temporal pattern of precipitation pulses, with a lagged response. When annual curves are stacked (Figure 3.9.1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2005, are easily contrasted with less productive years, such as 2008. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. The NDVI annual curves for Dinosaur NM are bi-modal, likely reflecting some combination of bi-modal precipitation and distinctly different vegetation/elevation interactions that cause peaks in NDVI at different times of year.

Weather data from the park's NWS Coop station were used to interpret NDVI variation (Figure 3.9-1a, c). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2006 had the narrowest range in annual maximum and minimum NDVI (7.0), while 2008 had the widest range (11.3) (Table 3.9-1). The largest maximum NDVI (136.3) occurred in 2005. It would be incorrect to suggest that higher cumulative precipitation years had higher median NDVI (Figure 3.9-2a, b). Rather, it is clear that the strength of bi-modal NDVI response is strongly associated with differences in

the temporal distribution of precipitation (Figure 3.9-1a, c). A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

3.9.2 Recent NDVI conditions

The NDVI curve was slightly below the historical average during the first and last thirds of 2009, but well above average at mid-year. These generalizations, as differences from the mean, also apply to precipitation, giving some indication of the tight coupling of precipitation and productivity at Dinosaur NM. A period of above-average precipitation (24.5 mm), centered on DOY 176 (June 25), increased NDVI well above the historical average until DOY 256 (September 13). Annual average NDVI for 2009 was 0.1% above the 10-year average. Weather data for 2009 indicated that the precipitation deficit was 36.8% below the 10-year average (Figure 3.9-3a, b). The slightly above-average annual NDVI in 2009, despite a cumulative annual precipitation deficit below the 10-year average, further highlights the importance of precipitation timing relative to magnitude in driving annual productivity.

The spatial distribution of below-average NDVI in 2009 was limited to the southern margin of the park boundary (Figure 3.9-3c). In general, north-facing aspects along the canyon of the Green River were above average, whereas only a few areas along the Yampa River near the eastern boundary were above average. On DOY 304 (October 31), most areas of Dinosaur NM were within ± 1.5 NDVI units, or $\pm 2.8\%$, of the long-term average. From a regional perspective, the monument straddled a spatial distribution in 2009 NDVI. Generally, NDVI was above normal north of the park, and below normal south of the park (see executive summary anomaly map).

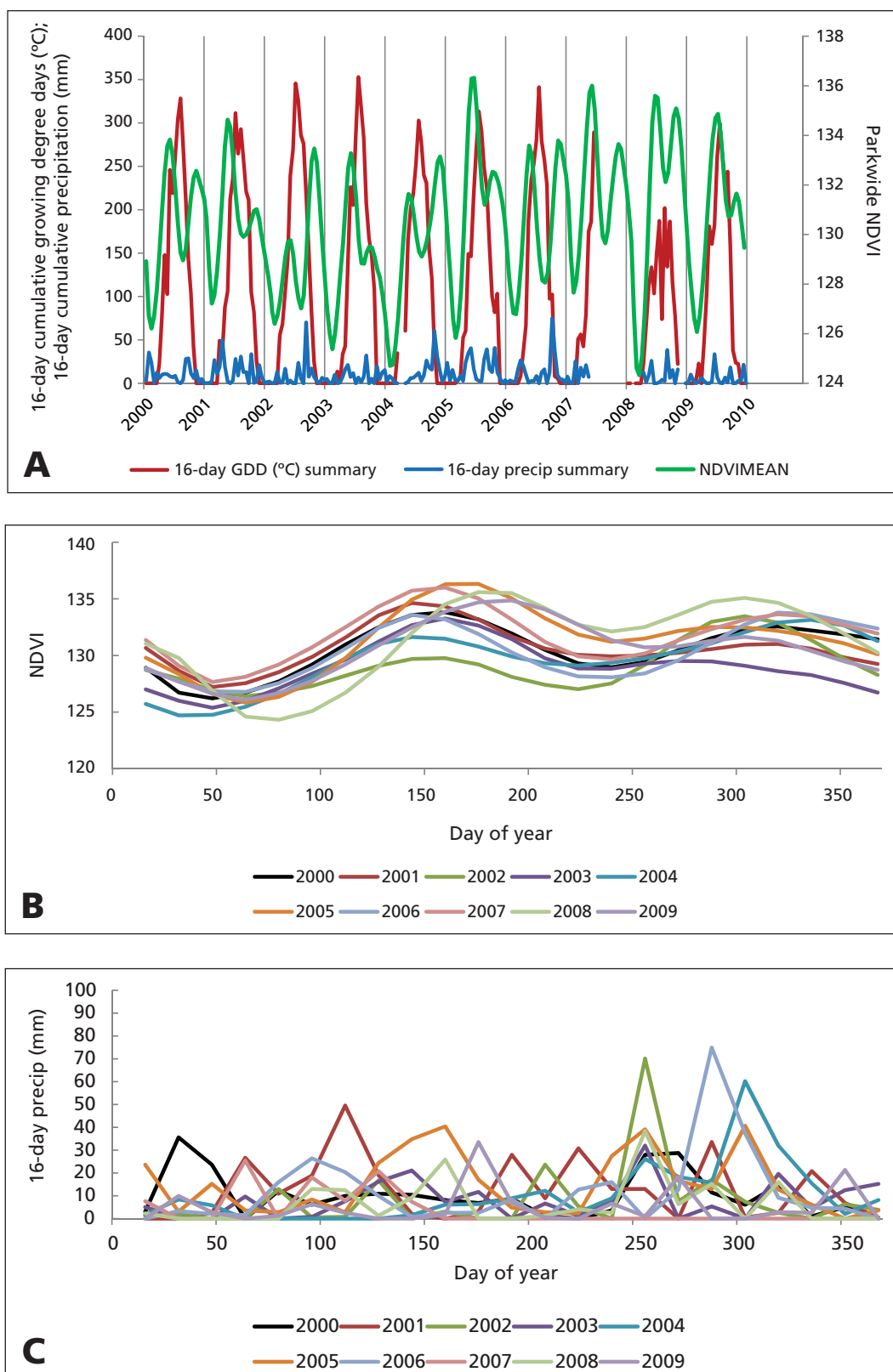


Figure 3.9-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Dinosaur NM.

Table 3.9-1. Annual descriptive statistics for parkwide average NDVI, Dinosaur NM.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	130.5	131.0	133.8	126.2	7.61	3002
2001	130.6	130.6	134.6	127.2	7.41	3004
2002	129.1	128.7	133.5	126.4	7.06	2969
2003	129.0	128.8	133.3	125.4	7.89	2967
2004	129.6	129.9	133.1	124.7	8.44	2981
2005	131.3	131.7	136.3	125.8	10.48	3019
2006	130.4	130.3	133.8	126.8	6.99	2998
2007	131.8	131.9	136.0	127.7	8.34	3032
2008	131.3	132.1	135.6	124.3	11.26	3020
2009	130.5	130.8	134.9	126.1	8.79	3002

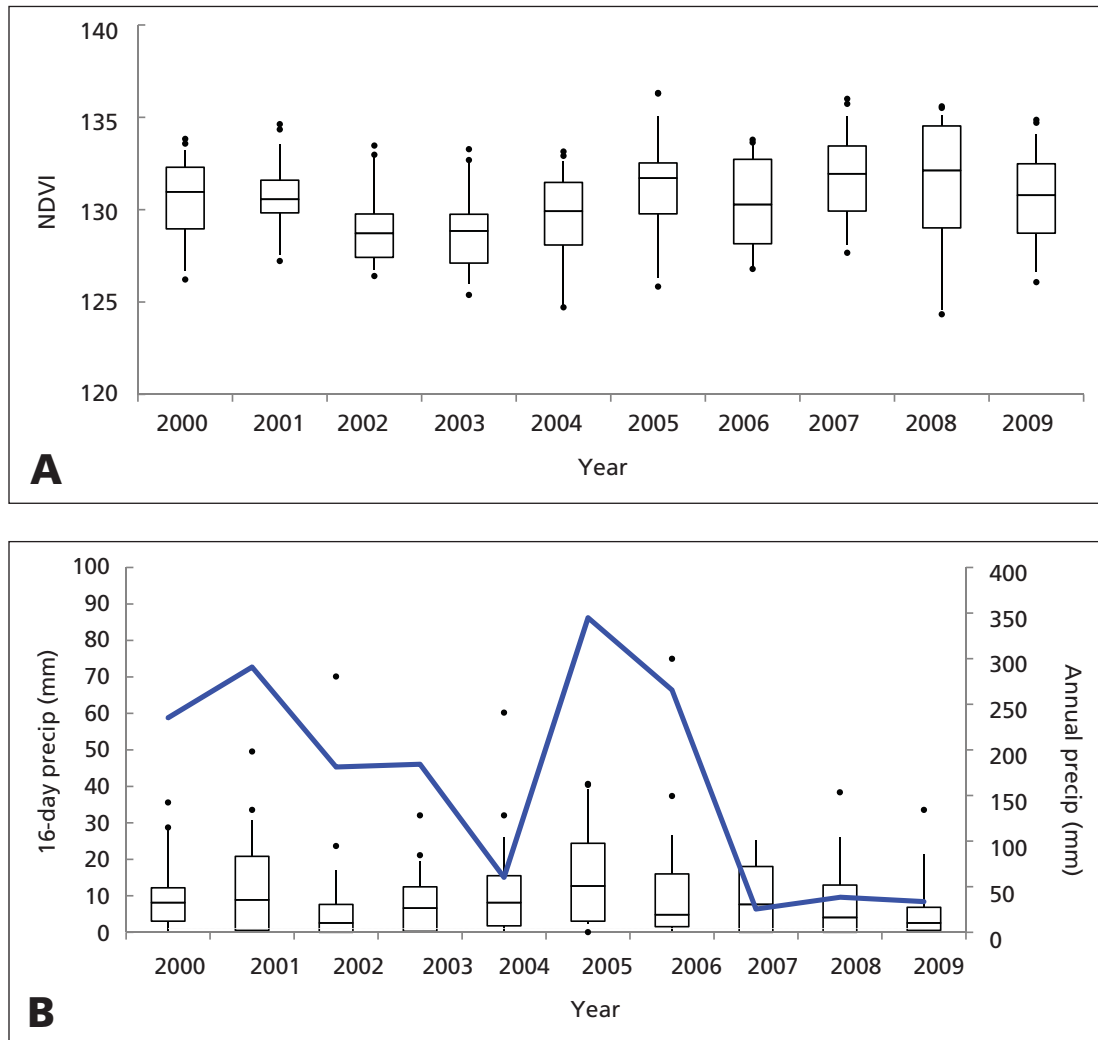


Figure 3.9-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Dinosaur NM. Due to missing weather station data for 2004, 2007, and 2008, box plots and cumulative precipitation do not reflect actual conditions.

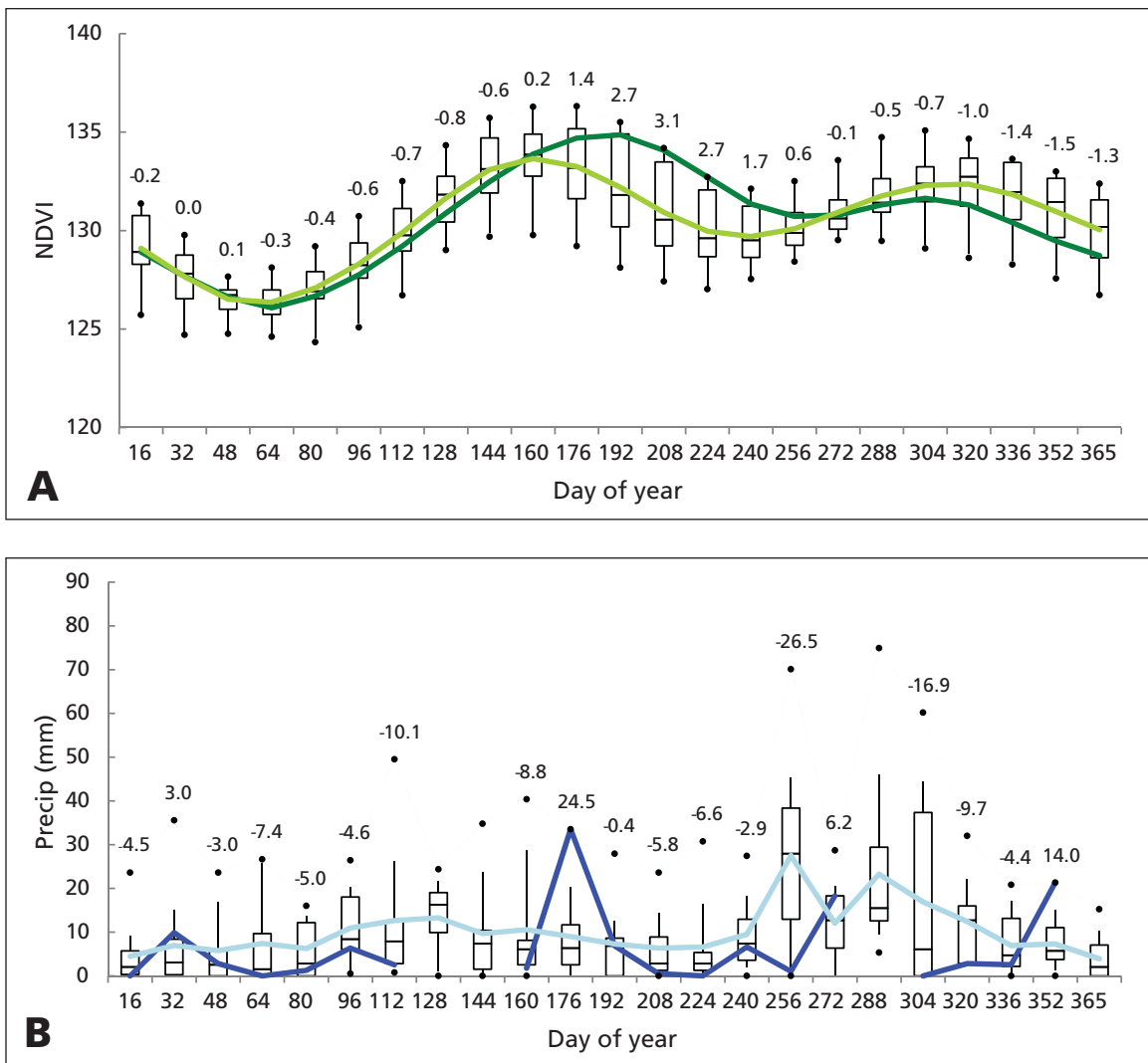


Figure 3.9-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Dinosaur NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

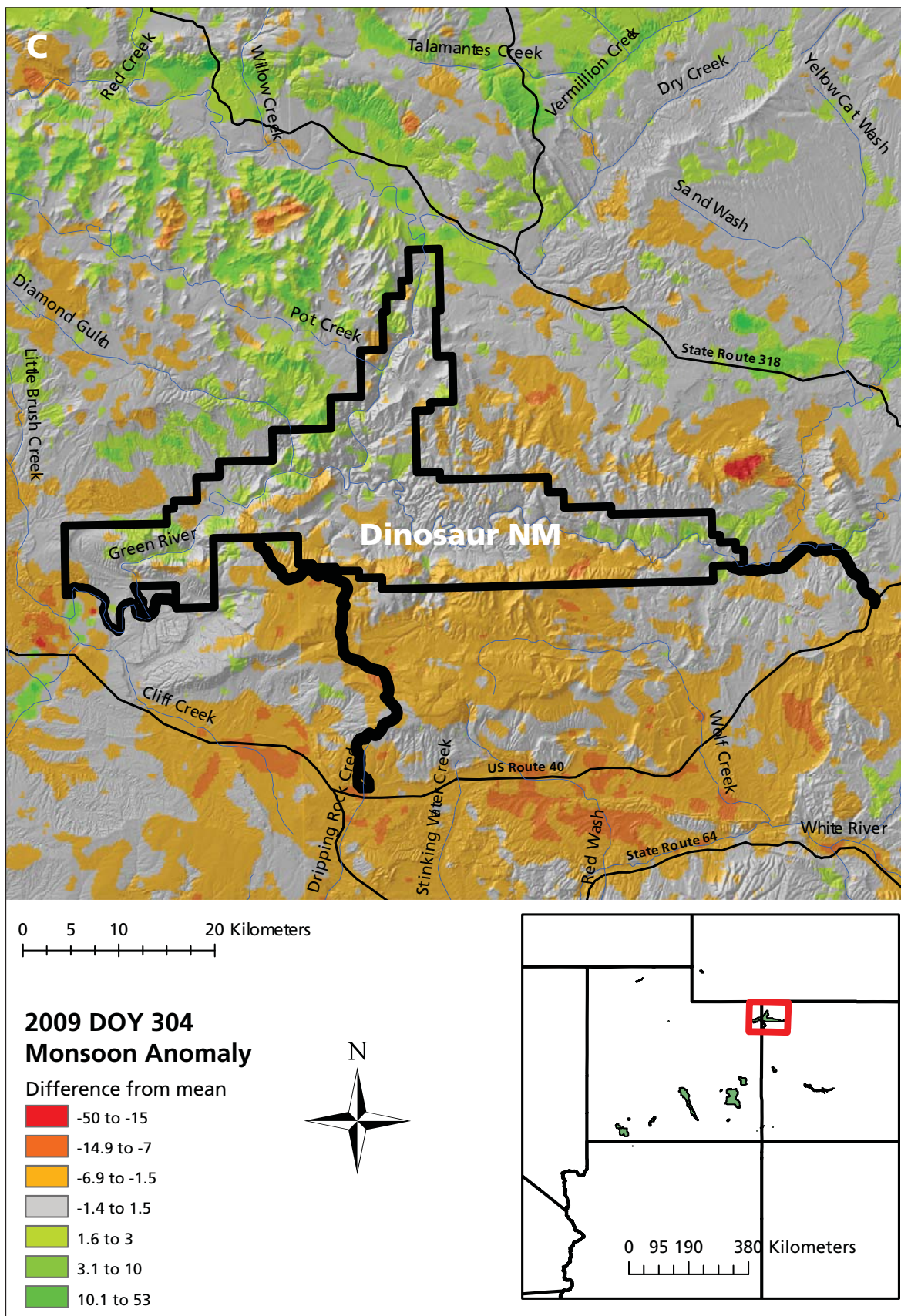


Figure 3.9-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Dinosaur NM.

3.9.3 Phenology

In most years, there are two distinct growing seasons at Dinosaur NM that represent the interaction of plant functional types (annual/perennial, early season/late season), phenology, and suitability of moisture for growth. The two seasons (spring and monsoon) are evaluated separately due to the distinct bi-modal nature of phenology observed at the park.

3.9.3.1 Spring

Over the 10-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 37, 38, 28, and 35 days, respectively. The most productive spring, based on I-NDVI, was 2007, while the least productive was 2008 (Table 3.9-2); these years corresponded to the third-longest (121 days) and second-shortest (107 days) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships, as was observed at Dinosaur NM. Statistically significant linear trends (p -value <0.1) for spring SOS, EOS, and DMAX were observed at the parkwide scale for the period of analysis (Table 3.9-2; Figure 3.9-3a). These trends indicate that spring SOS, EOS, and DMAX are occurring 2.2, 2.3, and 2.7 days later per year, respectively. Although all three trends are significant and consistent in their direction, they should be considered with caution because they are based on a short (10-year) record.

3.9.3.2 Monsoon

Over the nine-year historical record, the ranges of monsoon SOS, EOS, LOS, and DMAX were 20, 41, 29, and 30 days, respectively. The most productive monsoon season, based on I-NDVI, was 2007, while the least productive was 2002 (Table 3.9-3); these years corresponded to the

longest (156 days) and shortest (127 days) growing seasons, respectively. Based on visual examination of NDVI time series (Figure 3.9-1a), year 2003 may have had lower productivity than 2002, but the amount was too minor to be identified by the Timesat algorithm. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings. This was certainly the case for year 2002, which had a prominent monsoon peak but a shorter monsoon growing season than other years. The influence of precipitation variability on vegetation productivity is made apparent by the decoupling of seasonal productivity, in which productive spring seasons are not always followed by productive monsoon seasons and vice versa. There were no statistically significant linear trends (p -value <0.1) in the monsoon-season phenology metrics observed at the parkwide scale for the period of analysis (Table 3.9-3; Figure 3.9-4b).

3.9.3.3 Summary

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics show trends in spring season phenology (Table 3.9-3, Figure 3.9-4). A longer data record and more robust statistical techniques may provide better indication of broad-scale change in the future, if it occurs.

Table 3.9-2. Spring-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Dinosaur NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	84	153	212	128	1313	6.21
2001	88	147	202	114	1188	5.89
2002	95	151	201	106	1155	2.98
2003	84	157	209	124	1305	6.09
2004	78	144	197	119	1294	4.66
2005	102	165	218	115	1198	7.68
2006	91	147	203	112	1177	6.04
2007	86	154	208	121	1328	7.20
2008	115	176	221	107	1060	7.42
2009	102	179	235	133	1322	6.34
<i>correlation</i>	<i>0.59</i>	<i>0.66</i>	<i>0.60</i>	<i>0.07</i>	<i>-0.09</i>	<i>0.47</i>
<i>slope</i>	<i>2.17</i>	<i>2.68</i>	<i>2.29</i>	<i>0.19</i>	<i>-2.61</i>	<i>0.22</i>
<i>p-val slope</i>	0.07	0.04	0.06	<i>0.86</i>	<i>0.81</i>	<i>0.17</i>
<i>intercept</i>	<i>-4266</i>	<i>-5205</i>	<i>-4386</i>	<i>-272</i>	<i>6458</i>	<i>-431</i>
<i>p-val intercept</i>	<i>0.08</i>	<i>0.04</i>	<i>0.07</i>	<i>0.90</i>	<i>0.77</i>	<i>0.17</i>

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

Table 3.9-3. Monsoon-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Dinosaur NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	263	331	400	138	1438	4.31
2001	268	322	405	137	1426	2.80
2002	250	306	378	127	1304	7.17
2003	-	-	-	-	-	-
2004	267	336	405	138	1438	5.63
2005	258	310	392	134	1310	3.46
2006	270	334	398	129	1315	5.73
2007	262	334	419	156	1571	6.65
2008	261	312	390	129	1323	5.92
<i>correlation</i>	<i>0.14</i>	<i>0.14</i>	<i>0.14</i>	<i>0.16</i>	<i>0.13</i>	<i>0.38</i>
<i>slope</i>	<i>22.95</i>	<i>23.89</i>	<i>25.70</i>	<i>2.71</i>	<i>21.78</i>	<i>0.31</i>
<i>p-val slope</i>	<i>0.92</i>	<i>0.96</i>	<i>0.76</i>	<i>0.77</i>	<i>0.90</i>	<i>0.25</i>
<i>intercept</i>	<i>-45885</i>	<i>-47718</i>	<i>-51269</i>	<i>-5313</i>	<i>-42418</i>	<i>-615</i>
<i>p-val intercept</i>	<i>0.98</i>	<i>0.90</i>	<i>0.83</i>	<i>0.80</i>	<i>0.86</i>	<i>0.25</i>

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

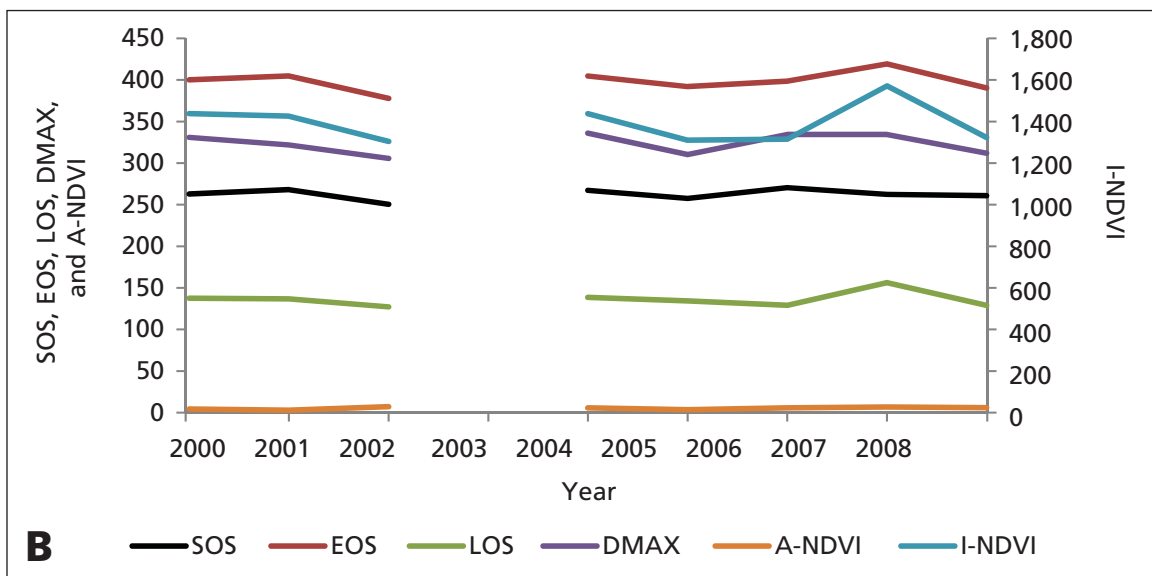
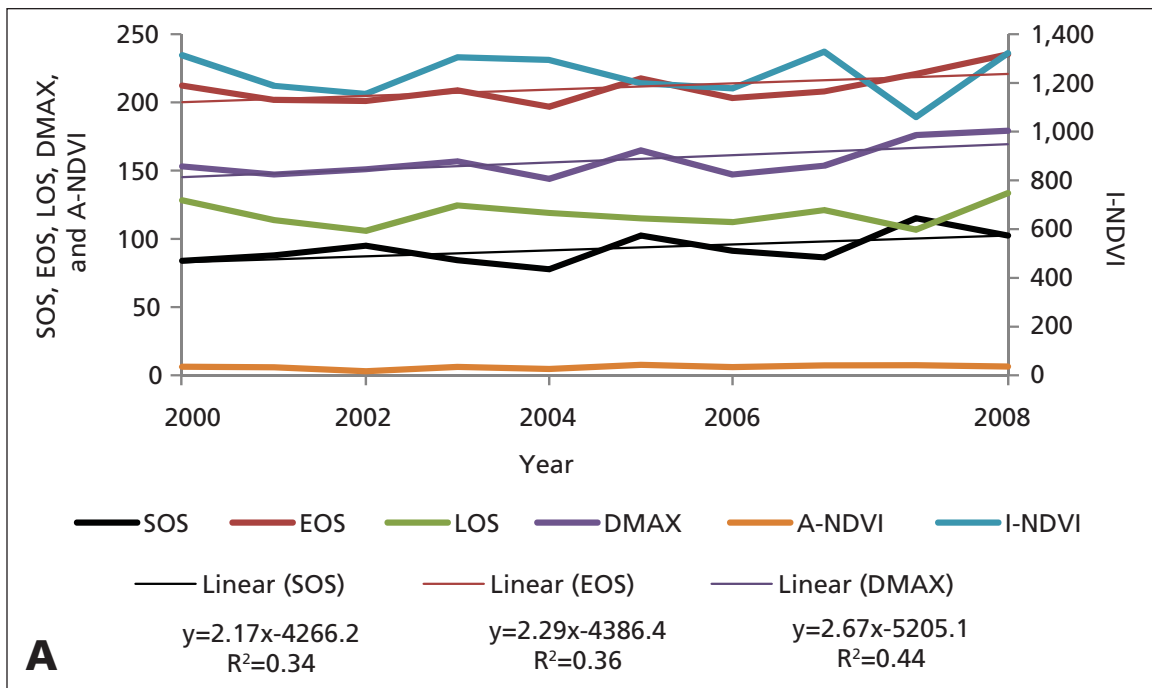


Figure 3.9-4 Annual (a) spring and (b) monsoon phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Dinosaur NM. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.9.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Dinosaur NM (Figure 3.9-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2008 and 2009 had the most extensive and persistent snow cover (Figure 3.9-5b) and that in 2009, more park area was snow-covered for longer than in the past 10 years (Figure 3.9-5c).

The relationship between snow-covered extent and water content available for plant growth when snow melts is generally stronger at higher elevations, and at Dinosaur NM, the relationship is stronger than at most other NCPN parks. Because snow is both a physical and thermal bar-

rier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. Earlier snowmelt could result in an earlier SOS, but snow cover is not the only factor driving SOS, as is shown by the positive relationship between snowmelt DOY and SOS ($R^2 = 0.016$) at the park-wide scale for the nine years of record (Figure 3.9-6). Stronger relationships may occur at finer spatial scales, where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Dinosaur NM, defined here as less than 5% coverage, occurred between DOYs 108 (April 18) and 300 (October 27). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.9-4).

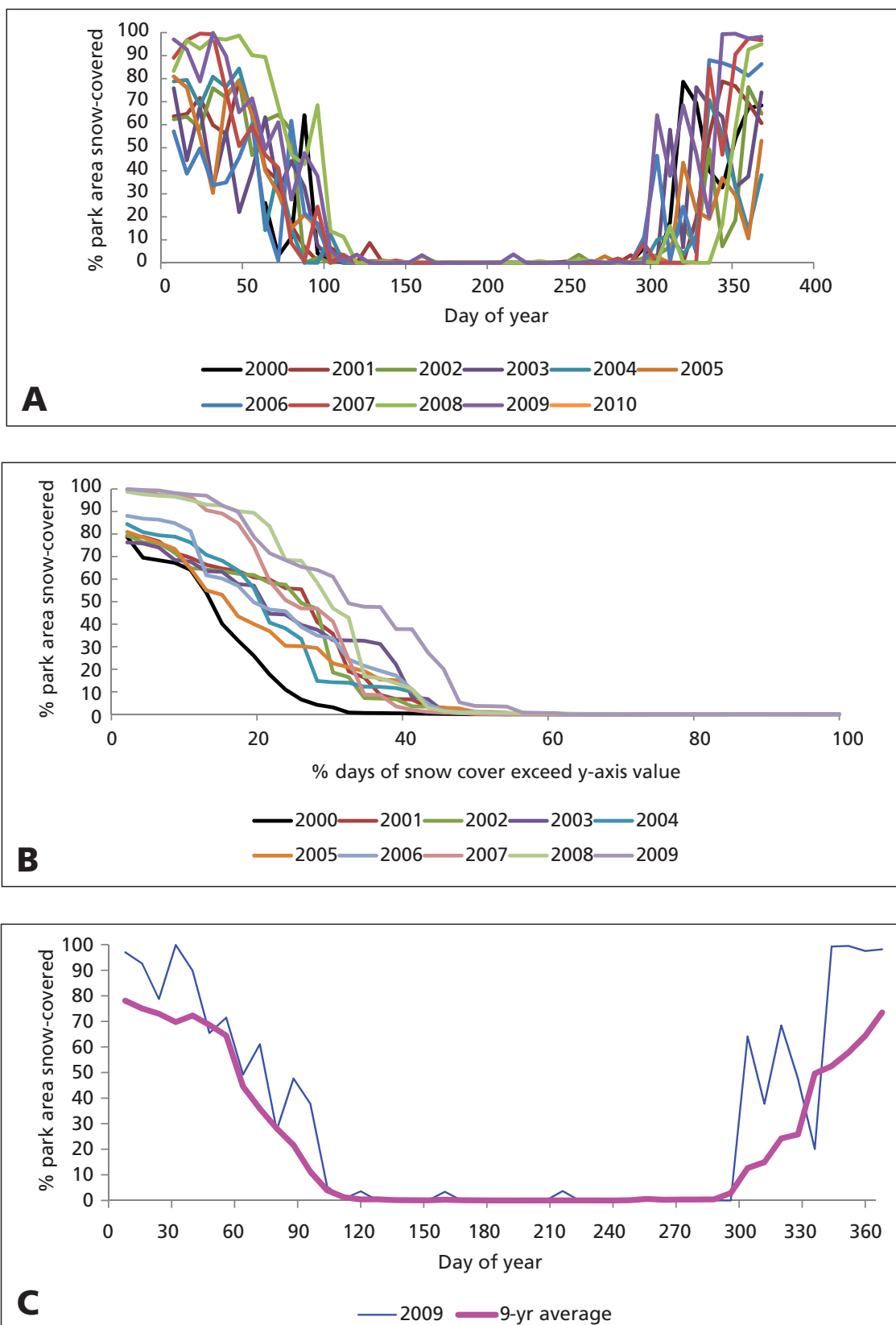


Figure 3.9-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Dinosaur NM.

Table 3.9-4. Timing and duration of snow cover, Dinosaur NM.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	4/5/2000	10/14/2000	96	288	192	173
2001	5/16/2001	11/16/2001	136	320	184	181
2002	3/30/2002	11/1/2002	88	304	216	149
2003	4/16/2003	11/2/2003	104	304	200	165
2004	4/24/2004	10/25/2004	112	296	184	181
2005	4/17/2005	11/11/2005	104	312	208	157
2006	4/18/2006	10/19/2006	104	288	184	181
2007	4/19/2007	10/20/2007	104	288	184	181
2008	5/5/2008	11/5/2008	120	304	184	181
2009	4/28/2009	10/29/2009	112	296	184	181
<i>correlation</i>			0.14	-0.26	-0.39	0.39
<i>slope</i>			0.63	-0.92	-1.55	1.55
<i>p-val slope</i>			0.69	0.47	0.26	0.26
<i>intercept</i>			-1155	2147	3302	-2937
<i>p-val intercept</i>			0.72	0.41	0.23	0.29

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

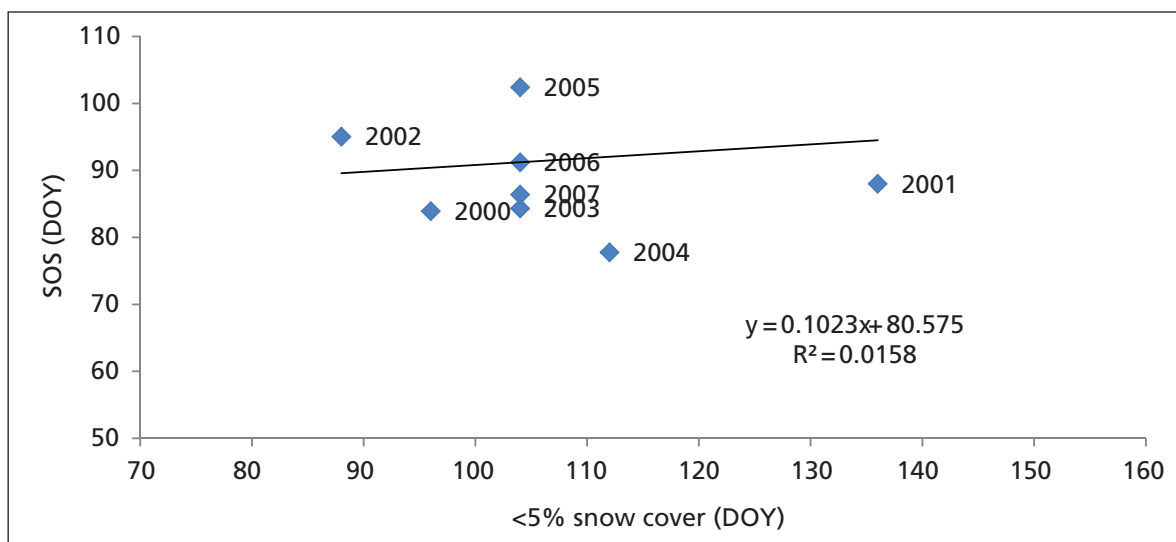


Figure 3.9-6. Relationship between snowmelt DOY and SOS, Dinosaur NM.

3.10 Fossil Butte National Monument

3.10.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.10-1a). In the 10-year time series, a strong uni-modal seasonal phenology was apparent in most years and peak NDVI magnitude appeared to follow larger spring precipitation (2005 and 2009). When annual curves are stacked (Figure 3.10-1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2005 and 2009, are easily contrasted with less productive years, such as 2003. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to lower-elevation NCPN parks, the NDVI annual curves for Fossil Butte NM are remarkably consistent, which may indicate that the park's precipitation is well-distributed, more abundant than elsewhere, and supports vegetation adapted to a single growing season.

Weather data from the park's NWS Coop station were used to interpret NDVI variation (Figure 3.10-1a). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2005 had the highest NDVI maximum value and the highest cumulative precipitation in the 10-year record (Figure 3.10-2). Year 2000 had the narrowest range in annual maximum and minimum NDVI (18.7), while 2009 had the widest (33.9) (Table 3.10-1). The wide range in 2009 may be related to the extent and depth of snow cover in winter 2008–2009, when snow covered more than 5% of the park on DOYs 248 (September 10, 2008) through 120 (May 6, 2009) (Table 3.10-3). More information on snow cover is presented in a later section. Other years with low minimum NDVI included 2003 and 2004, but they did not have snow cover for as long as in 2009. The minimum NDVI in 2003 and 2004 may have resulted from lack of snow cover insulation, which might have suppressed vegeta-

tion response early in the year. Lack of snow cover, coupled with extreme cold, can damage roots (Peng et al. 2010). Nevertheless, the years after 2004 showed no indication of unusually low winter NDVI, indicating that if growth was stunted by severe winter conditions, recovery occurred by the following year. Data for year 2001 were incomplete, starting shortly after the satellite was launched in March 2000.

Temperature effects on vegetation productivity at Fossil Butte NM are intertwined with moisture effects, and these interactions may help explain differences in annual productivity. A better understanding of the relationship between temperature, moisture, snow cover, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

Differences in median annual NDVI were minimal for the 10-year period of record, with the exception of years 2005 and 2009, which had the two highest values for cumulative precipitation and the two highest maximum annual NDVI values in the record (Table 3.10-1; Figure 3.10-1a, b). This highlights the importance of precipitation abundance for productivity and indicates that precipitation timing is generally distributed evenly enough—even in years of lowest precipitation—to support the climate-adapted vegetation at Fossil Butte NM.

3.10.2 Recent NDVI conditions

The seasonal curve for NDVI fluctuated around the 10-year average in 2009, but its relative position above or below average generally followed periods of precipitation that were above or below average. Annual NDVI for 2009 was 0.47% above the 10-year average, which corresponded to a precipitation surplus of 47.7% above the 10-year average (Figure 3.10-3a, b).

The entire park experienced above-average NDVI in 2009, as did most of the surrounding region (Figure 3.10-3c). On DOY 304 (October 31), most areas of Fossil Butte NM were within +1 to +4 NDVI units, or +2 to +7.6%, of the long-term average.

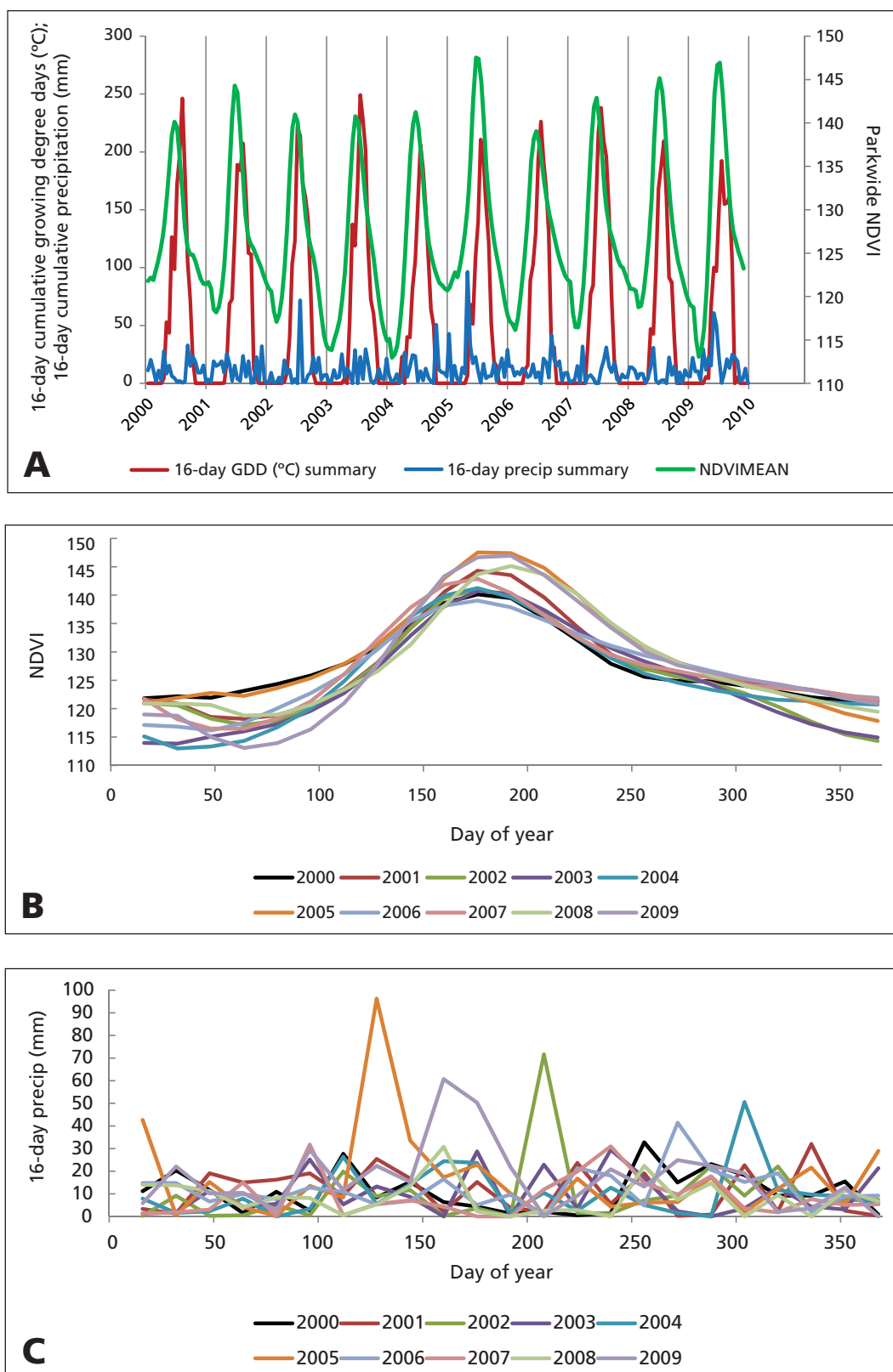


Figure 3.10-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Fossil Butte NM.

Table 3.10-1. Descriptive statistics for parkwide average NDVI, Fossil Butte NM.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	127.6	124.9	140.1	121.4	18.71	2934
2001	127.5	124.8	144.3	118.2	26.12	2931
2002	125.5	123.3	141.0	114.3	26.66	2887
2003	124.7	122.7	140.8	113.8	26.92	2868
2004	125.4	123.3	141.2	113.0	28.27	2884
2005	129.6	126.1	147.5	117.8	29.69	2980
2006	126.9	126.0	139.0	116.2	22.88	2918
2007	127.3	125.4	142.9	116.5	26.42	2927
2008	127.9	124.1	145.1	118.8	26.37	2941
2009	127.6	125.2	146.9	113.1	33.87	2934

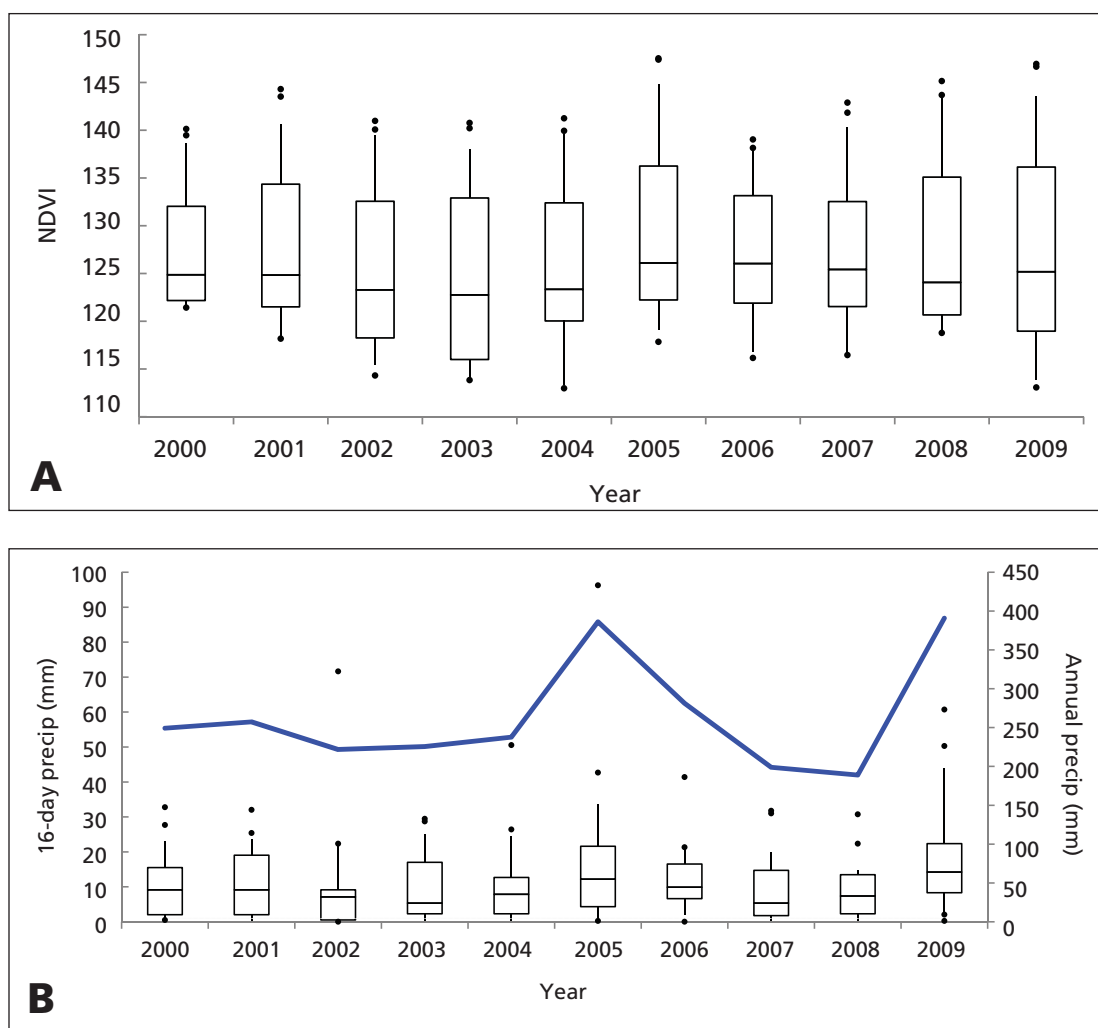


Figure 3.10-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Fossil Butte NM. Due to missing weather station data for 2007, 2008, and 2009, box plots and cumulative precipitation do not reflect actual conditions.

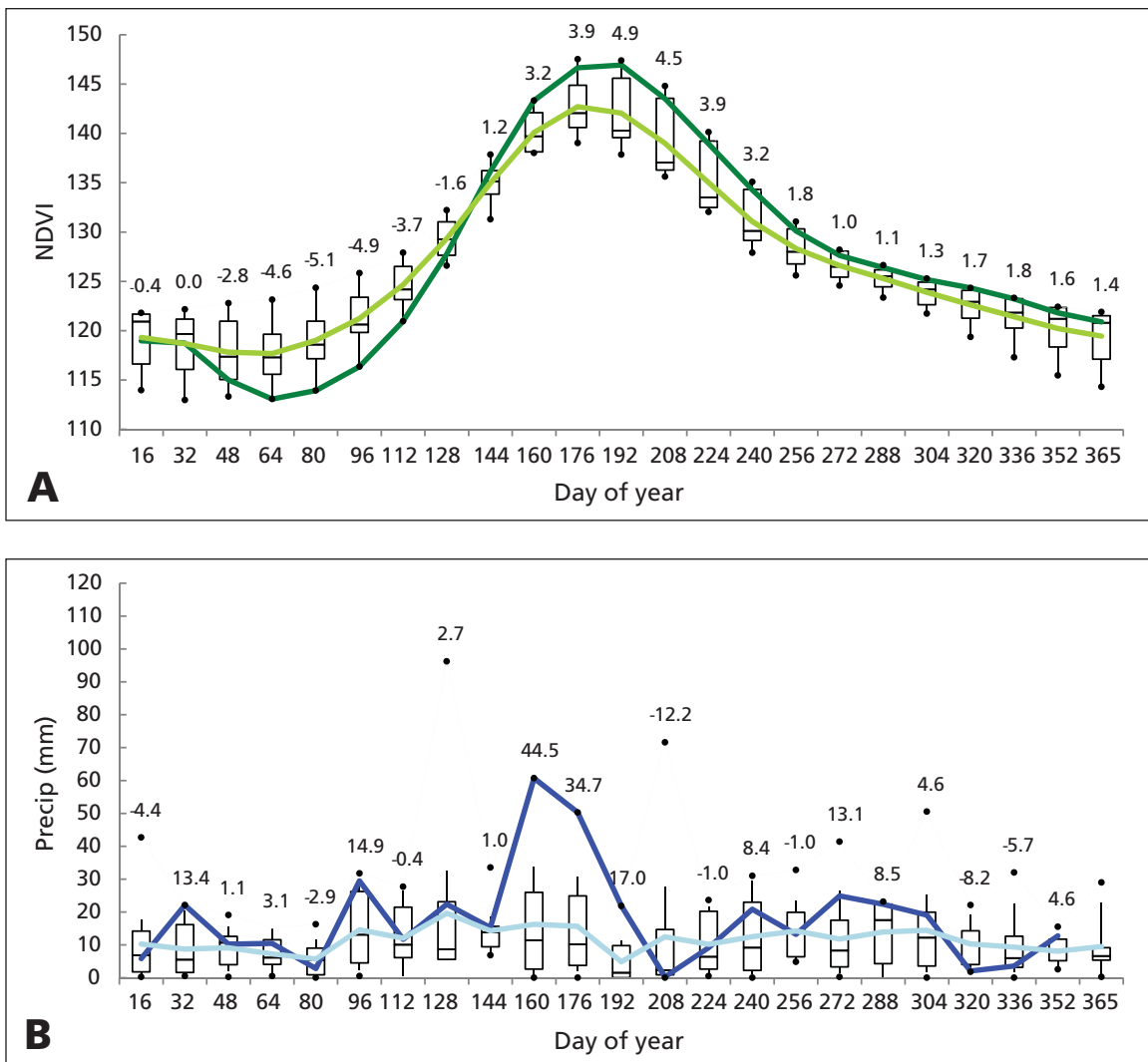


Figure 3.10-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Fossil Butte NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

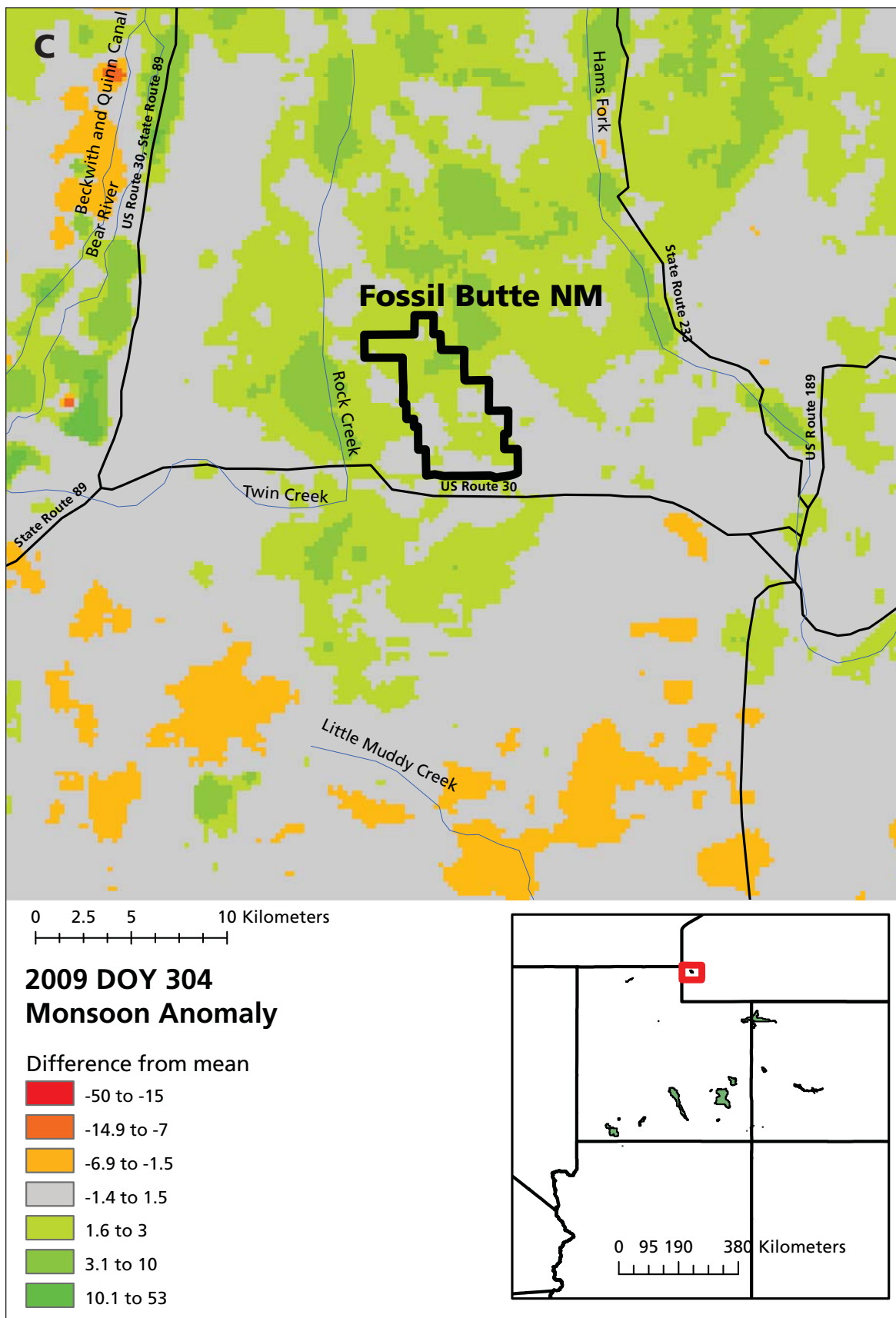


Figure 3.10-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Fossil Butte NM.

3.10.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 30, 109, 113, and 24 days, respectively. The most productive year, based on I-NDVI, was 2006, while the least productive was 2004 (Table 3.10-2); these years corresponded to the longest (278) and shortest (164) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. There were no statistically significant linear trends (p -value <0.1) in the phenology metrics observed at the parkwide scale for the period of analysis (Table 3.10-2; Figure 3.10-3).

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends (Table 3.10-2, Figure 3.10-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

3.10.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Fossil Butte NM (Figure 3.10-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also

noise present, as indicated by occasional spikes during times of year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2005, 2006, and 2008 had the most extensive and persistent snow cover (Figure 3.10-5b) and that less park area was snow-covered for less time in 2009 than in the past 10 years (Figure 3.10-5c).

Although water content cannot be directly inferred from snow cover, they are related. The earliest snowmelt occurred in 2007, at DOY 104 (April 14), while the latest snowmelt occurred in years 2000 and 2002, both at DOY 144 (May 24). Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both. The 10-year average snow-free period in Fossil Butte NM, defined here as less than 5% coverage, occurred between DOYs 122 (May 2) and 286 (October 13). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.10-3).

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. A very weak positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.01$) for the nine years of record (Figure 3.10-6). Stronger relationships may occur at finer spatial scales where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

Table 3.10-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Fossil Butte NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	98	180	311	213	1956	20.47
2001	116	183	323	208	1969	26.34
2002	112	182	318	206	1945	25.57
2003	101	185	316	215	1943	27.14
2004	96	173	261	164	1698	24.16
2005	109	189	306	197	2011	28.97
2006	93	179	370	278	2572	22.50
2007	101	173	296	195	1845	24.95
2008	123	197	341	218	2101	29.06
<i>correlation</i>	0.12	0.21	0.20	0.17	0.29	0.42
<i>slope</i>	0.45	0.57	2.21	1.81	25.50	0.43
<i>p-val slope</i>	0.75	0.59	0.60	0.67	0.45	0.27
<i>intercept</i>	-802	-967	-4109	-3424	-49098	-839
<i>p-val intercept</i>	0.78	0.65	0.63	0.69	0.47	0.28

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

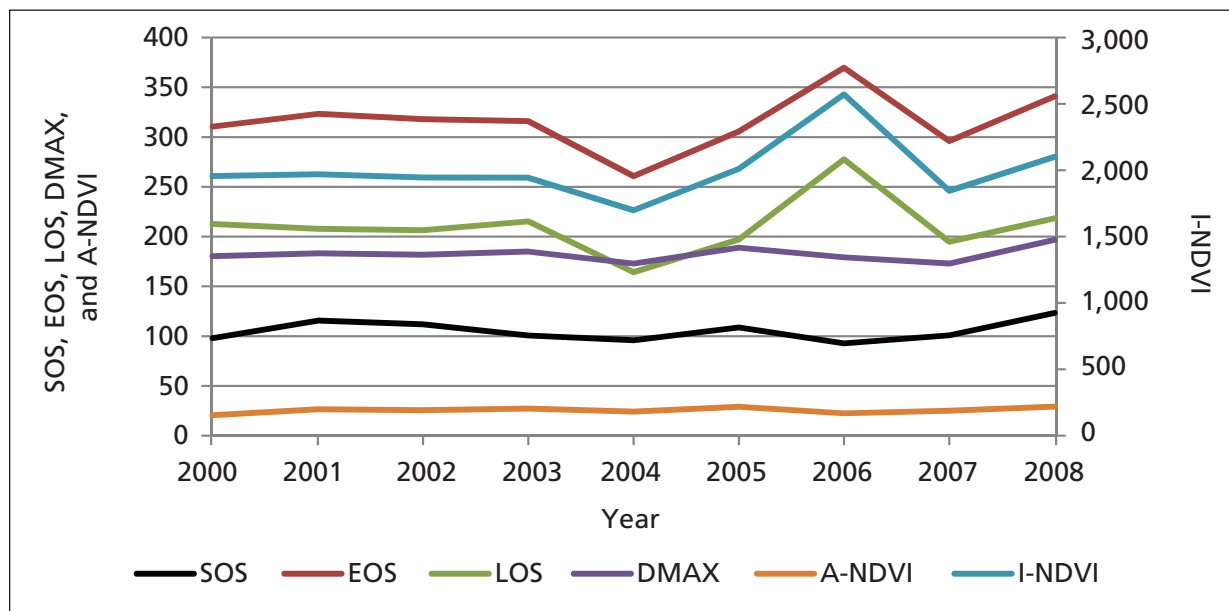


Figure 3.10-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Fossil Butte NM. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

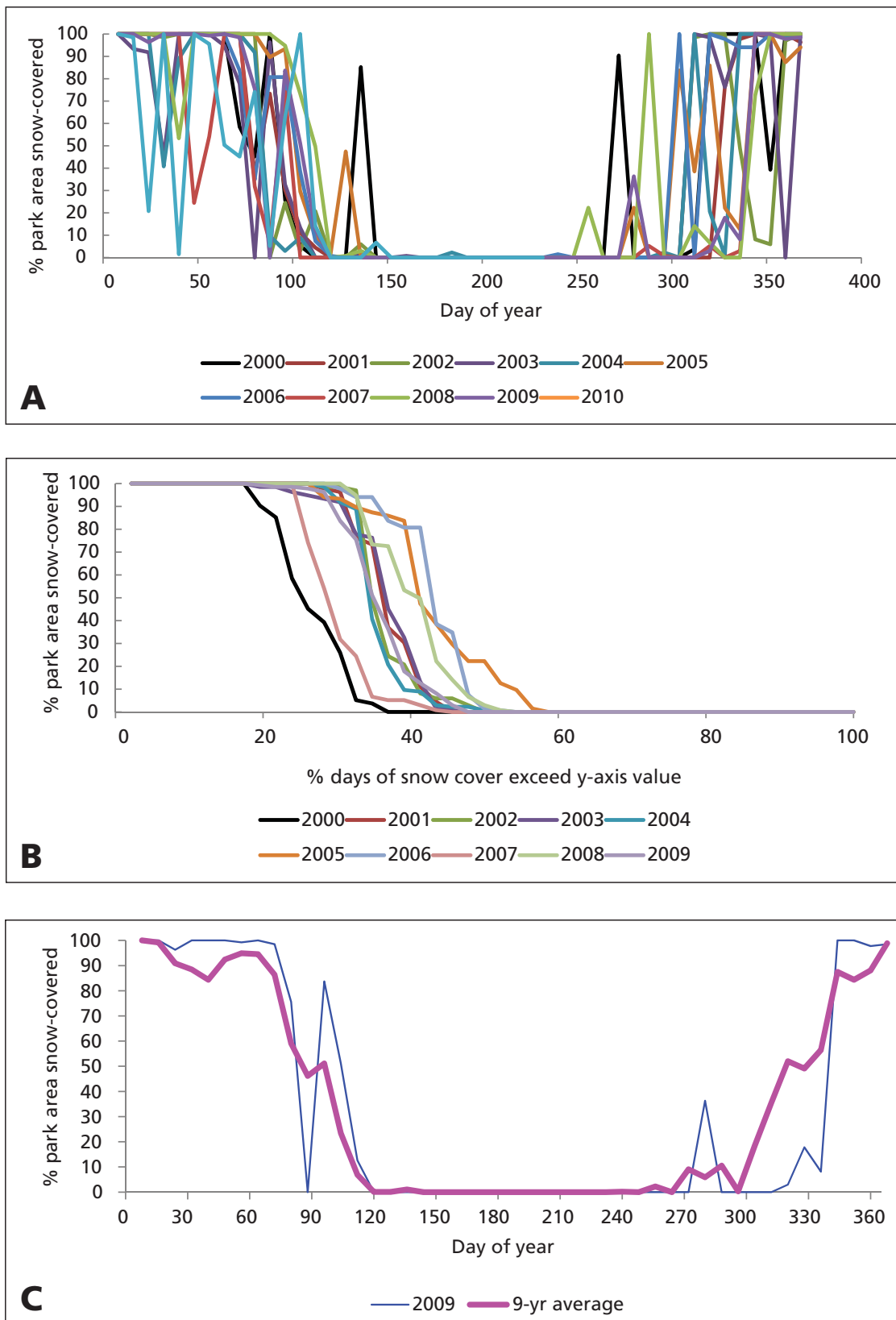


Figure 3.10-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Fossil Butte NM.

Table 3.10-3. Timing and duration of snow cover, Fossil Butte NM.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	5/23/2000	9/20/2000	144	264	120	245
2001	4/22/2001	11/16/2001	112	320	208	157
2002	5/25/2002	11/1/2002	144	304	160	205
2003	4/24/2003	11/2/2003	112	304	192	173
2004	4/24/2004	11/2/2004	112	304	192	173
2005	5/19/2005	10/2/2005	136	272	136	229
2006	5/4/2006	10/27/2006	120	296	176	189
2007	4/19/2007	10/12/2007	104	280	176	189
2008	5/5/2008	9/10/2008	120	248	128	237
2009	5/6/2009	10/5/2009	120	272	152	213
<i>correlation</i>			-0.40	-0.49	-0.18	0.18
<i>slope</i>			-1.89	-3.68	-1.79	1.79
<i>p-val slope</i>			0.25	0.15	0.61	0.61
<i>intercept</i>			3913	7673	3760	-3395
<i>p-val intercept</i>			0.23	0.13	0.60	0.63

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

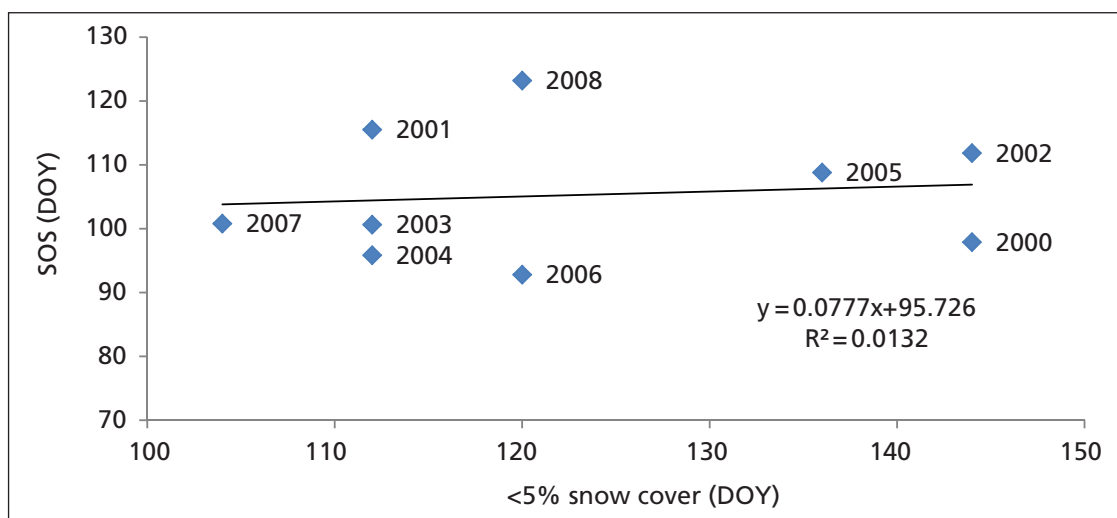


Figure 3.10-6. Relationship between snowmelt DOY and SOS, Fossil Butte NM.

3.11 Golden Spike National Historic Site

3.11.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.11-1a). In the 10-year time series, a strong bi-modal seasonal phenology was apparent in most years, with the exceptions of years 2003, 2005, and 2008, when bi-modal seasonality was present but weakly expressed in the second season. When annual curves are stacked (Figure 3.11-1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2005, are easily contrasted with less productive years, such as 2001 and 2004. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to higher-elevation NCPN parks, the NDVI annual curves for Golden Spike National Historic Site (NHS) are bi-modal and “jagged,” reflecting unevenly distributed and less abundant precipitation that supports vegetation adapted to multiple growing seasons in a single year. No weather data were available for analysis.

Year 2008 had the narrowest range in annual maximum and minimum NDVI (12.7), while 2003 had the widest range (29.4) (Table 3.11-1). The largest maximum NDVI (150) was in 2005. Based on analysis in other parks that have weather data, it is clear that the strength of bi-modal NDVI response is strongly associated with differences in the temporal distribution of precipitation; thus, annual summaries do not illustrate the full variation in precipitation magnitude and

timing and associated vegetation response (Figure 3.11-1). However, the range and distribution in NDVI is likely an indicator of precipitation abundance and distribution (Figure 3.11-2). For instance, summary statistics and phenology metrics suggest that 2005 was wetter than other years. A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

3.11.2 Recent NDVI conditions

The 2009 NDVI curve was above the historical average until DOY 256 (September 13), most likely corresponding to precipitation that was above average early in the year and below average late in the year (Figure 3.11-3a). These generalizations are based on the strong correlation between precipitation and NDVI observed in other NCPN park units. Annual average NDVI for 2009 was 2% above the 10-year average, indicating that cumulative precipitation in 2009 was likely well above the 10-year average.

Below-average NDVI in 2009 was observed in the northern- and southernmost portions of the park, whereas the central portion was above average (Figure 3.11-3b). NDVI was above average for most of the area north of the monument, while south-facing aspects of hills south of the monument were below average. It may be instructive to investigate the relationships between soil, geology, and vegetation to improve understanding of how precipitation changes might impact different parts of the landscape. On DOY 304 (October 31), most areas of Golden Spike NHS were within -6.9 and -1.5 NDVI units, or -13 to -2.8%, of the long-term average.

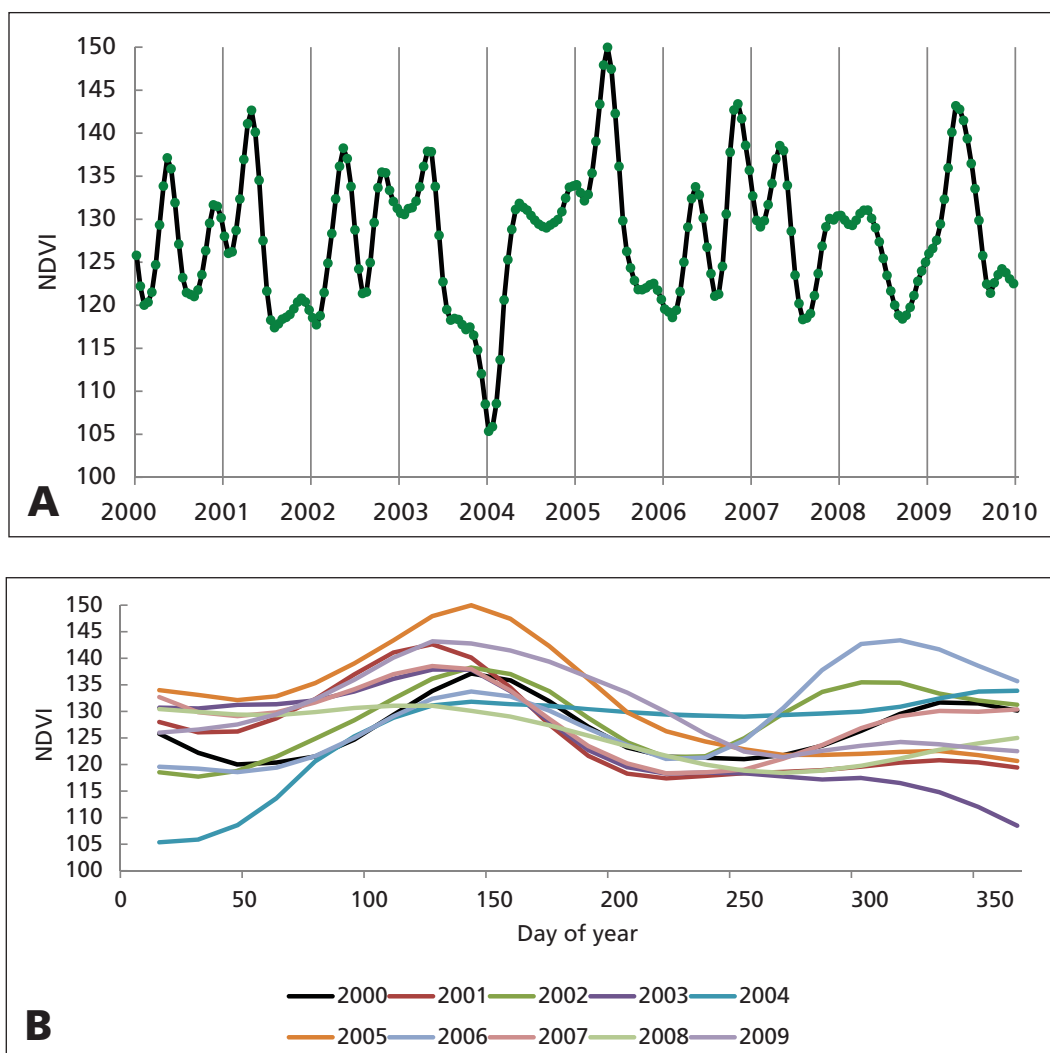


Figure 3.11-1. (a) 10-year parkwide average NDVI time series on 16-day intervals; (b) Annual NDVI curves stacked for inter-annual comparison, Golden Spike NHS.

Table 3.11-1. Annual descriptive statistics for parkwide average NDVI, Golden Spike NHS.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	126.6	125.8	137.1	120.0	17.12	2911
2001	125.9	121.6	142.7	117.4	25.27	2896
2002	128.6	129.6	138.3	117.7	20.53	2959
2003	124.6	122.7	137.9	108.5	29.39	2865
2004	126.1	129.6	133.9	105.3	28.51	2901
2005	131.7	132.1	150.0	120.7	29.31	3030
2006	129.1	129.1	143.4	118.6	24.83	2969
2007	128.4	129.8	138.5	118.3	20.21	2954
2008	125.5	125.4	131.1	118.4	12.65	2887
2009	130.2	127.5	143.2	121.4	21.79	2994

Figure 3.11-2. Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency, Golden Spike NHS.

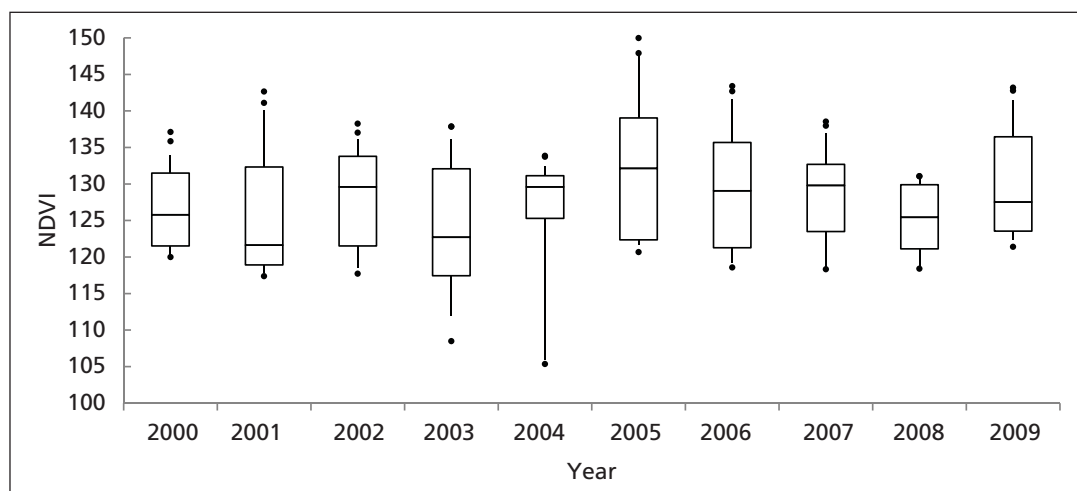
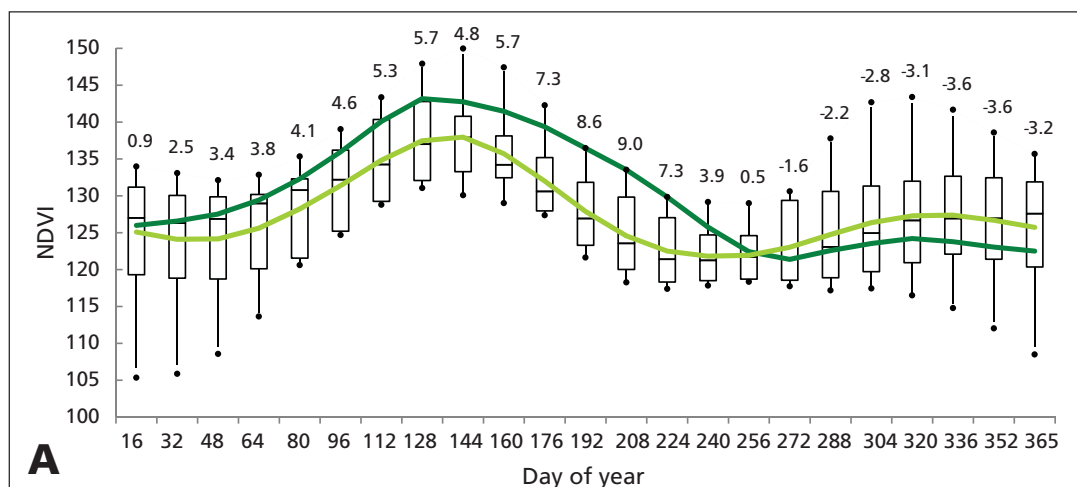


Figure 3.11-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green, Golden Spike NHS. Numbers above box plots are the difference between 10-year average and 2009 NDVI for each 16-day period.



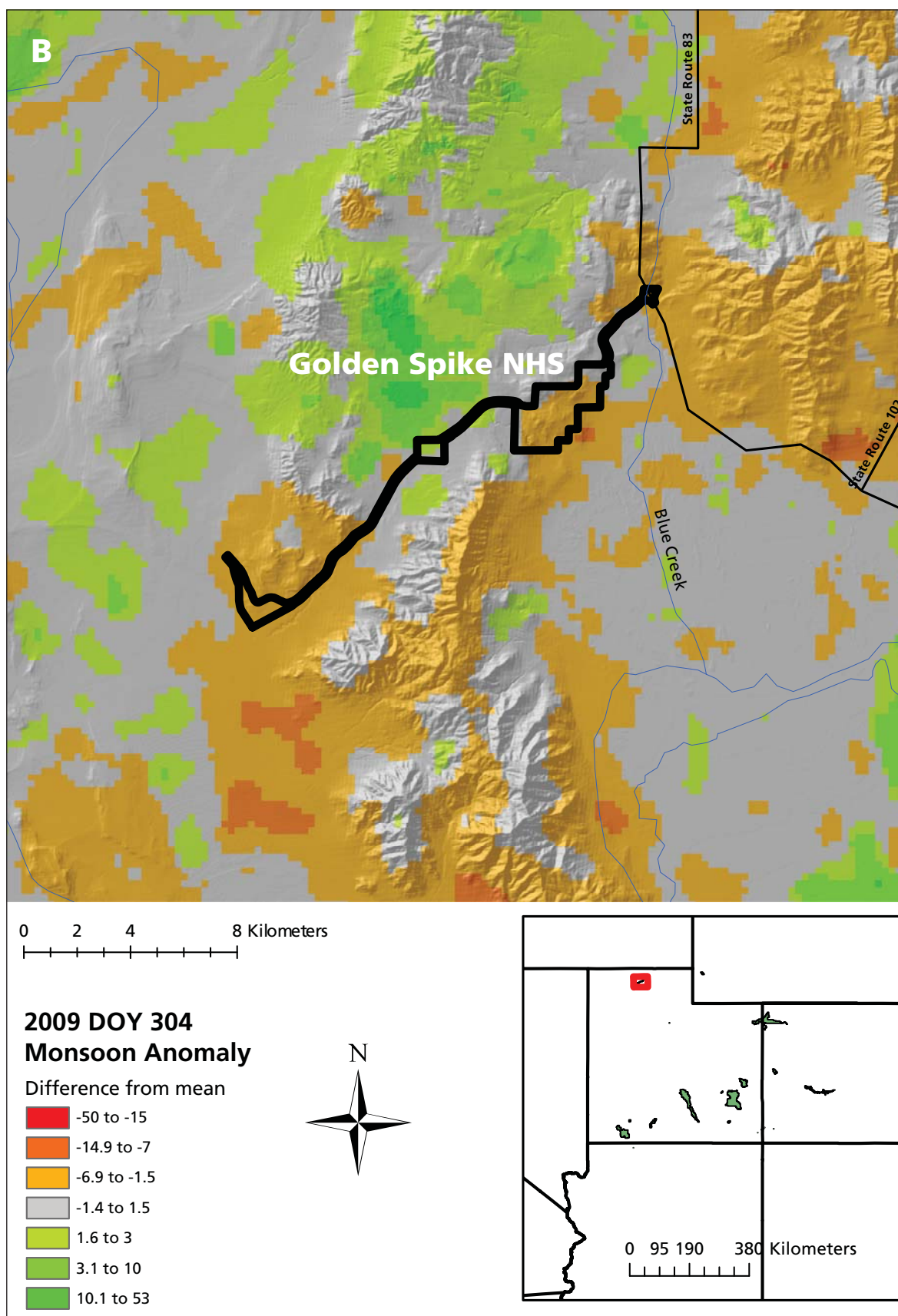


Figure 3.11-3. (b) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Golden Spike NHS.

3.11.3 Phenology

In most years, there are two distinct growing seasons at Golden Spike NHS that represent the interaction of plant functional types (annual/perennial, early season/late season), phenology, and suitability of moisture for growth. The two seasons (spring and monsoon) are evaluated separately due to the distinct bi-modal nature of phenology observed at the park.

3.11.3.1 Spring

Over the 10-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 44, 48, 78, and 19 days, respectively. The most productive spring, based on I-NDVI, was 2009, while the least productive was 2006 (Table 3.11-2); these years correspond to the longest (186 days) and third-shortest (120 days) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships, as was observed at Golden Spike NHS. Statistically significant linear trends (p-value <0.1) for spring EOS, LOS, and I-NDVI were observed at the parkwide scale for the period of analysis (Table 3.11-2; Figure 3.11-4a). The trends indicate that spring EOS is occurring three days later per year and LOS is increasing by five days per year, while productivity, as estimated by I-NDVI curve, is increasing by 45 NDVI units per year. Although all three trends are significant and are consistent in their direction, they should be considered and evaluated with caution because they are based on a short, 10-year record. It could be instructive to learn what types of land use or vegetation species assemblage changes may have occurred on the monument during this period that might help explain trends in spring NDVI phenology metrics.

3.11.3.2 Monsoon

Over the nine-year historical record, the ranges of monsoon SOS, EOS, LOS, and DMAX were 55, 54, 39, and 61 days respectively. The most productive monsoon season, based on I-NDVI, was 2007, while the least productive was 2000 (Table 3.11-3); these years corresponded to the longest (136 days) and second-shortest (99 days) growing seasons, respectively. Based on visual examination of NDVI time series (Figure 3.11-4a), any of years 2003, 2005, or 2008 may have had lower productivity than 2000, but the differences were too minor to be identified by the Timesat algorithm. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings. The influence of precipitation variability on vegetation productivity is made apparent by the decoupling of seasonal productivity, in which productive spring seasons are not always followed by productive monsoon seasons and vice versa. There were no statistically significant linear trends (p-value <0.1) in the monsoon-season phenology metrics observed at the parkwide scale for the period of analysis (Table 3.11-3; Figure 3.11-4 b).

3.11.3.3 Summary

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. This is even more true for the monsoon season, for which three of eight years showed insufficient growth to register a season in the Timesat phenology algorithms. Presently, the annual phenology metrics show trends in spring-season phenology (Table 3.11-3, Figure 3.11-4). A longer data record and more robust statistical techniques may provide better indication of broad-scale change in the future, if it occurs.

Table 3.11-2. Spring-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Golden Spike NHS.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	93	148	201	108	1165	16.12
2001	71	128	187	116	1205	20.65
2002	71	145	203	132	1305	18.33
2003	83	138	203	120	1182	15.27
2004	59	134	213	154	1512	14.36
2005	85	146	214	128	1398	22.62
2006	83	146	203	120	1155	13.69
2007	78	134	194	115	1315	14.93
2008	77	133	224	147	1529	7.20
2009	50	144	235	186	1758	20.84
<i>correlation</i>	-0.41	-0.05	0.67	0.63	0.69	-0.27
<i>slope</i>	-1.76	-0.12	3.14	4.87	45.21	-0.40
<i>p-val slope</i>	0.24	0.89	0.03	0.05	0.03	0.45
<i>intercept</i>	3598	376	-6094	-9626	-89275	808
<i>p-val intercept</i>	0.23	0.82	0.04	0.06	0.03	0.45

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

Table 3.11-3. Monsoon-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Golden Spike NHS.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	288	342	388	99	1027	7.95
2001	254	334	381	127	1193	3.08
2002	256	306	355	99	1055	9.44
2003	-	-	-	-	-	-
2004	309	366	406	97	1060	3.37
2005	-	-	-	-	-	-
2006	262	317	384	122	1227	18.30
2007	274	352	410	136	1281	6.55
2008	-	-	-	-	-	-
<i>correlation</i>	-0.51	-0.51	-0.50	-0.25	-0.28	-0.03
<i>slope</i>	-226.56	-230.06	-231.98	-5.39	-58.33	-0.06
<i>p-val slope</i>	0.16	0.16	0.17	0.51	0.47	0.94
<i>intercept</i>	453560	460618	464500	10884	117660	128
<i>p-val intercept</i>	0.16	0.16	0.17	0.51	0.47	0.94

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable. Years 2003, 2005, and 2008 had very small spring NDVI response. Timesat has difficulty computing phenology metrics when NDVI amplitude is small.

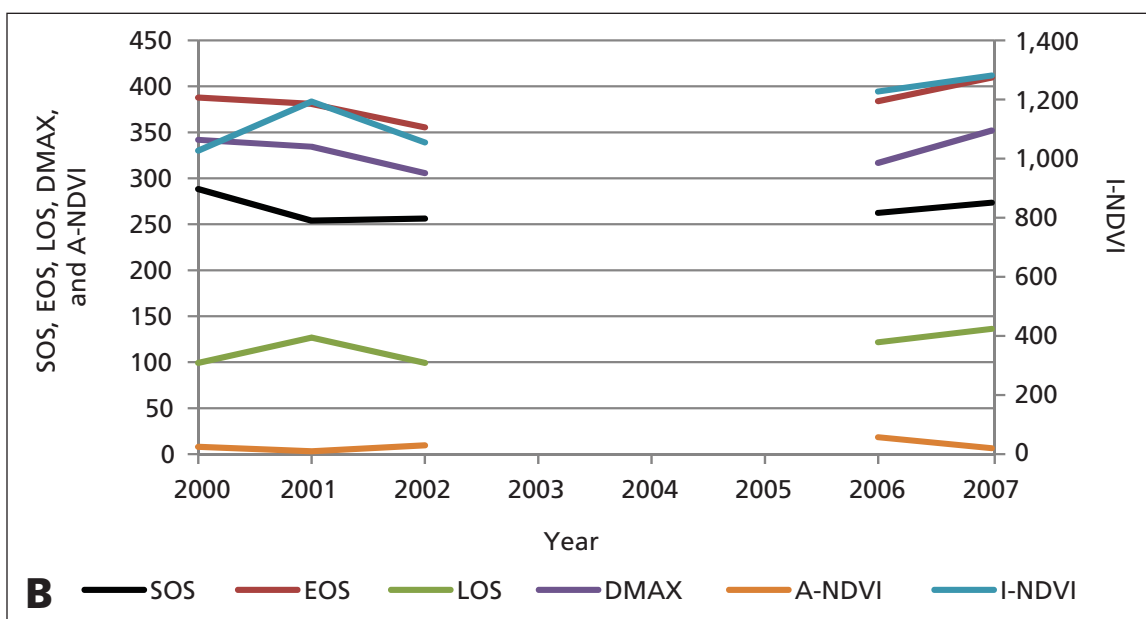
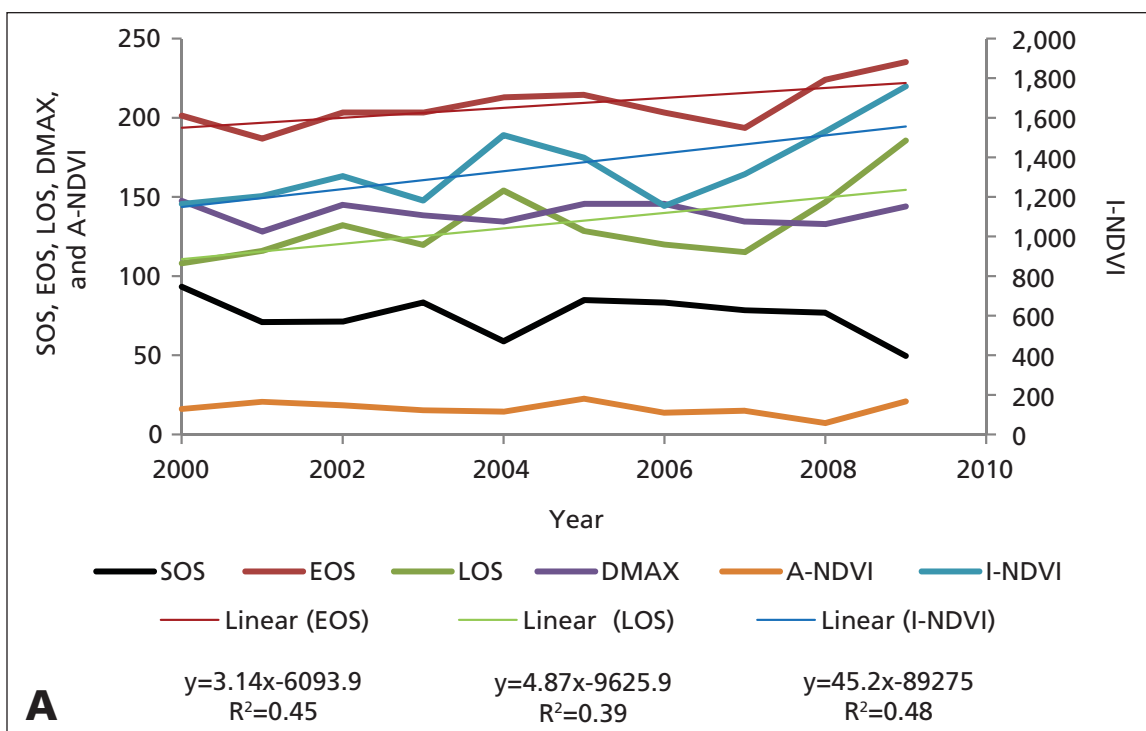


Figure 3.11-4. Annual (a) spring and (b) monsoon phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Golden Spike NHS. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.11.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Golden Spike NHS (Figure 3.11-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2002, 2008, and 2009 had the most extensive and persistent snow cover (Figure 3.11-5b) and that in 2009, more park area was snow-covered for longer than in the past 10 years (Figure 3.11-5c).

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. The

relationship between snow-covered extent and water content available for plant growth when snow melts is generally stronger at higher elevations. At Golden Spike NHS, the relationship is weak—perhaps because air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship. Earlier snowmelt could result in an earlier SOS, but snow cover is not the only factor driving SOS, as is shown by the negative relationship between snowmelt DOY and SOS ($R^2 = 0.05$) for nine years of record at the parkwide scale (Figure 3.11-6).

The 10-year average snow-free period in Golden Spike NHS, defined here as less than 5% coverage, occurred between DOYs 78 (March 19) and 327 (November 23). A statistically significant trend ($p\text{-value} < 0.10$; $R^2 = 0.42$) was observed at the parkwide scale for snowmelt DOY, which increased 4.3 days per year during the period of record (Table 3.11-4).

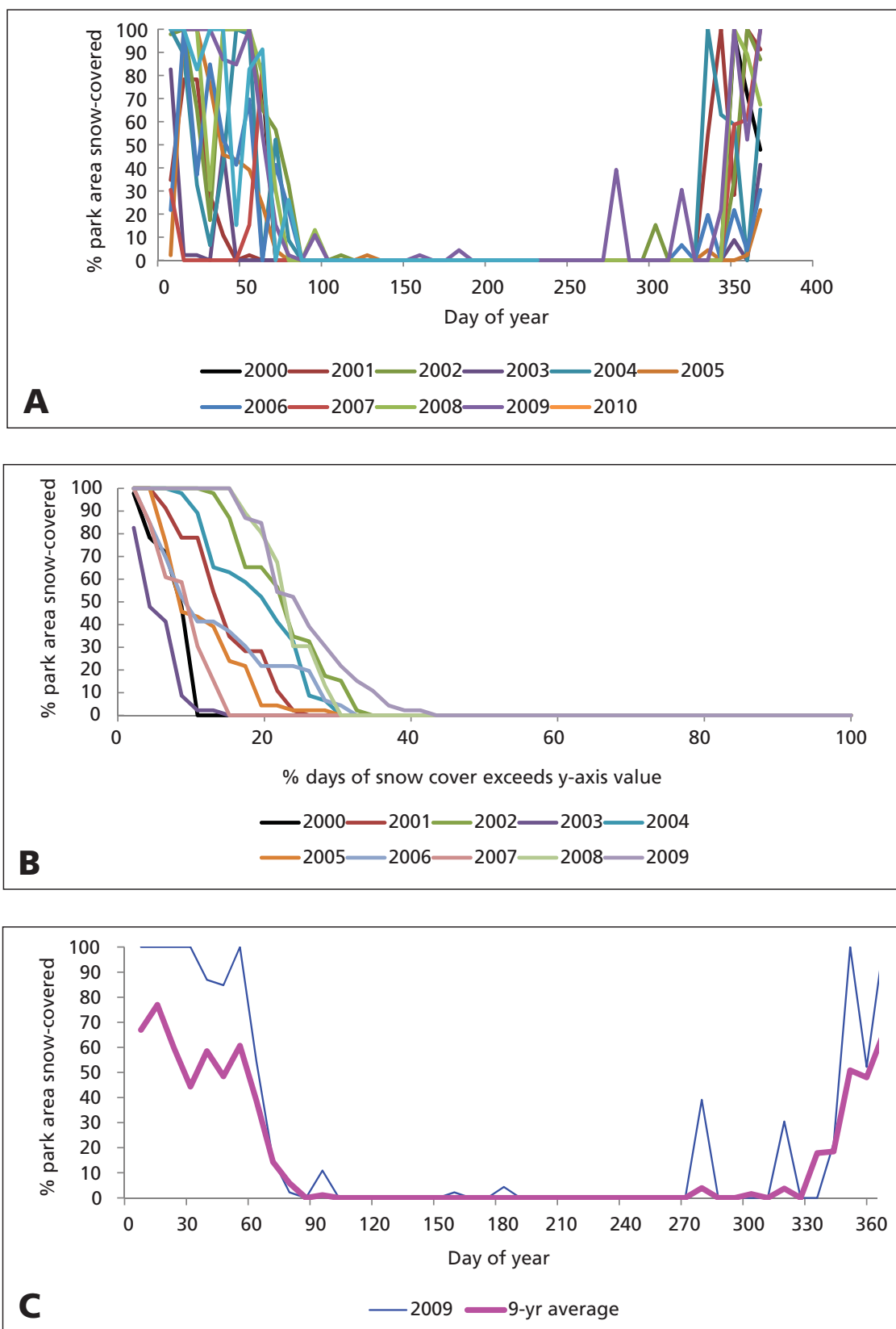


Figure 3.11-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Golden Spike NHS.

Table 3.11-4. Timing and duration of snow cover, Golden Spike NHS.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	3/12/2000	12/9/2000	72	344	272	93
2001	2/17/2001	11/24/2001	48	328	280	85
2002	3/30/2002	10/24/2002	88	296	208	157
2003	2/19/2003	12/12/2003	48	344	296	69
2004	3/31/2004	11/26/2004	88	328	240	125
2005	3/16/2005	12/29/2005	72	360	288	77
2006	4/2/2006	11/12/2006	88	312	224	141
2007	3/18/2007	12/15/2007	72	344	272	93
2008	4/19/2008	12/15/2008	104	344	240	125
2009	4/20/2009	10/5/2009	104	272	168	197
<i>correlation</i>			0.65	-0.25	-0.48	0.48
<i>slope</i>			4.27	-2.18	-6.45	6.45
<i>p-val slope</i>			0.04	0.49	0.16	0.16
<i>intercept</i>			-8474	4701	13175	-12810
<i>p-val intercept</i>			0.04	0.46	0.15	0.16

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

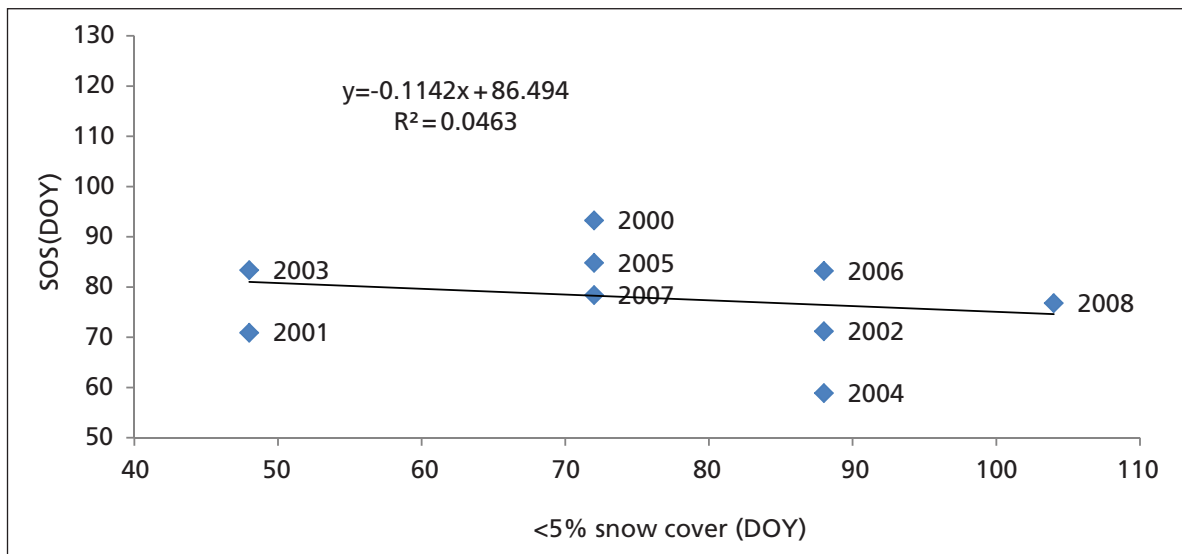


Figure 3.11-6. Relationship between snowmelt DOY and SOS, Golden Spike NHS.

3.12 Hovenweep National Monument

3.12.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.12-1a). A strong bi-modal seasonal phenology was apparent in the 10-year time series, and in some years, even higher-order “seasonality” was expressed in response to variable precipitation. However, fall-season peaks often occurred in November or December, confounding the precise determination of seasonality at Hovenweep NM. Peaks at this time of year may be diagnostic of early season annuals, such as invasive cheatgrass (*Bromus tectorum*). Variations in precipitation can also accentuate or diminish the strength of the seasonal NDVI signal.

Native vegetation on the Colorado Plateau typically begins growing in the spring, in response to winter soil-moisture recharge (Comstock and Ehleringer 1992). However, if invasive annuals are present, then soil moisture that would normally be stored for spring growth may be consumed in the fall and winter, thus becoming unavailable to support spring growth. This is the scenario shown in the annual variation in NDVI curves at Hovenweep NM, albeit moderated by variation in precipitation: monsoon moisture supports fall/winter growth, which depletes soil moisture so that there is a strong spring NDVI response only in years with substantial spring precipitation. Year 2002 showed a lack of NDVI response to minimal spring precipitation, and years 2003 and 2006 showed a moderate NDVI response to moderate amounts of spring precipitation. Year 2005 showed a strong NDVI response to abundant spring precipitation.

Tree species at Hovenweep NM seem to have adapted to consistent summer precipitation by growing shallow roots that can utilize shallow soil moisture. This is supported by the consis-

tency between summer precipitation events that are followed by increases in NDVI. If the shallow roots were absent, then the response to shallow summer precipitation events would be muted. Higher-elevation, cooler summer temperatures and consistent monsoons may support temperature and moisture regimes that justify expenditure of resources to grow and support shallow root systems. A similar response appears at Natural Bridges NM.

When annual curves are stacked (Figure 3.12-1b) a more direct year-to-year comparison is possible, in which more productive years, such as 2005, are easily contrasted with less productive years, such as 2002. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to higher-elevation NCPN parks, the NDVI annual curves for Hovenweep NM are bi-modal and “jagged,” reflecting unevenly distributed and less abundant precipitation that supports vegetation adapted to multiple growing seasons in a single year.

Weather data from the park’s NWS Coop station were used to interpret NDVI variation (Figure 3.12-2). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Years 2008 and 2009 had the narrowest range in annual maximum and minimum NDVI (3.1), while 2004 had the widest range (9.1) (Table 3.12-1). The largest maximum NDVI (128.7) was in 2005. Years with higher cumulative precipitation generally had higher median NDVI (Figure 3.12-2), but it is clear that the strength of bi-modal NDVI response is strongly associated with differences in the temporal distribution of precipitation (Figure 3.12-1a, c). A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

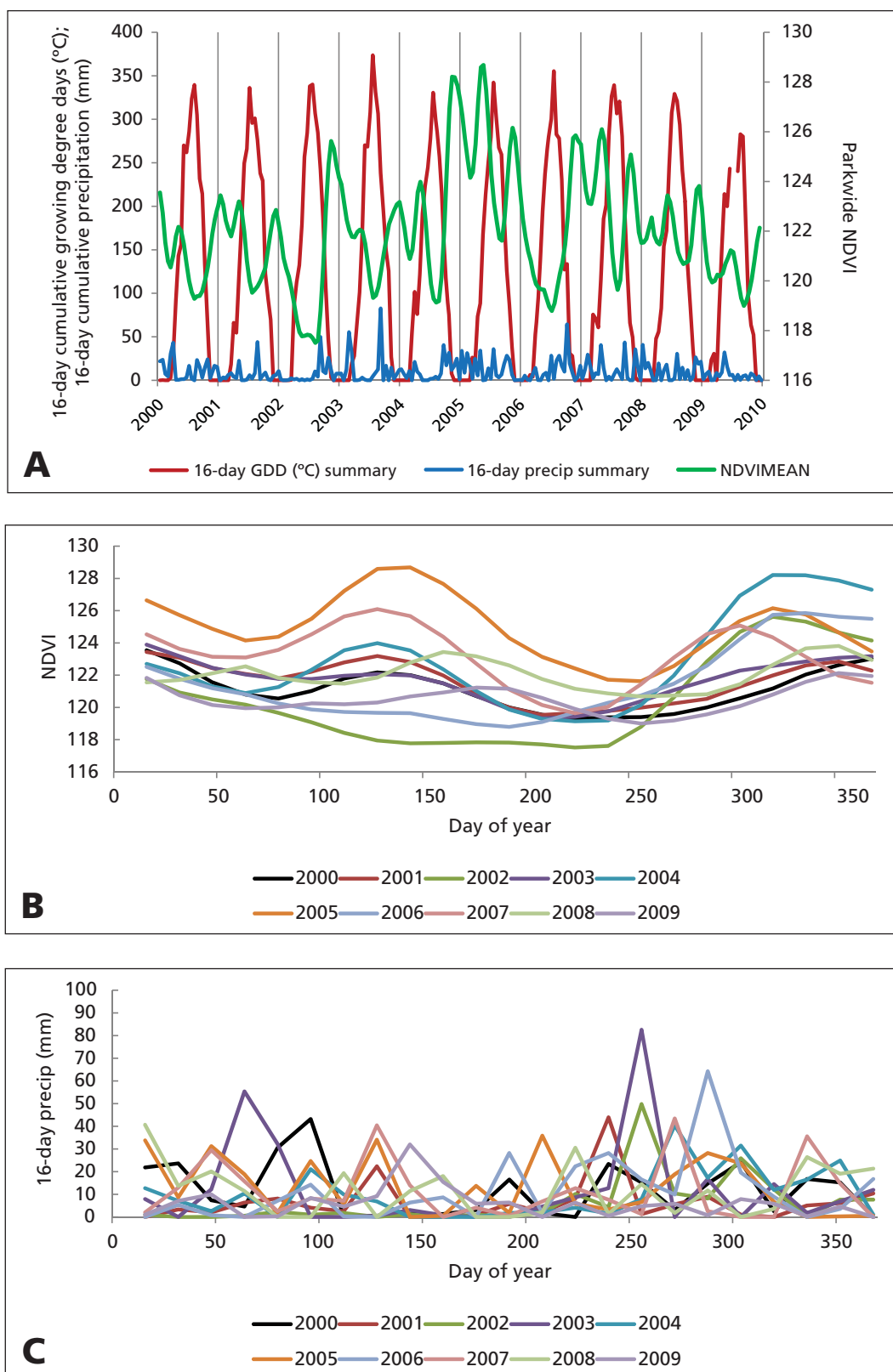


Figure 3.12-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Hovenweep NM.

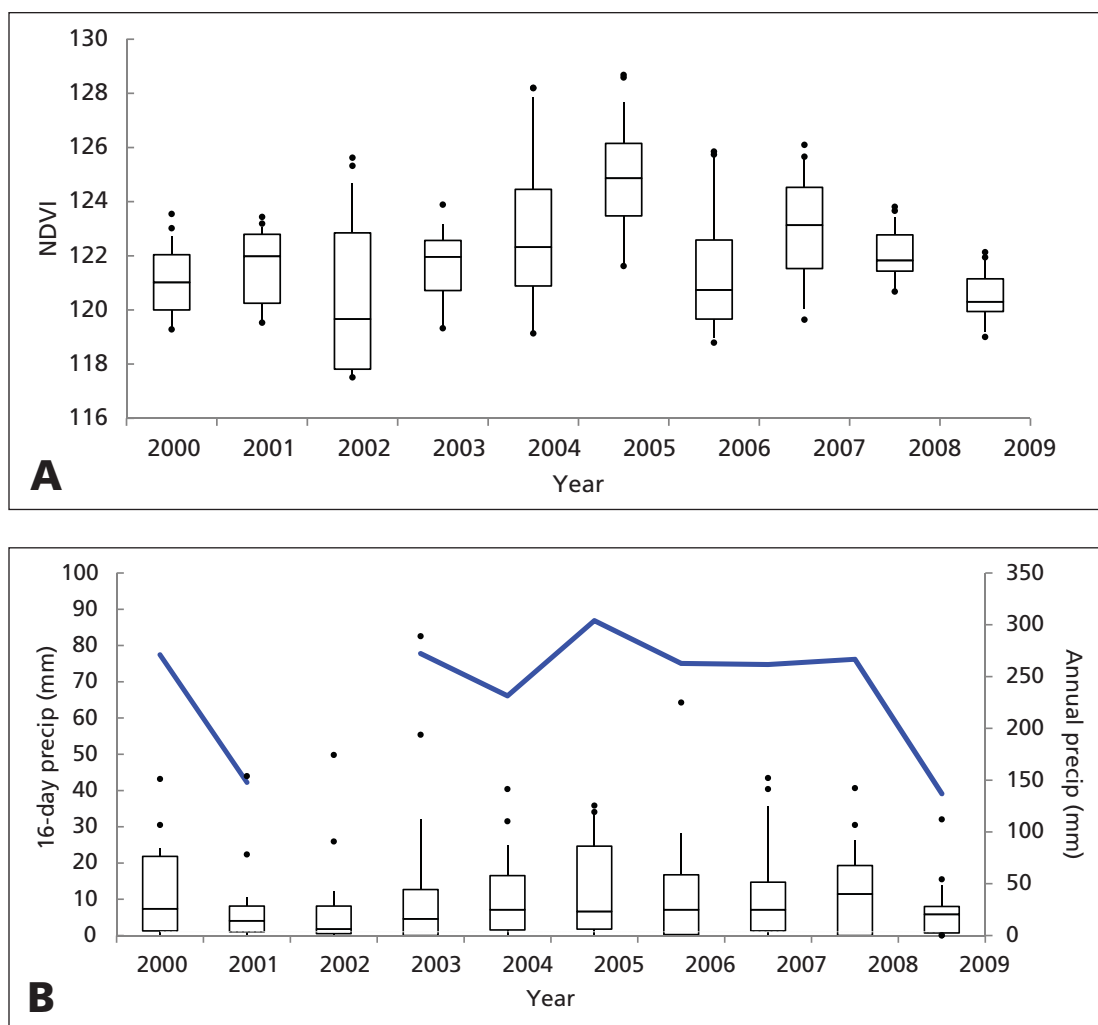


Figure 3.12-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Hovenweep NM. Due to missing weather station data for 2004, 2007, and 2008, box plots and cumulative precipitation do not reflect actual conditions.

Table 3.12-1. Annual descriptive statistics for parkwide average NDVI, Hovenweep NM.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	121.1	121.0	123.5	119.3	4.26	2785
2001	121.6	122.0	123.4	119.5	3.91	2797
2002	120.4	119.7	125.6	117.5	8.11	2769
2003	121.7	122.0	123.9	119.3	4.57	2799
2004	122.9	122.3	128.2	119.1	9.08	2828
2005	125.0	124.9	128.7	121.6	7.06	2875
2006	121.4	120.7	125.8	118.8	7.06	2793
2007	123.2	123.1	126.1	119.6	6.45	2833
2008	122.0	121.8	123.8	120.7	3.13	2807
2009	120.5	120.3	122.1	119.0	3.13	2771

3.12.2 Recent NDVI conditions

The 2009 NDVI curve was below the historical average for most of the year, but slightly above average at mid-year. These generalizations, as difference from the mean, also aptly describe the variation in precipitation, giving some indication of the tight coupling of precipitation and productivity at the park. A period of above-average precipitation (32.0 mm), centered on DOY 144 (May 24), bumped NDVI slightly above the historical average until DOY 224 (August 12). Annual average NDVI was 1.2% below the 10-year average in 2009, when weather data indicated that the precipitation deficit was 41.3% below the 10-year average (Figure 3.12-3a, b). As a result, the lowest NDVI in the 10-year record occurred during the fall season, when NDVI at the park typically peaks. Concurrent with the low monsoon precipitation in 2009, the lowest flows since 2004 were recorded at several park springs (NCPN 2010).

NDVI in 2009 was below average in all units of Hovenweep NM (Figure 3.12-3c). More extreme divergence below average was observed on mesa tops east of the monument. On DOY 304 (October 31), most areas in and near Hovenweep NM were within -6 and -2 NDVI units, or -11.4 to -3.8%, of the long-term average.

3.12.3 Phenology

In most years, there are two distinct growing seasons at Hovenweep NM that represent the interaction of plant functional types (annual/perennial, early season/late season), phenology, and suitability of moisture for growth. The two seasons (spring and monsoon) are evaluated separately due to the distinct bi-modal nature of phenology observed in the park.

3.12.3.1 Spring

Over the 10-year historical record, the ranges of spring SOS, EOS, LOS, and DMAX were 43, 49, 31, and 50 days, respectively. The most productive spring, based on I-NDVI, was 2005, while the least productive was 2003 (Table 3.12-2); these years corresponded to the second-longest (111 days) and the shortest (85 days) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these

relationships, as was observed at Hovenweep NM. Statistically significant linear trends (p-value <0.1) for spring EOS and DMAX were observed at the parkwide scale for the period of analysis (Table 3.12-2; Figure 3.12-3a). The trends indicate that spring EOS and DMAX are both occurring about 4.5 days later per year. Although both trends are significant and are consistent in their direction, they should be considered with caution because they are based on a short, 10-year record in which phenology metrics for the spring season of two years (2002, 2006) are missing because they were not expressed strongly enough to be detected by the Timesat algorithms.

3.12.3.2 Monsoon

Over the nine-year historical record, the ranges of monsoon SOS, EOS, LOS, and DMAX were 51, 114, 86, and 75 days, respectively. The most productive monsoon season, based on I-NDVI, was 2001, while the least productive was 2008 (Table 3.12-3); these years corresponded to the longest (183 days) and shortest (96 days) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings. The influence of precipitation variability on vegetation productivity is made apparent by the decoupling of seasonal productivity, in which productive spring seasons are not always followed by productive monsoon seasons and vice versa. There were statistically significant linear trends (p-value <0.1) for monsoon-season EOS, LOS, and I-NDVI at the parkwide scale for the period of analysis (Table 3.12-3; Figure 3.12-3b). EOS decreased by 7.9 days per year, LOS decreased by 6.8 days per year, and I-NDVI decreased by 49 NDVI units per year for the period of analysis.

3.12.3.3 Summary

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently the phenology metrics show trends in spring-season phenology for EOS and DMAX, and in monsoon-season phenology for EOS, LOS, and I-NDVI (Table 3.12-3, Figure 3.12-4). A longer data record and more robust statistical techniques may provide better indication of broad-scale change in the future, if it occurs.

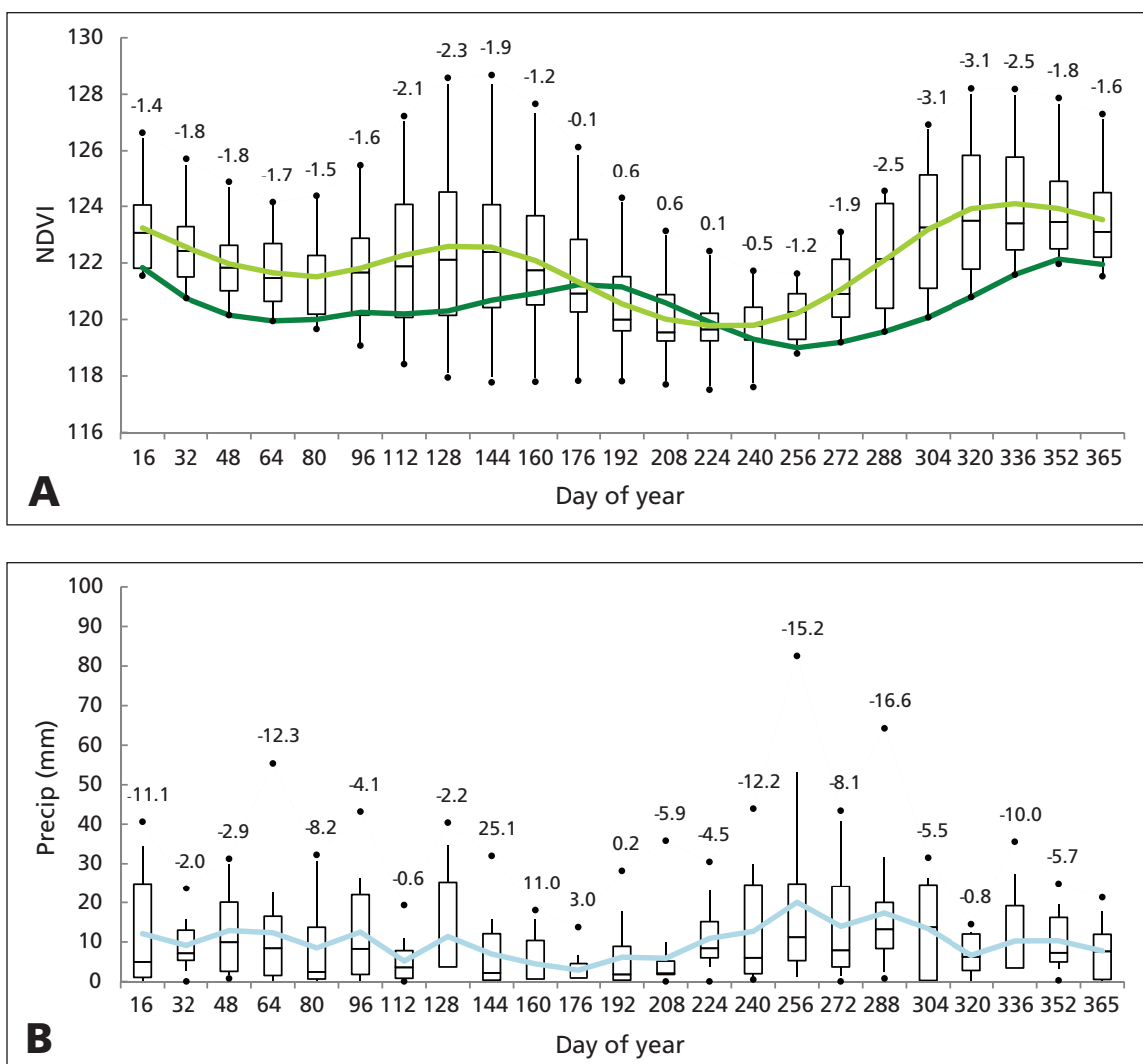


Figure 3.12-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Hovenweep NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

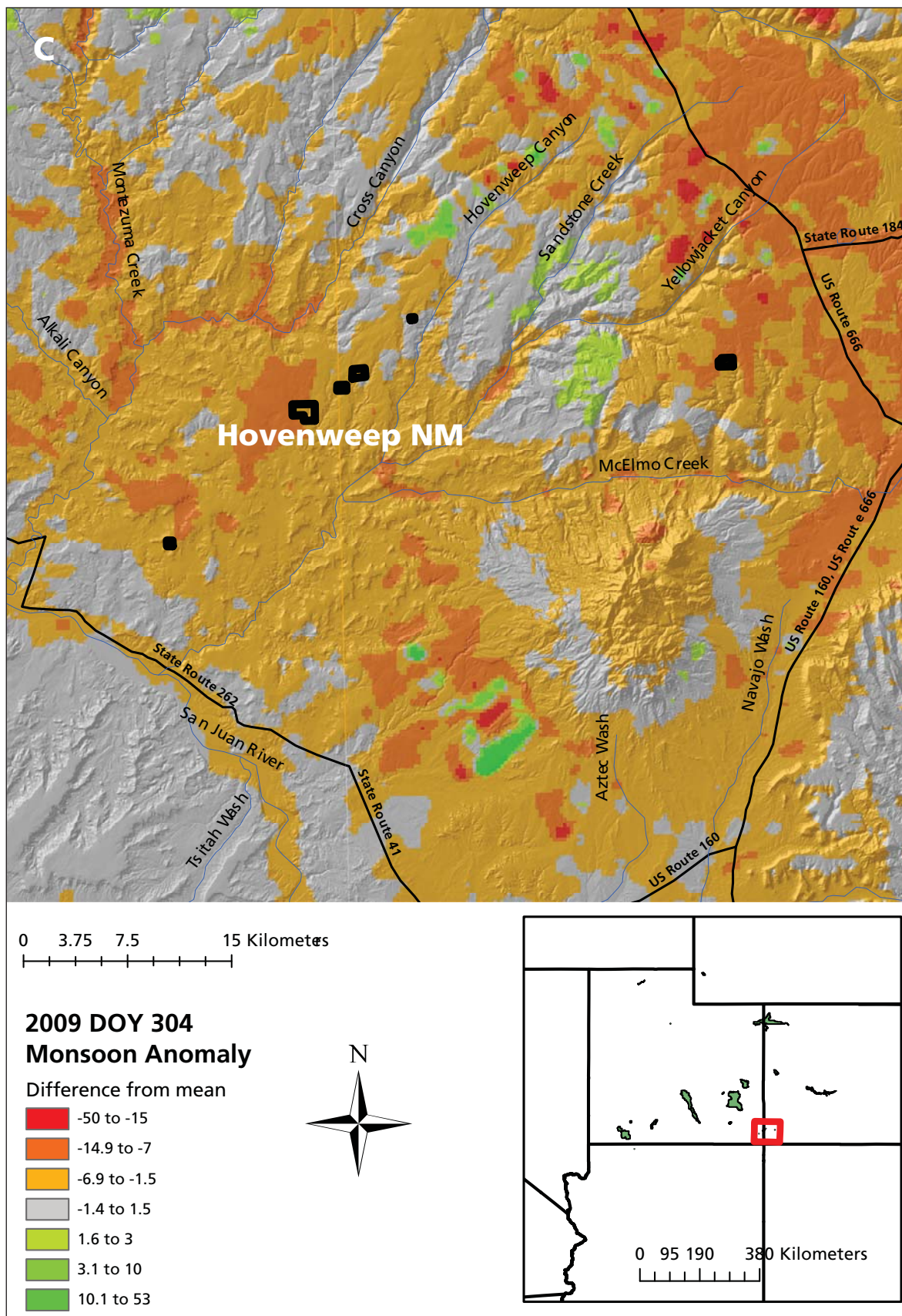


Figure 3.12-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Hovenweep NM.

Table 3.12-2. Spring-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Hovenweep NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	94	136	192	98	970	2.18
2001	96	133	183	87	854	2.37
2002	-	-	-	-	-	-
2003	104	140	189	85	850	1.49
2004	86	131	187	101	978	3.97
2005	93	141	205	111	1136	5.67
2006	-	-	-	-	-	-
2007	85	133	190	107	994	4.69
2008	128	168	219	91	857	2.24
2009	117	181	232	116	1084	1.71
<i>correlation</i>	-0.06	-0.05	-0.04	0.21	0.16	0.15
<i>slope</i>	-14.51	-12.39	-11.67	2.95	21.99	0.09
<i>p-val slope</i>	0.17	0.03	0.01	0.12	0.34	0.74
<i>intercept</i>	28878	24656	23260	-5830	-43298	-186
<i>p-val intercept</i>	0.18	0.03	0.01	0.12	0.36	0.74

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

Table 3.12-3. Monsoon-season phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Hovenweep NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	297	375	424	127	1220	2.72
2001	279	352	461	183	1574	3.96
2002	262	324	411	149	1356	5.89
2003	254	348	413	158	1463	2.95
2004	266	333	408	142	1382	6.63
2005	275	326	414	140	1237	5.36
2006	251	338	397	146	1360	4.94
2007	251	301	347	96	984	4.40
2008	302	349	398	96	978	3.43
<i>correlation</i>	-0.15	-0.55	-0.72	-0.66	-0.67	0.16
<i>slope</i>	-1.05	-4.22	-7.86	-6.73	-49.29	0.08
<i>p-val slope</i>	0.70	0.13	0.03	0.05	0.05	0.69
<i>intercept</i>	2382	8798	16162	13620	100058	-150
<i>p-val intercept</i>	0.66	0.11	0.02	0.05	0.05	0.69

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

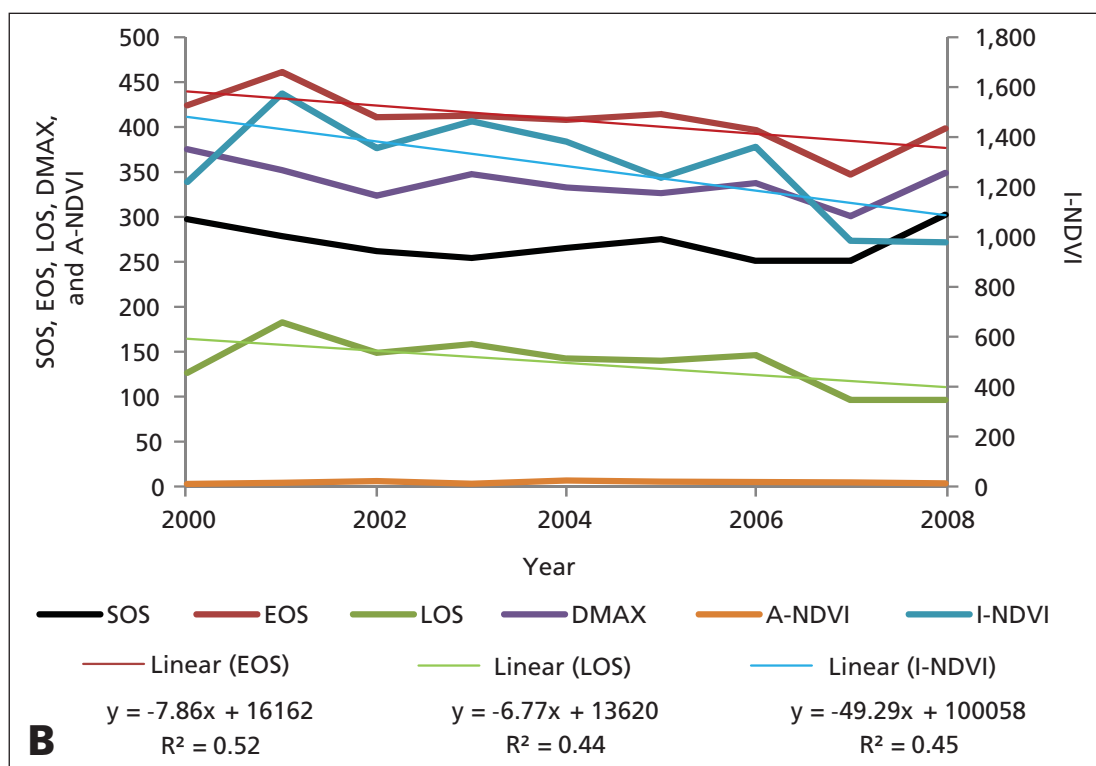
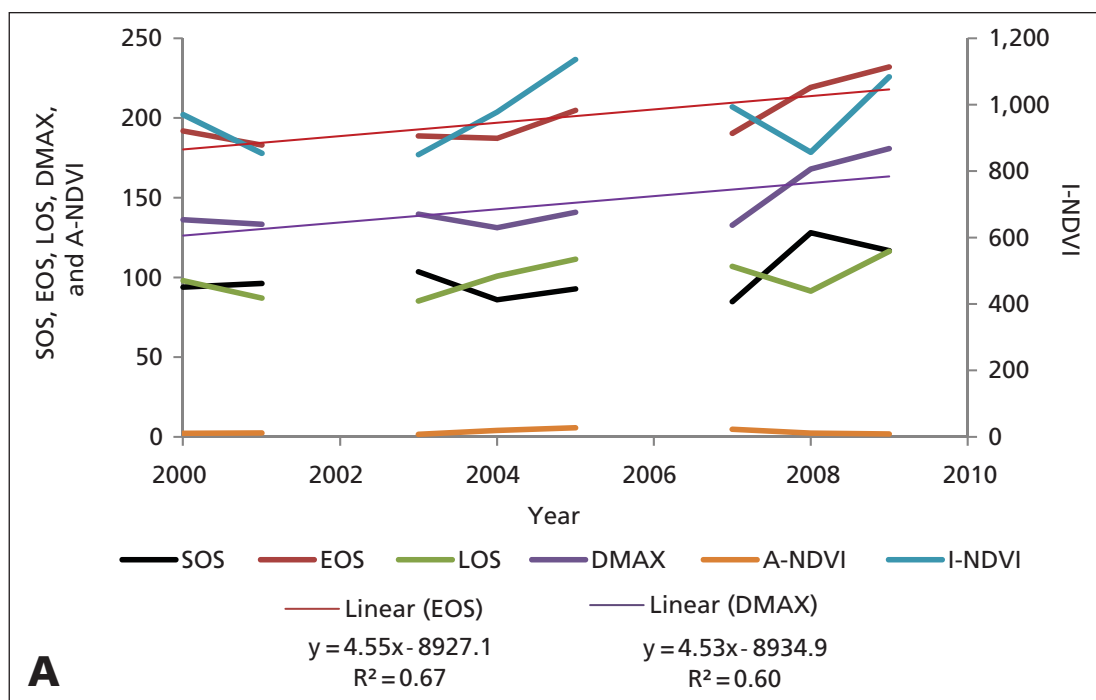


Figure 3.12-4. Annual (a) spring and (b) monsoon phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Hovenweep NM. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI. For both figures, metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.12.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Hovenweep NM (Figure 3.12-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2008 and 2009 had the most extensive and persistent snow cover (Figure 3.12-5b) and that more park area was snow-covered for longer in 2009 than in the past 10 years (Figure 3.12-5c). It is interesting to note that snow-cover extent did not reach 100% in the 10-year record.

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. The relationship between snow-covered extent

and water content available for plant growth when snow melts is generally stronger at higher elevations. At Hovenweep NM, the relationship is stronger than at most other NCPN parks that have similar snow cover. Earlier snowmelt could result in an earlier SOS, but snow cover is not the only factor driving SOS, as is shown by the positive relationship between snowmelt DOY and SOS ($R^2 = 0.44$) at the parkwide scale for seven years of record (Figure 3.12-6). Stronger relationships may occur at other spatial scales where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period in Hovenweep NM, defined here as less than 5% coverage, occurred between DOYs 83 (March 24) and 314 (November 10). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.12-4).

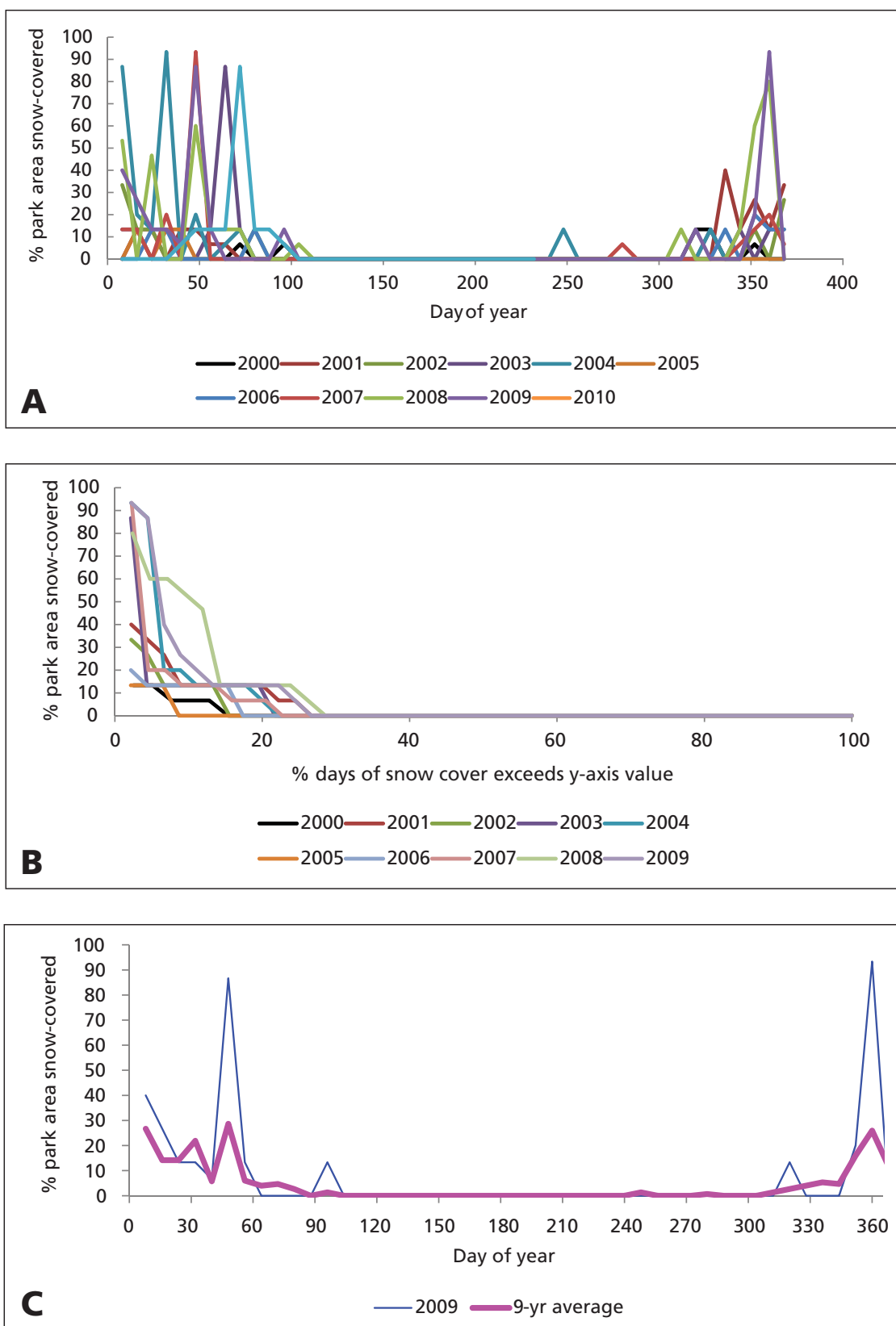


Figure 3.12-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Hovenweep NM.

Table 3.12-4. Timing and duration of snow cover, Hovenweep NM.

Year	Snow off	Snow on	DOY <1% cover	DOY >1% cover	Days snow-free	Days snow-covered
2000	4/13/2000	11/7/2000	104	312	208	157
2001	3/13/2001	11/24/2001	72	328	256	109
2002	3/30/2002	12/11/2002	88	344	256	109
2003	3/23/2003	11/18/2003	80	320	240	125
2004	3/23/2004	8/30/2004	80	240	160	205
2005	2/20/2005	1/20/2006	48	381	334	31
2006	4/2/2006	11/28/2006	88	328	240	125
2007	3/2/2007	10/4/2007	56	272	216	149
2008	4/27/2008	11/5/2008	112	304	192	173
2009	4/20/2009	11/14/2009	104	312	208	157
<i>correlation</i>			0.10	-0.17	-0.19	0.19
<i>slope</i>			0.68	-2.20	-2.87	2.87
<i>p-val slope</i>			0.79	0.63	0.61	0.61
<i>intercept</i>			-1277	4724	5989	-5624
<i>p-val intercept</i>			0.80	0.61	0.59	0.62

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

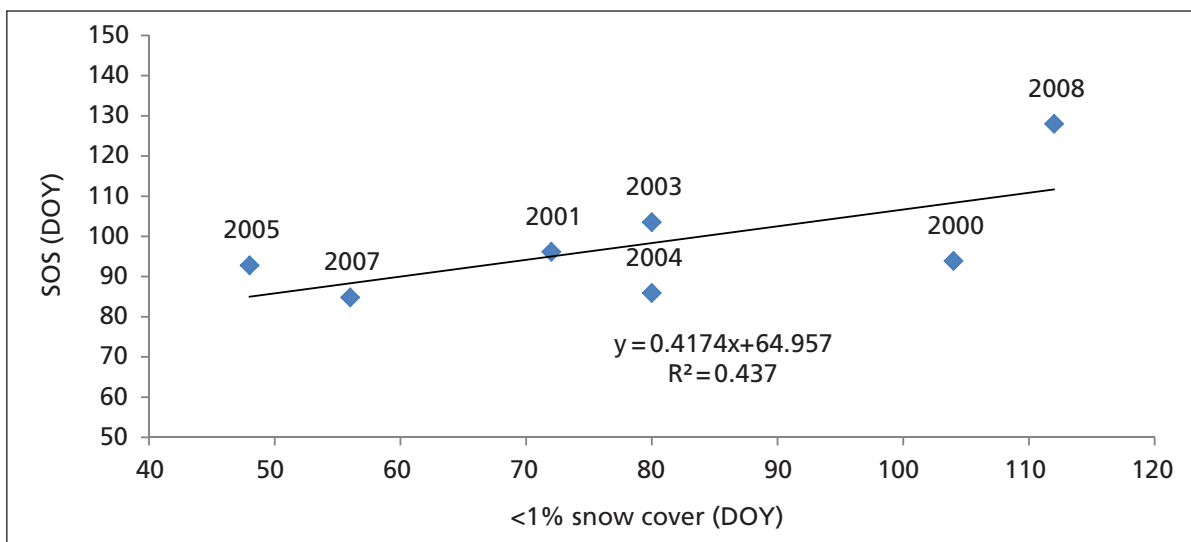


Figure 3.12-6. Relationship between snowmelt DOY and SOS, Hovenweep NM.

3.13 Natural Bridges National Monument

3.13.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.13-1a). Unlike in other NCPN parks, it is difficult to determine seasonal modality in the 10-year time series for Natural Bridges NM, due to the high degree of annual variability. Most areas on the Colorado Plateau have either uni-modal or bi-modal seasonality, reflecting dominant precipitation patterns and consequent vegetation adaptation. At Natural Bridges NM, NDVI peaks in fall or winter in most years, but the peak is so strongly moderated by precipitation that it appears intermittently and at very different times in the 10-year record. In fact, the timing and consistency were so variable that the Timesat phenology algorithms could not identify bi-modal seasonality with the Savitsky-Golay fit and had difficulty selecting even one season for each year of the record.

Increases in fall-season NDVI can eventually peak in November, December, or even January of the following year, which tends to confound the determination of seasonality at Natural Bridges NM. The complexity of the park's NDVI signal is clearly tied to variation in the precipitation that moderates the strength of the seasonal NDVI signal. In general, periods of low rainfall are followed by lower NDVI and periods of high precipitation are followed by periods of higher NDVI, almost without respect to time of year. Thus, although precipitation timing generally follows the typical monsoon pattern, with June being the driest month (Figure 3.13-1c), precipitation at any time of year appears to stimulate an NDVI response at Natural Bridges NM.

Native vegetation on the Colorado Plateau typically begins growing in the spring, in response to winter soil-moisture recharge (Comstock and Ehleringer 1992). However, additional spring moisture appears to strongly affect the strength of spring NDVI response. Monsoon and fall precipitation recharge soil moisture, but there is a strong spring NDVI response only in years with substantial spring precipitation. Year 2002 showed a lack of NDVI response to minimal spring precipita-

tion and year 2003 showed a moderate NDVI response to moderate amounts of spring precipitation. Year 2005 showed a strong NDVI response to abundant winter and spring precipitation.

Tree species at Natural Bridges NM seem to have adapted to consistent summer precipitation by growing shallow roots that can utilize shallow soil moisture. This is supported by the consistency between summer precipitation events that are followed by increases in NDVI. If the shallow roots were absent, then the response to shallow summer precipitation events would be muted. Higher-elevation, cooler summer temperatures and consistent monsoons may support temperature and moisture regimes that justify expenditure of resources to grow and support shallow root systems. A similar response appears at Hovenweep NM.

When annual curves are stacked (Figure 3.13-1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2005, are easily contrasted with less productive years, such as 2002. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to higher-elevation NCPN parks, the NDVI annual curves for NABR are "jagged," reflecting unevenly distributed and less abundant precipitation that supports vegetation adapted to multiple growing seasons in a single year.

Weather data from the park's NWS Coop station were used to interpret NDVI variation (Figure 3.13-1a, c). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. Year 2007 had the narrowest range in annual maximum and minimum NDVI (1.7), while 2004 had the widest range (7.0) (Table 3.13-1). The largest maximum NDVI (124.5) was in 2004. Years with higher cumulative precipitation generally had higher median NDVI (Figure 3.13-2a, b), but the strength of NDVI response is strongly associated with differences in the temporal distribution of precipitation (Figure 3.13-1a, c). A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

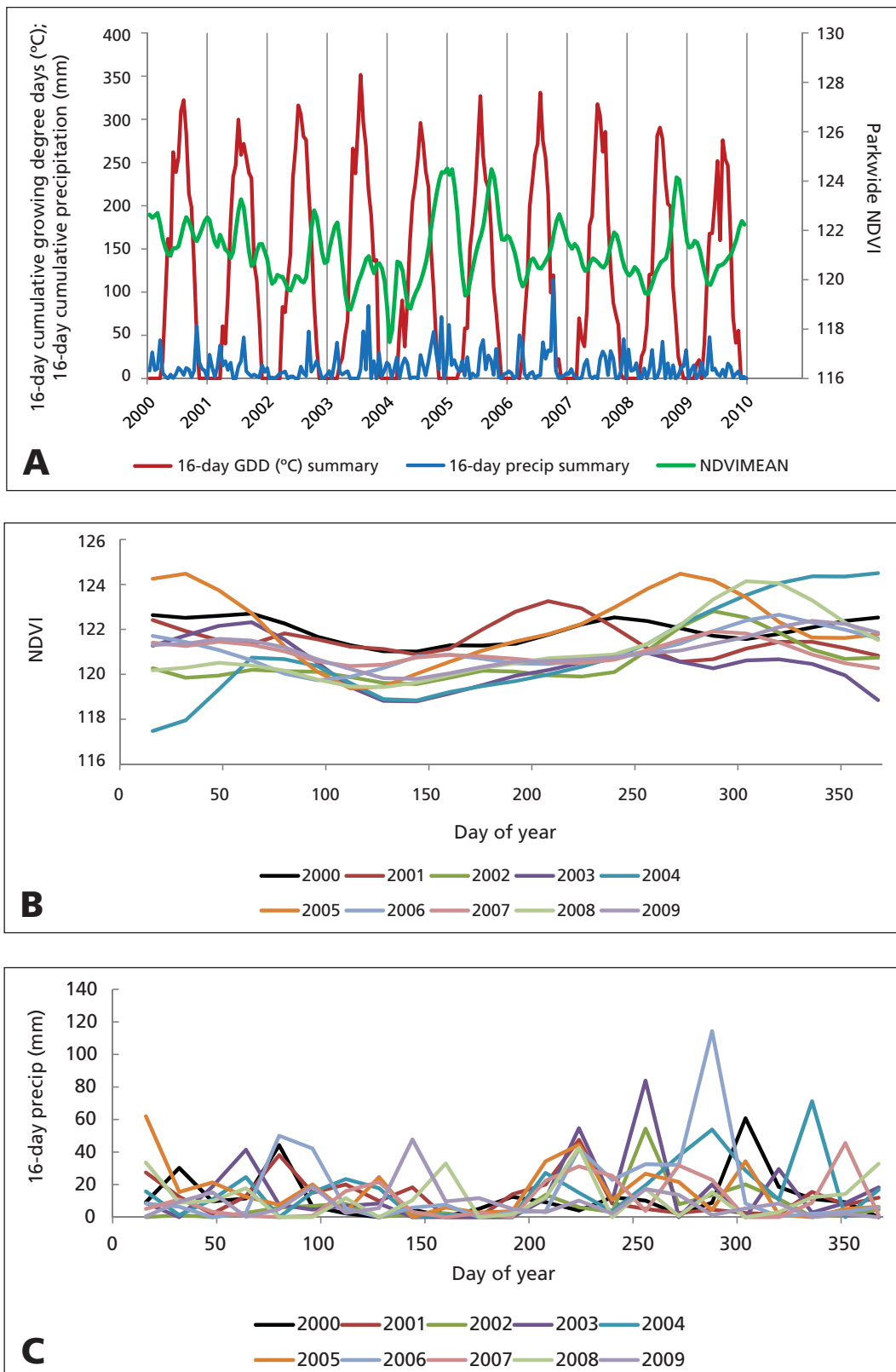


Figure 3.13-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Natural Bridges NM.

Table 3.13-1. Annual descriptive statistics for parkwide average NDVI, Natural Bridges NM.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	121.9	122.1	122.7	121.0	1.69	2805
2001	121.6	121.4	123.3	120.6	2.70	2796
2002	120.5	120.1	122.8	119.6	3.24	2772
2003	120.4	120.5	122.3	118.8	3.52	2769
2004	120.9	120.4	124.5	117.5	7.03	2781
2005	122.1	121.8	124.5	119.4	5.11	2809
2006	121.1	120.9	122.6	119.7	2.92	2785
2007	121.0	120.9	121.9	120.3	1.65	2782
2008	121.1	120.5	124.1	119.4	4.72	2785
2009	121.0	121.1	122.4	119.8	2.58	2784

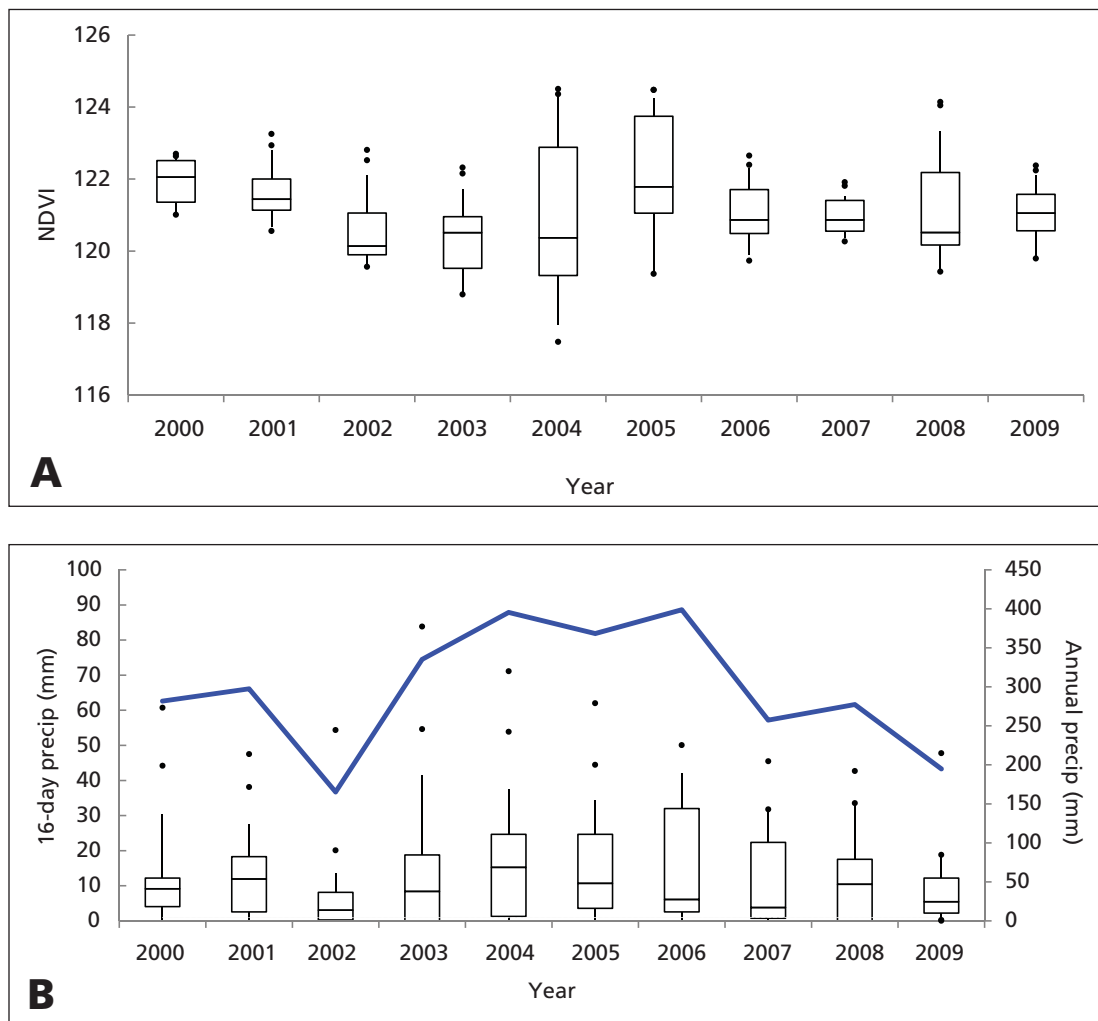


Figure 3.13-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Natural Bridges NM. Due to missing weather station data for 2004, 2007, and 2008, box plots and cumulative precipitation do not reflect actual conditions.

3.13.2 Recent NDVI conditions

The NDVI curve for 2009 matched the historical average until DOY 128 (May 8), when it fell below the 10-year average until DOY 320 (November 16)—at which point it climbed above the average for the remainder of the year. These generalizations, as difference from the mean, also aptly describe the variation in precipitation, giving some indication of the tight coupling of precipitation and productivity at the park. It is odd that a period of above-average precipitation (38.5 mm), centered on DOY 144 (May 24), did not boost NDVI above the historical average. This may be related to an absence of vegetation that could respond to precipitation at that time of year. Below-average precipitation between DOYs 144 and 320 (November 16) explains the steady decrease in 2009 NDVI relative to the long-term average during that period, but it is unclear why average precipitation centered on DOY 320 would cause 2009 NDVI to climb above the long-term average. It could be that invasive species are increasing over time at Natural Bridges NM, and are driving the late-season NDVI response. Annual average NDVI for 2009 was 0.10% below the 10-year average. Weather data for 2009 indicate that the precipitation deficit was 34.7% below the 10-year average (Figure 3-13-3a, b).

Monsoon NDVI in 2009 was average at the park (Figure 3.13-3c). However, a few areas outside the park, on the southern and western boundary, were below average. Regionally, monsoon NDVI was at or just below average. On DOY 304 (October 31), most areas in and near Natural Bridges NM were within -2 and 0 NDVI units, or between -3.8 and 0%, of the long-term average.

3.13.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 125, 256, 265, and 140 days, respectively. The most productive season, based on I-NDVI, was 2000, while the least productive was 2003 (Table 3.13-2); these years corresponded to the longest (503 days) and the shortest (238 days) growing seasons, respectively. It should be noted that Timesat grouped years 2000 and 2001; hence, the unusually long “season” for 2000. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships, as was observed at Natural Bridges NM. A statistically significant linear trend (p-value <0.1) for DMAX was observed at the parkwide scale for the period of analysis (Table 3.13-2; Figure 3.13-4a). The trends indicate that DMAX is occurring about 11.6 days earlier per year. Although this trend is significant, it should be considered with caution because it is based on a short, 10-year record in which phenology metrics for the year 2001 are missing due to weak expression that was not detectable by the Timesat algorithms. When year 2001 is removed, there is no statistically significant relationship between DMAX and year.

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not show trends in phenology (Table 3.13-2, Figure 3.13-4). A longer data record and more robust statistical techniques may provide better indication of broad-scale change in the future, if it occurs.

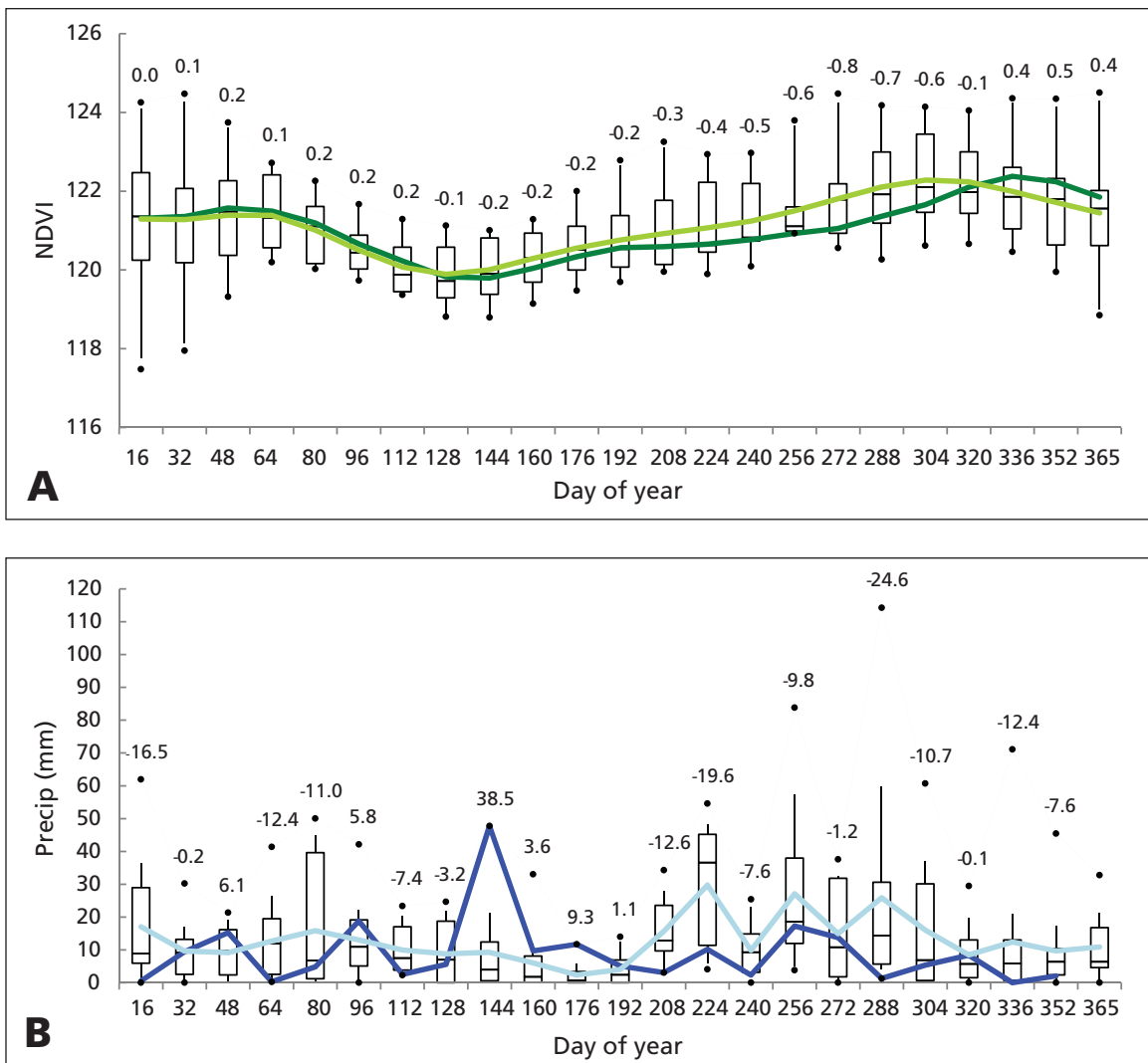


Figure 3.13-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Natural Bridges NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

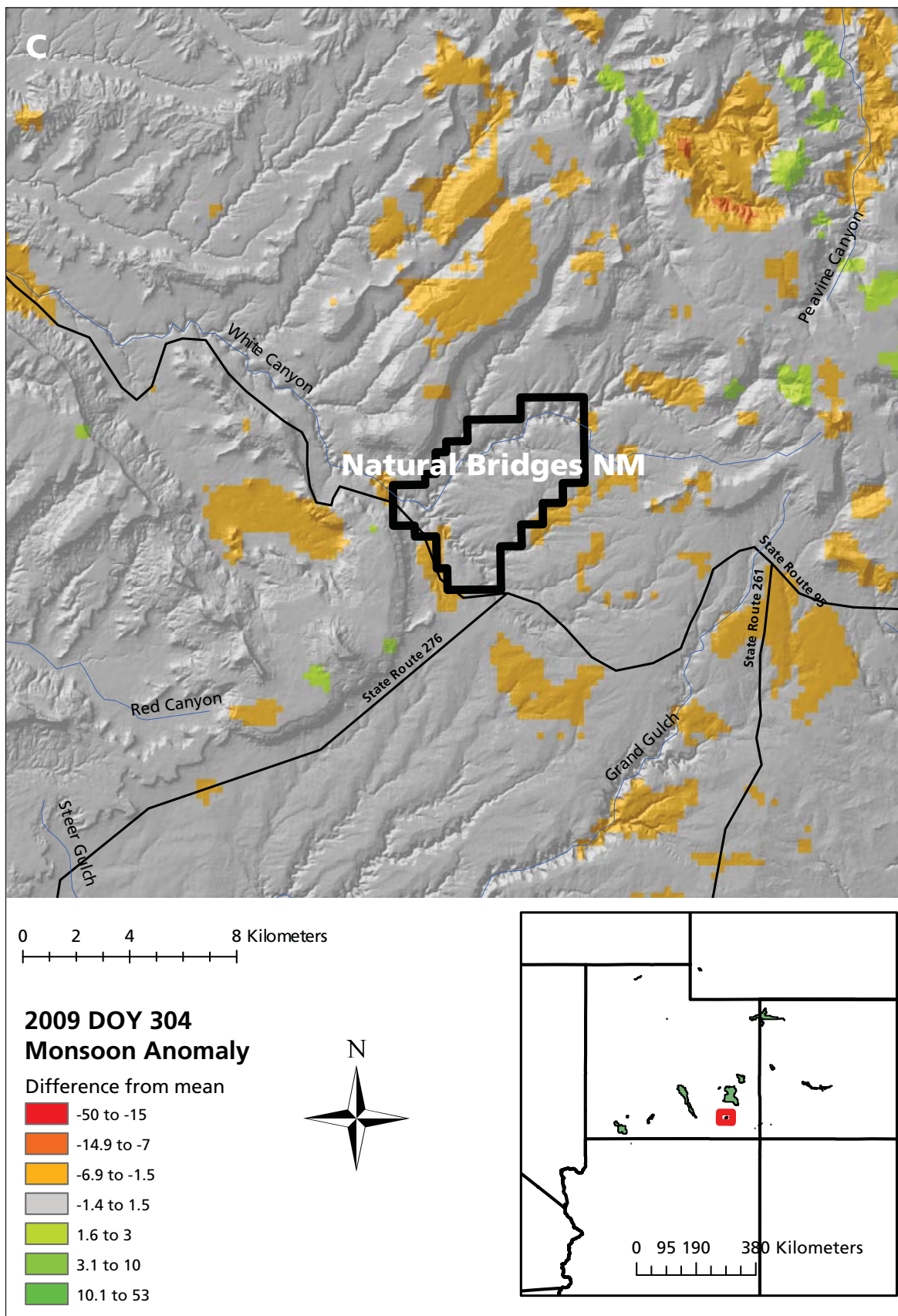


Figure 3.13-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Natural Bridges NM.

Table 3.13-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Natural Bridges NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	136	415	639	503	4019	1.70
2001	-	-	-	-	-	-
2002	146	355	496	350	2780	3.50
2003	145	282	384	238	1919	2.61
2004	21	357	478	457	3637	5.86
2005	128	275	461	333	2677	4.76
2006	99	318	478	379	3027	2.50
2007	115	298	486	372	3015	1.96
2008	131	312	499	368	3032	4.46
<i>correlation</i>	-0.17	-0.66	-0.40	-0.27	-0.23	0.25
<i>slope</i>	-2.64	-11.64	-10.63	-7.95	-53.95	0.14
<i>p-val slope</i>	0.68	0.07	0.32	0.52	0.58	0.56
<i>intercept</i>	5400	23659	21796	16318	111149	-270
<i>p-val intercept</i>	0.68	0.06	0.31	0.51	0.57	0.56

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable. Year 2001 had very small spring NDVI response. Timesat has difficulty computing phenology metrics when NDVI amplitude is small.

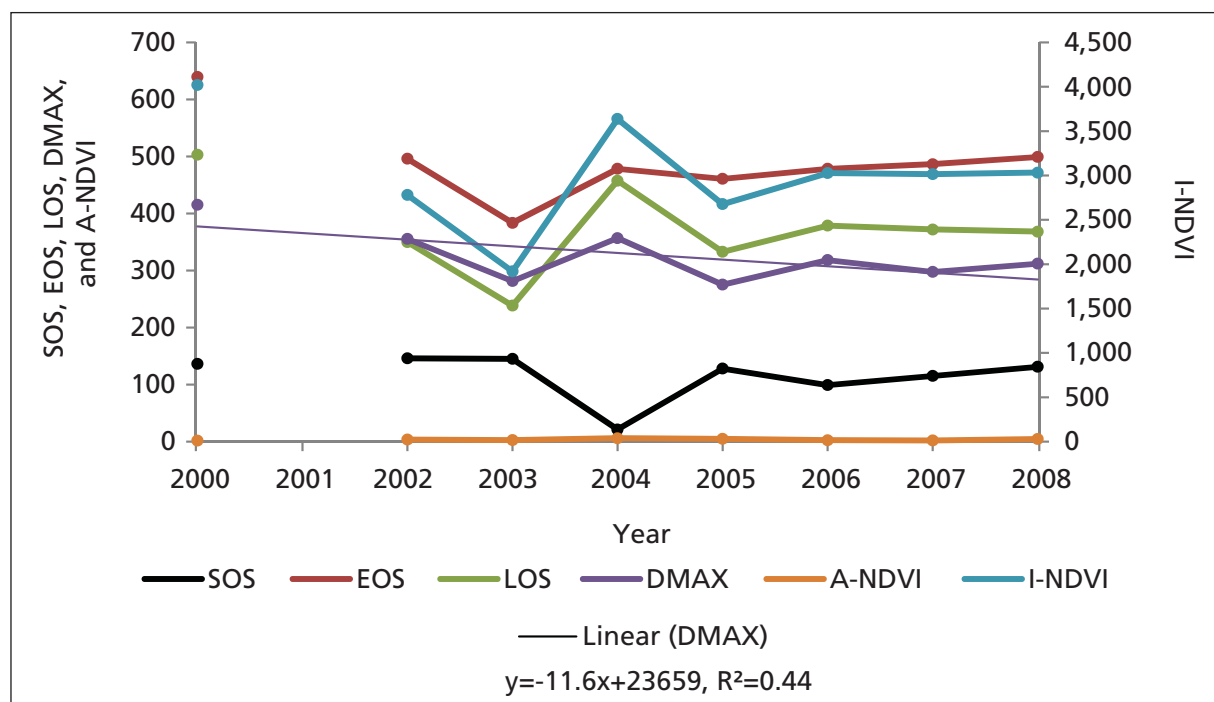


Figure 3.13-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Natural Bridges NM. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.13.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Natural Bridges NM (Figure 3.13-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2008 and 2009 had the most extensive and persistent snow cover (Figure 3.13-5b) and that more park area was snow-covered for longer in 2009 than in the past 10 years (Figure 3.13-5c), with an exception near DOY 40 (February 9).

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. At Natural Bridges NM, the relationship between snowmelt and SOS is strongly inverse. Snow cover is not the only factor driving SOS, as is shown by the negative relationship between snowmelt DOY and SOS ($R^2 = 0.74$) at the parkwide scale for eight years of record (Figure 3.13-6). Stron-

ger relationships may occur at other spatial scales or at higher elevations, where snowmelt/SOS coupling may be more mechanistic. Air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship. The relationship between snowmelt and SOS at the park scale could indicate that spring rain after snowmelt, rather than moisture stored in and eventually released by the snowpack, is the primary source of moisture for spring growth. That could mean either that snow-cover extent is not related to snow water content, or fall/winter annuals consume much of the previous year's stored soil moisture and spring rains are required to trigger substantial spring growth. Other factors that complicate understanding precipitation and vegetation response include rooting depths and preferential use of water from different soil depths by different species (Williams and Ehleringer 2000).

The 10-year average snow-free period in Natural Bridges NM, defined here as less than 3% coverage, occurred between DOYs 72 (March 13) and 316 (November 12). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.13-3).

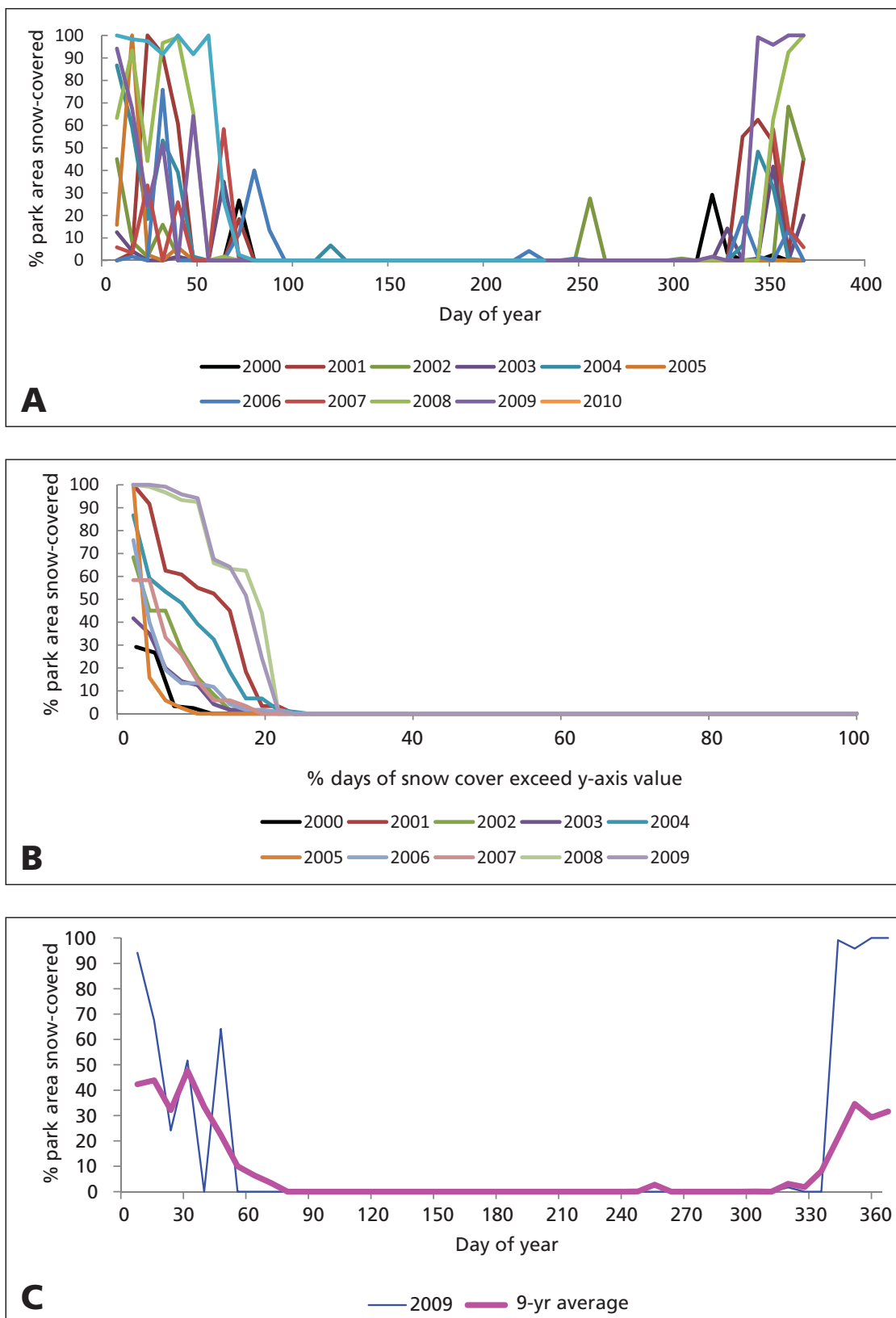


Figure 3.13-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Natural Bridges NM.

Table 3.13-3. Timing and duration of snow cover, Natural Bridges NM.

Year	Snow off	Snow on	DOY <3% cover	DOY >3% cover	Days snow-free	Days snow-covered
2000	3/20/2000	11/7/2000	80	312	232	133
2001	3/21/2001	11/24/2001	80	328	248	117
2002	2/10/2002	9/6/2002	40	248	208	157
2003	3/15/2003	11/18/2003	72	320	248	117
2004	5/10/2004	11/26/2004	128	328	200	165
2005	2/20/2005	1/28/2006	48	389	342	23
2006	4/10/2006	8/8/2006	96	216	120	245
2007	3/18/2007	12/15/2007	72	344	272	93
2008	3/2/2008	12/15/2008	56	344	288	77
2009	3/3/2009	12/8/2009	56	336	280	85
<i>correlation</i>			-0.17	0.21	0.24	-0.24
<i>slope</i>			-1.41	3.38	4.79	-4.79
<i>p-val slope</i>			0.65	0.57	0.50	0.50
<i>intercept</i>			2891	-6450	-9354	9719
<i>p-val intercept</i>			0.64	0.59	0.51	0.50

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

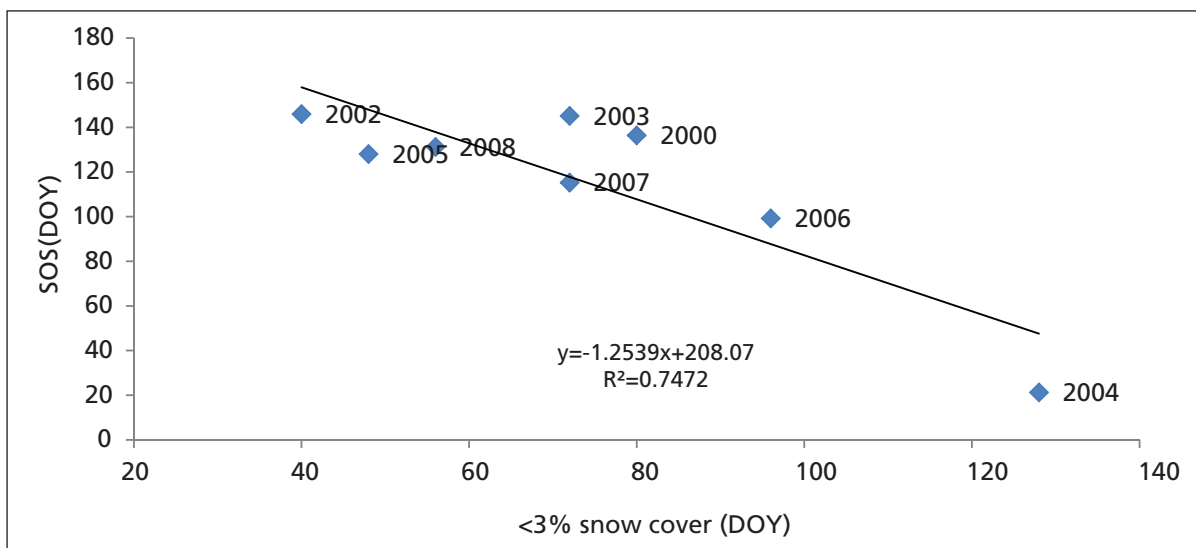


Figure 3.13-6. Relationship between snowmelt DOY and SOS, Natural Bridges NM.

3.14 Pipe Spring National Monument

3.14.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.14-1a). Unlike in most other NCPN parks, it is difficult to determine the modality of seasonality in the 10-year time series for Pipe Spring NM, due to the high degree of annual variability. Most areas on the Colorado Plateau have either uni-modal or bi-modal seasonality, reflecting the dominant precipitation patterns and consequent vegetation adaptation. In higher precipitation years, there are spring and monsoon peaks in NDVI at Pipe Spring NM. However, precipitation so strongly moderates the magnitude of peaks that seasonal peaks appear intermittently and at very different times in the 10-year record. In fact, the timing and consistency was so variable that the Timesat phenology algorithms could not identify bi-modal seasonality and had difficulty selecting even one season for each year of the record.

The complexity of NDVI signal at the park is clearly tied to variation in precipitation that accentuates or diminishes the strength of the seasonal NDVI signal. Periods of low precipitation are generally followed by lower NDVI and periods of high precipitation are followed by periods of higher NDVI. Thus, although precipitation timing generally follows the typical monsoon pattern, with June being the driest month (Figure 3.14-1c), precipitation at any time of year stimulates an NDVI response. Also, soil-moisture recharge in winter and spring plays an important role in determining the magnitude of spring NDVI. In the future, this analysis may be more meaningful if carried out for a larger spatial context to indicate what types of vegetation changes may be occurring regionally that may affect other resources of concern in and near the park.

Another complicating factor at Pipe Spring NM is that the area used in analysis is smaller than an individual MODIS pixel. Variability in image registration increases the variation in NDVI signal,

as successive images may not represent exactly the same ground location. Also, because the park is a managed landscape, activities related to landscaping, gardening, prescribed fire, and mowing all influence the NDVI signal. A more appropriate and perhaps informative area for analysis might be the watershed catchment for the springs.

Weather data from the park's NWS Coop station were used to interpret NDVI variation (Figure 3.14-1a, c). Year 2007 had the narrowest range in annual maximum and minimum NDVI (3.5), while 2007 had the widest range (15.5) (Table 3.14-1). The largest maximum NDVI (134.0) was in 2005. Years with higher cumulative precipitation generally had higher median NDVI (Figure 3.14-2a, b), but it is clear that the strength of NDVI response is strongly associated with differences in the temporal distribution of precipitation (Figure 3.14-1a, c). A better understanding of the relationship between temperature, moisture, and NDVI will help improve understanding of potential impacts on vegetation caused by weather and climate.

3.14.2 Recent NDVI conditions

The 2009 NDVI curve was well below the historical average until DOY 176 (June 25), when it matched the historical average for one month then fell below the average for the remainder of the year. These generalizations, as difference from the mean, also aptly describe the variation in precipitation, giving some indication of the tight coupling of precipitation and productivity at the park. Annual average NDVI for 2009 was 2.1% below the 10-year average. Weather data for 2009 indicate that the precipitation deficit was 57.6% below the 10-year average (Figure 3.14-3a, b).

Monsoon NDVI in 2009 was below average at Pipe Spring NM. Areas to the east, south, and west of the park were further below average than the area to the north (Figure 3.14-3c). Regionally, monsoon NDVI was below average. On DOY 304 (October 31), most areas in and near Pipe Spring NM were within -2 and 0 NDVI units, or between -3.8 and 0%, of the long-term average.

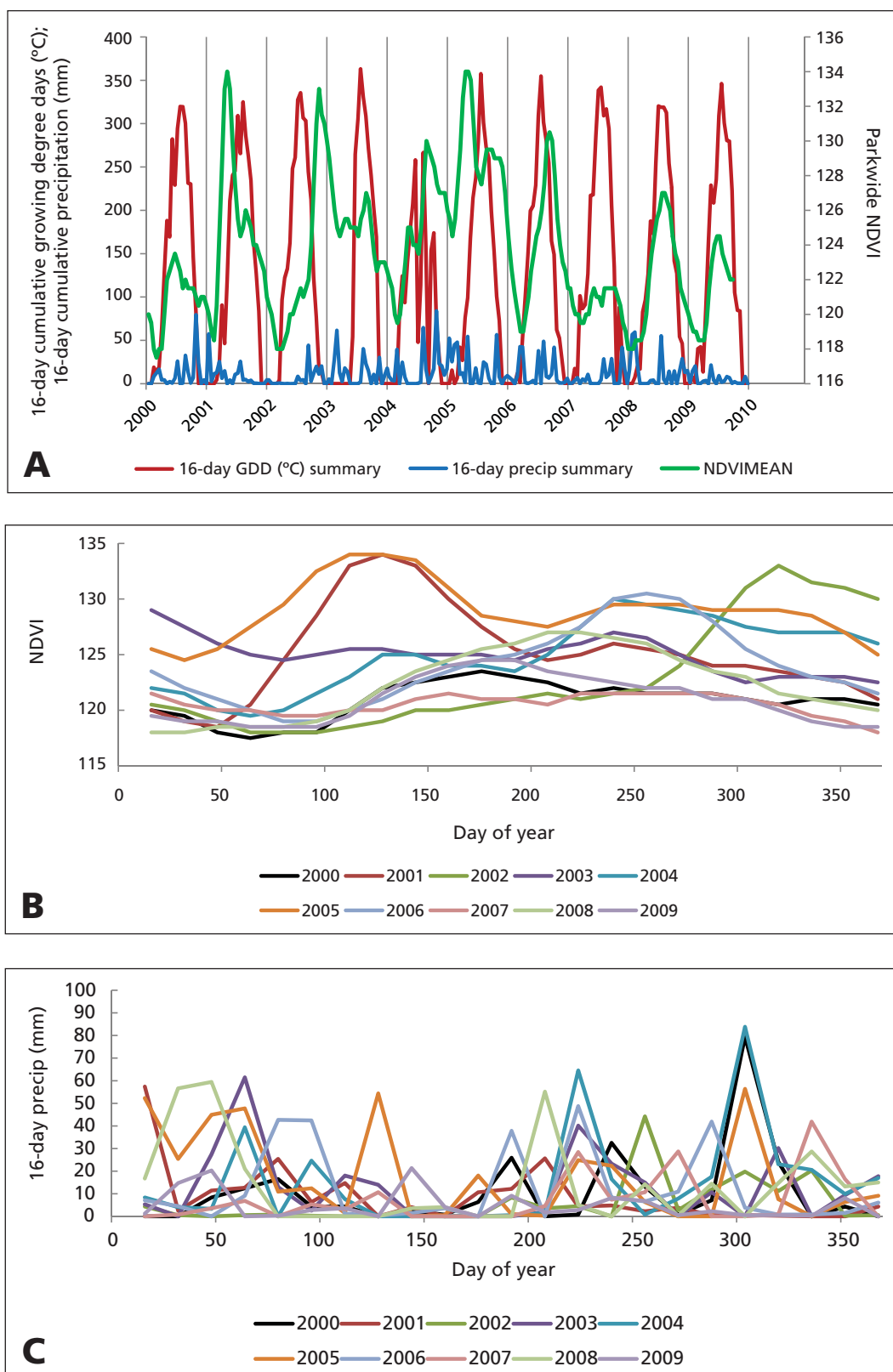


Figure 3.14-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Pipe Spring NM.

Table 3.14-1. Annual descriptive statistics for parkwide average NDVI, Pipe Spring NM.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	120.8	121.0	123.5	117.5	6.00	2780
2001	125.1	124.5	134.0	118.5	15.50	2878
2002	122.9	121.0	133.0	118.0	15.00	2827
2003	125.0	125.0	129.0	122.5	6.50	2875
2004	124.9	125.0	130.0	119.5	10.50	2873
2005	129.0	129.0	134.0	124.5	9.50	2966
2006	123.9	123.5	130.5	119.0	11.50	2850
2007	120.5	120.5	121.5	118.0	3.50	2772
2008	122.3	122.0	127.0	118.0	9.00	2813
2009	120.9	121.0	124.5	118.5	6.00	2781

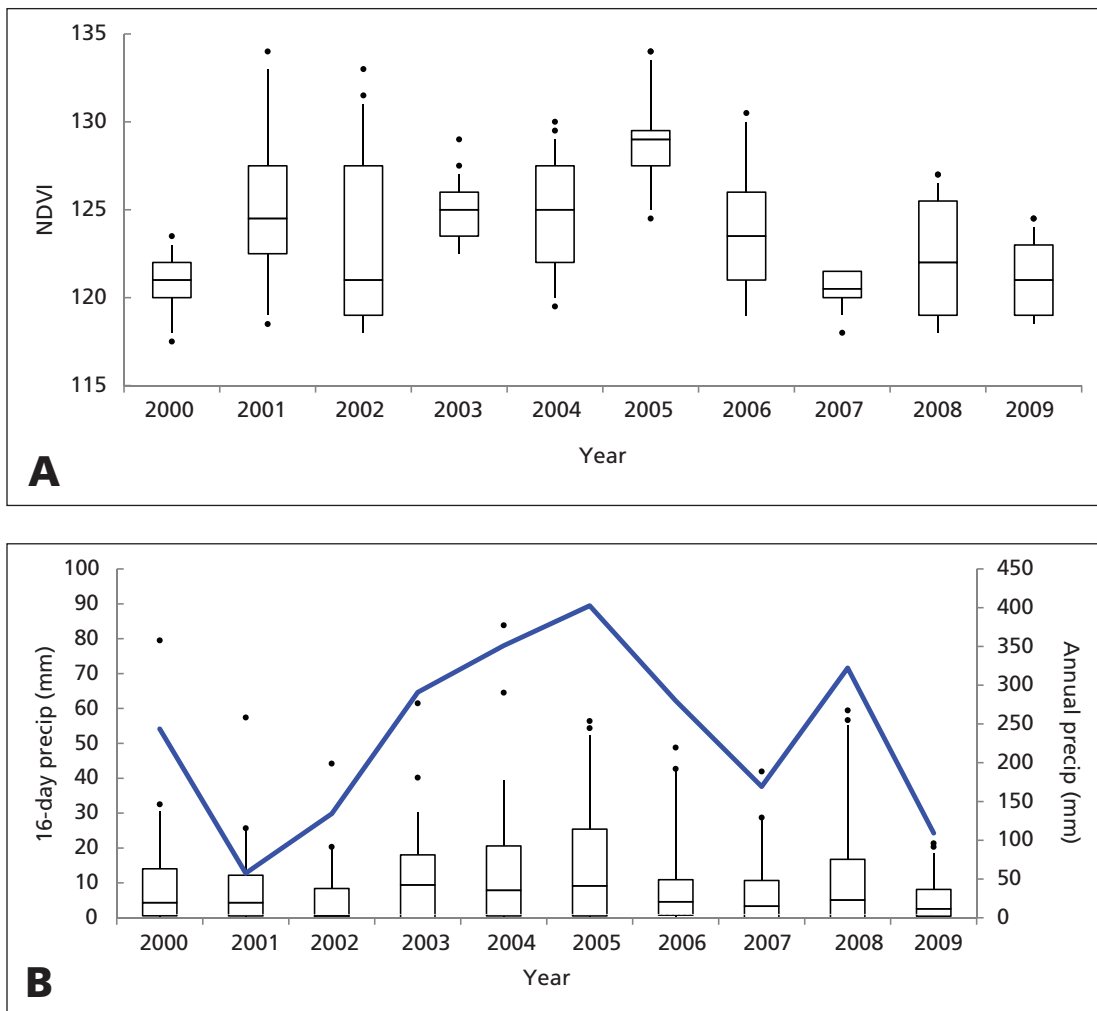


Figure 3.14-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Pipe Spring NM. Due to missing weather station data for 2004, 2007, and 2008, box plots and cumulative precipitation do not reflect actual conditions.

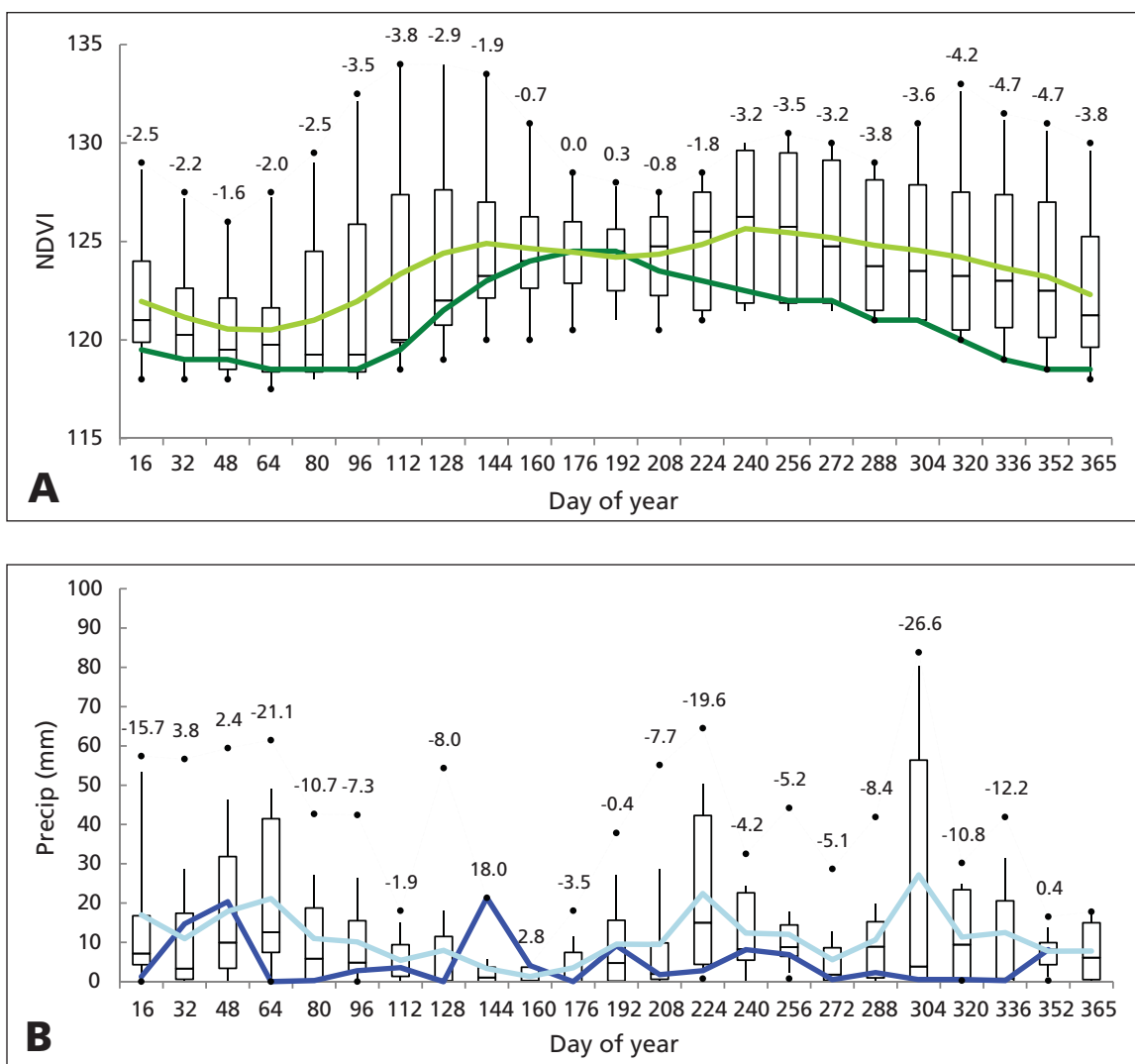


Figure 3.14-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Pipe Spring NM. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period (where a difference could be determined).

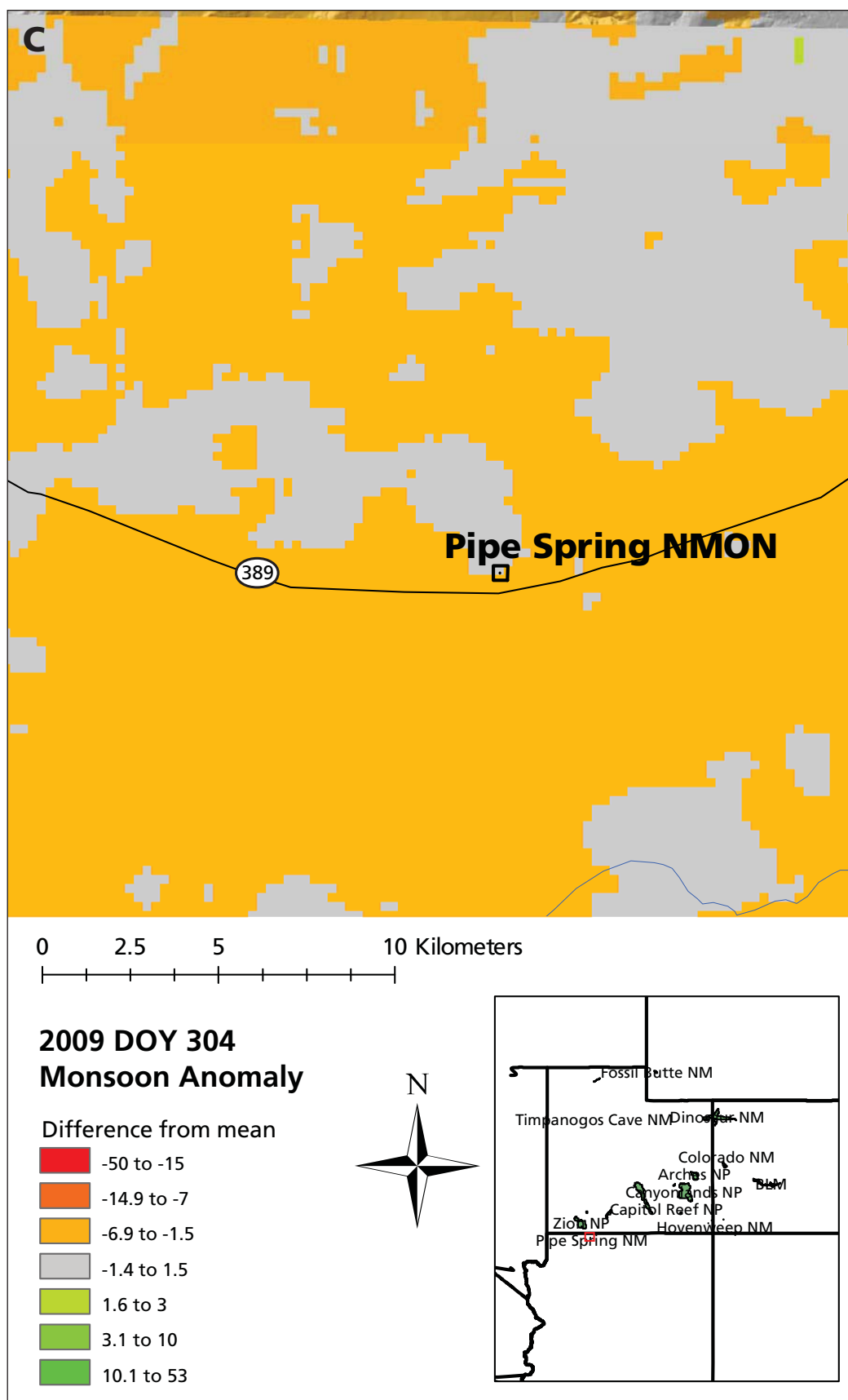


Figure 3.14-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Pipe Spring NM.

3.14.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 77, 40, 116, and 128 days, respectively. The most productive year, based on I-NDVI, was 2005, while the least productive was 2006 (Table 3.14-2); these years corresponded to the longest (390 days) and the shortest (350 days) growing seasons, respectively. It should be noted that Timesat grouped years 2002 and 2003, producing meaningless results for phenology metrics in those years. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. No statistically significant trends (p -value < 0.1) in phenology metrics were observed for the period of analysis (Table 3.14-2; Figure 3.14-4).

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity caused by pixel-to-pixel misregistration (Table 3.14-2, Figure 3.14-4). Future analysis would probably be better done at broader spatial scales that although not directly representative of park conditions, may aid interpretations of resources important to the park.

3.14.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Pipe Spring NM (Figure 3.14-5a) is highly variable due to variation in

regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of year when snow cover is unlikely (e.g., between DOYs 150 and 300). Also, because only one pixel was evaluated for snow cover, the percentage of park area covered was either zero or 100%. Lastly, there were several years with no snow cover; in these cases, it did not make sense to determine dates for snowmelt or first snowfall.

Cumulative exceedance frequency curves indicate that years 2008 and 2009 had the most extensive and persistent snow cover (Figure 3.14-5b), and that more park area was snow-covered for longer in 2009 than in the past 10 years (Figure 3.14-5c), with an exception near DOY 30 (January 30).

Snow presence or absence could only be determined reliably for three years. Stronger relationships may occur at other spatial scales where snowmelt/SOS coupling may be more mechanistic. Air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

The 10-year average snow-free period at Pipe Spring NM, defined here as less than 3% coverage, occurred between DOYs 43 (February 12) and 300 (October 28). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.14-3).

Table 3.14-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Pipe Spring NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	103	171	384	281	2426	5.16
2001	72	131	357	284	2521	15.84
2002	-	-	-	-	-	-
2003	-	-	-	-	-	-
2004	102	251	371	269	2395	7.61
2005	62	128	390	328	2961	12.27
2006	139	256	350	212	1883	11.29
2007	122	232	352	230	1932	2.86
2008	112	218	350	239	2101	8.88
<i>correlation</i>	0.46	0.55	-0.51	-0.52	-0.48	-0.21
<i>slope</i>	4.09	9.99	-2.85	-6.91	-61.27	-0.31
<i>p-val slope</i>	0.29	0.19	0.23	0.21	0.26	0.65
<i>intercept</i>	-8095	-19824	6083	14106	125126	628
<i>p-val intercept</i>	0.29	0.19	0.21	0.20	0.25	0.64

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable. Years 2002 and 2003 had very small spring NDVI response. Timesat has difficulty computing phenology metrics when NDVI amplitude is small.

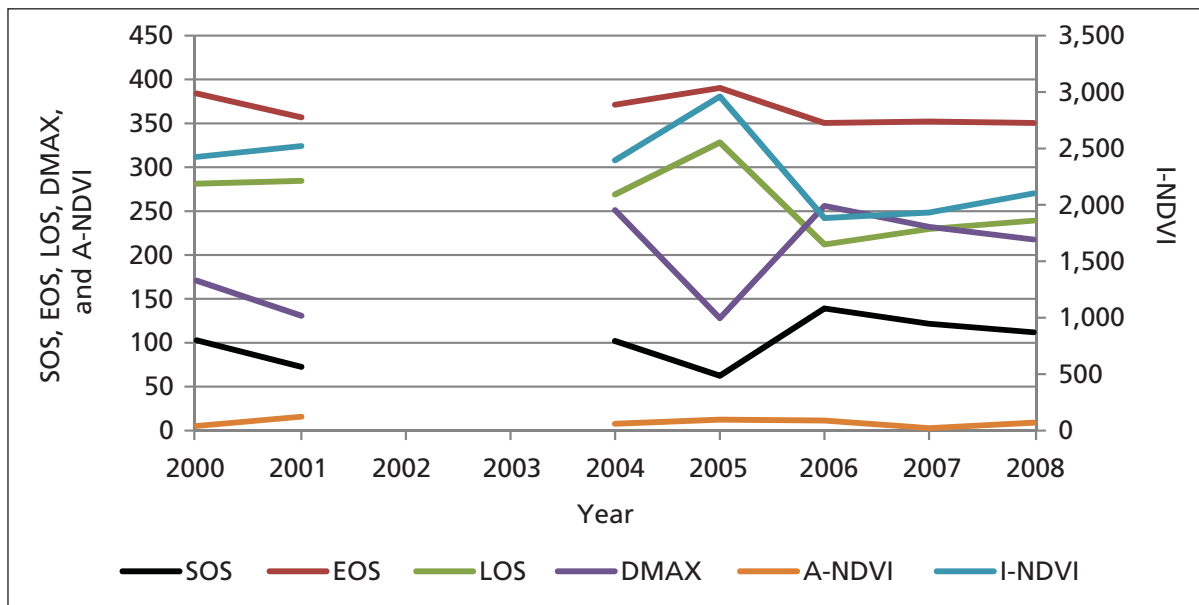


Figure 3.14-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Pipe Spring NM. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

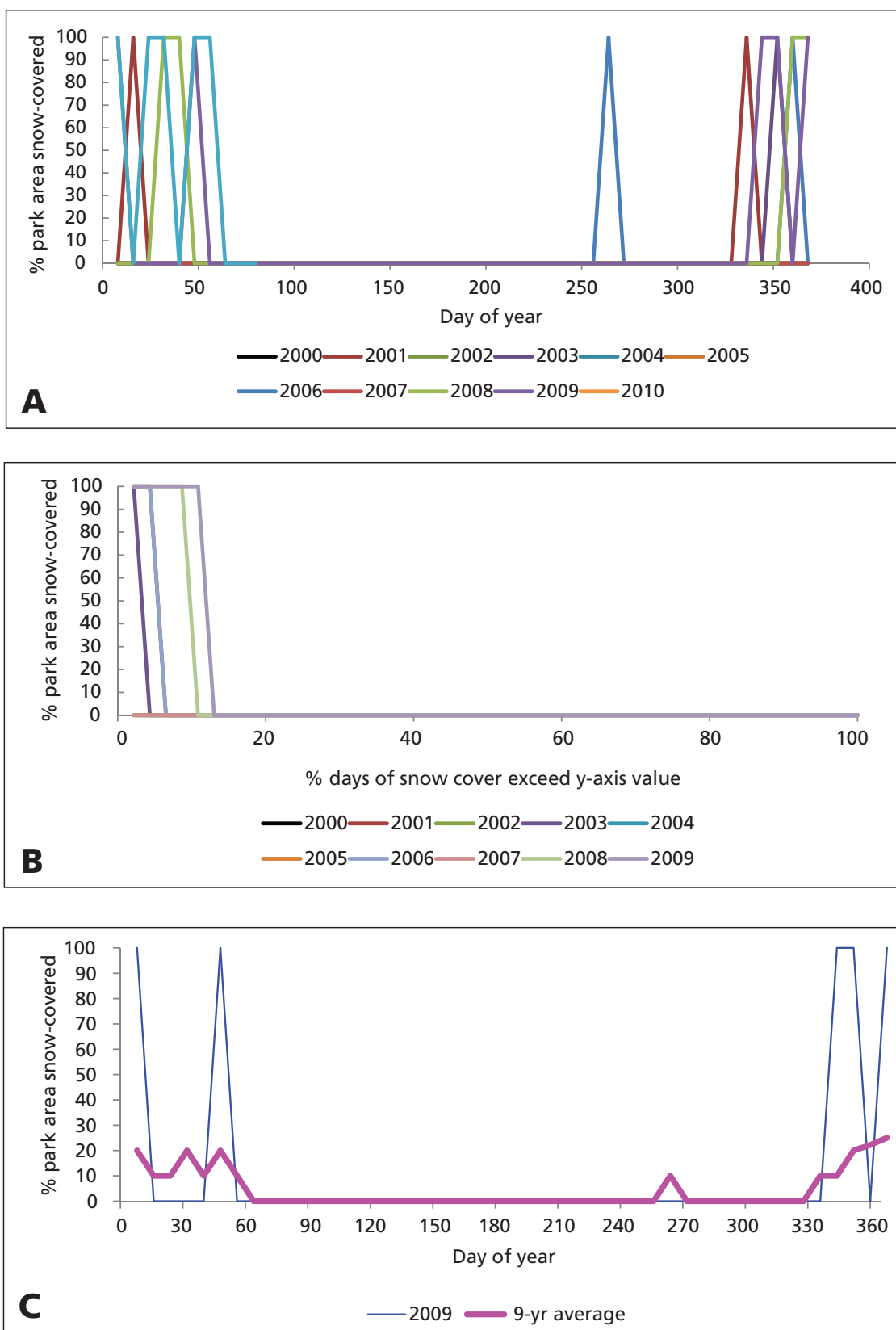


Figure 3.14-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Pipe Spring NM.

Table 3.14-3. Timing and duration of snow cover, Pipe Spring NM.

Year	Snow off	Snow on	DOY <3% cover	DOY >3% cover	Days snow- free	Days snow- covered
2000	-	-	-	-	365	0
2001	1/24/2001	11/24/2001	24	328	304	61
2002	-	-	-	-	365	0
2003	-	12/12/2003	-	344	344	21
2004	-	-	-	-	365	0
2005	-	-	-	-	365	0
2006	-	9/17/2006	-	-	264	101
2007	-	-	-	-	365	0
2008	2/23/2008	12/23/2008	48	352	304	61
2009	3/3/2009	12/8/2009	56	336	280	85
<i>correlation</i>					-0.46	0.60
<i>slope</i>					-6.09	0.01
<i>p-val slope</i>					0.18	0.18
<i>intercept</i>					12541	-130
<i>p-val intercept</i>					0.17	0.18

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

3.15 Timpanogos Cave National Monument

3.15.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrates the degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.15-1a). In the 10-year time series, a strong uni-modal seasonal phenology was apparent in most years. When annual curves are stacked (Figure 3.15-1b), a more direct year-to-year comparison is possible, in which more productive years, such as 2002 and 2000, are easily contrasted with less productive years, such as 2006. Viewed this way, the stacked annual curves can be directly compared between years to determine differences in NDVI magnitude and timing. Relative to lower-elevation NCPN parks, the NDVI annual curves for Timpanogos Cave NM are remarkably consistent, which may indicate that the park's precipitation is well-distributed, more abundant than elsewhere, and supports vegetation adapted to a single growing season.

Weather data from the park's NWS Coop station were too intermittent for use in interpreting NDVI variation. Year 2009 had the narrowest range in annual maximum and minimum NDVI (23.6), while 2004 had the widest (54.0) (Table 3.15-1). The wide range in 2004 may be related to extent and depth of snow cover in winter 2004–2005. No year after 2004 had a winter NDVI as extreme; thus, if the low winter NDVI was due to vegetation changes, it had largely recovered by subsequent years. More information on snow cover is presented in a later section.

Differences in median annual NDVI were minimal for the 10-year period of record (Table 3.15-1; Figure 3.15-2). This highlights the importance of precipitation abundance for productivity and indicates that precipitation timing is generally distributed evenly enough—even in the years of lowest precipitation—to support the climate-adapted vegetation at Timpanogos Cave NM.

3.15.2 Recent NDVI conditions

The seasonal curve for NDVI in 2009 started well above the 10-year average, but starting on about DOY 128 (May 8), it began tracking the average curve and did so for the remainder of the year. Annual NDVI for 2009 was 1.6% above the 10-year average, likely due to above-average cumulative annual precipitation (Figure 3.15-3).

NDVI was average at Timpanogos Cave NM in 2009, with mountainous areas to the north, south, and east well above average (Figure 3.15-3c). Regionally, monsoon NDVI was above average in the mountains and below average in the valley along the Wasatch Front. On DOY 304 (October 31), most areas of Timpanogos Cave NM were within -1 and 0 NDVI units, or between -1.9 and 0%, of the long-term average.

3.15.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 92, 92, 117 and 62 days, respectively. The most productive year, based on I-NDVI, was 2001, while the least productive was 2003 (Table 3.15-2); these years corresponded to the second-longest (311) and shortest (202) growing seasons, respectively. In normal years, LOS, more than peak NDVI magnitude, primarily determines annual productivity rankings, but variation in precipitation can introduce much variability to these relationships. There were no statistically significant linear trends (p -value <0.1) in the phenology metrics observed at the parkwide scale for the period of analysis (Table 3.15-2; Figure 3.15-4).

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends (Table 3.15-2, Figure 3.15-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs.

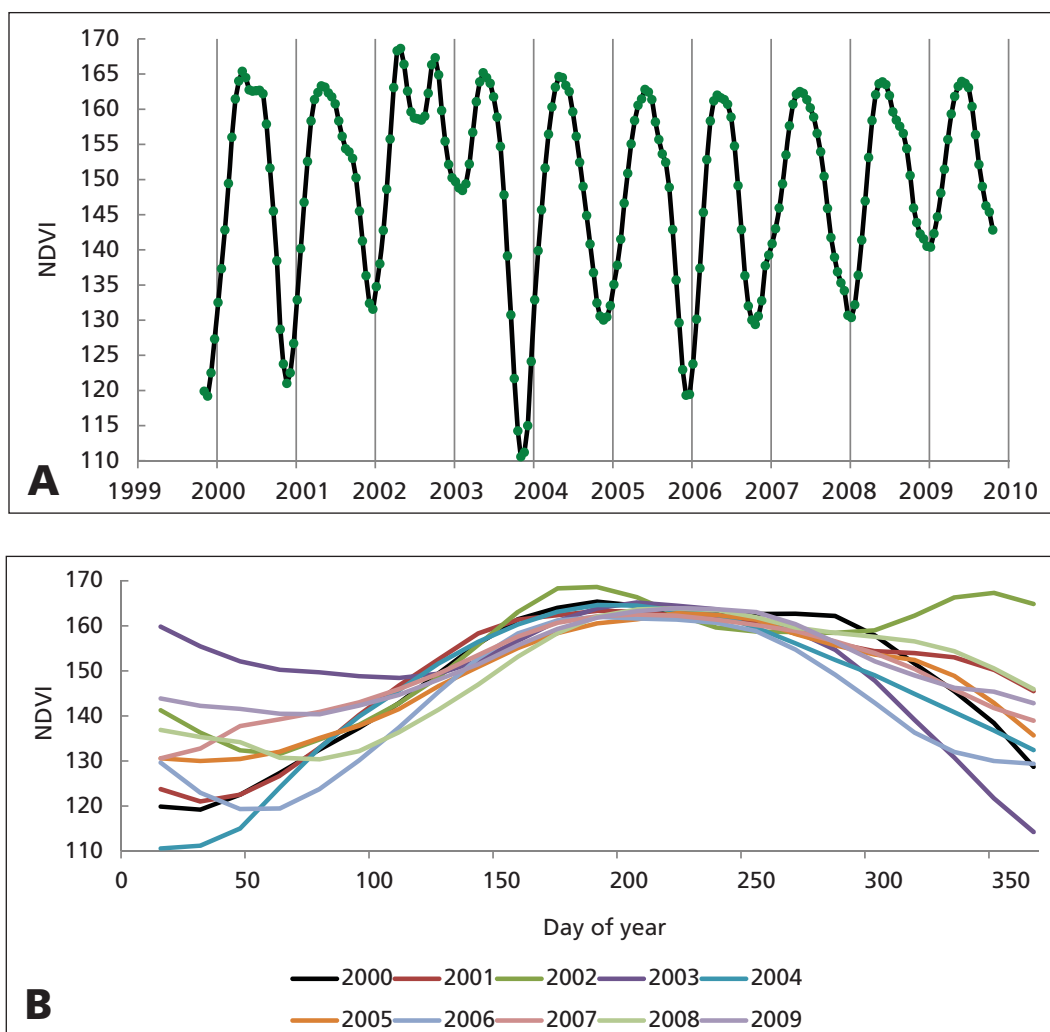


Figure 3.15-1. (a) 10-year parkwide average NDVI time series on 16-day intervals; (b) Annual NDVI curves stacked for inter-annual comparison, Timpanogos Cave NM.

Table 3.15-1. Annual descriptive statistics for parkwide average NDVI, Timpanogos Cave NM.

Year	Scaled NDVI					
	Mean	Median	Max	Min	Range	Sum
2000	127.6	124.9	140.1	121.4	18.71	2934
2001	127.5	124.8	144.3	118.2	26.12	2931
2002	125.5	123.3	141.0	114.3	26.66	2887
2003	124.7	122.7	140.8	113.8	26.92	2868
2004	125.4	123.3	141.2	113.0	28.27	2884
2005	129.6	126.1	147.5	117.8	29.69	2980
2006	126.9	126.0	139.0	116.2	22.88	2918
2007	127.3	125.4	142.9	116.5	26.42	2927
2008	127.9	124.1	145.1	118.8	26.37	2941
2009	127.6	125.2	146.9	113.1	33.87	2934

Figure 3.15-2. Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency, Timpanogos Cave NM. Due to missing weather station data for 2007, 2008, and 2009, box plots and cumulative precipitation do not reflect actual conditions. Also, weather data could not be used for interpretation with NDVI, as was done elsewhere in this report.

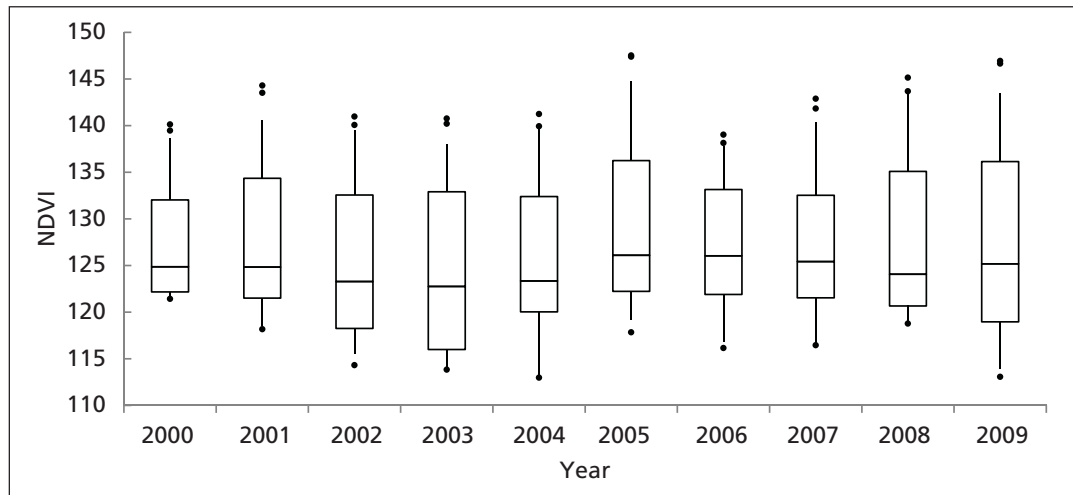
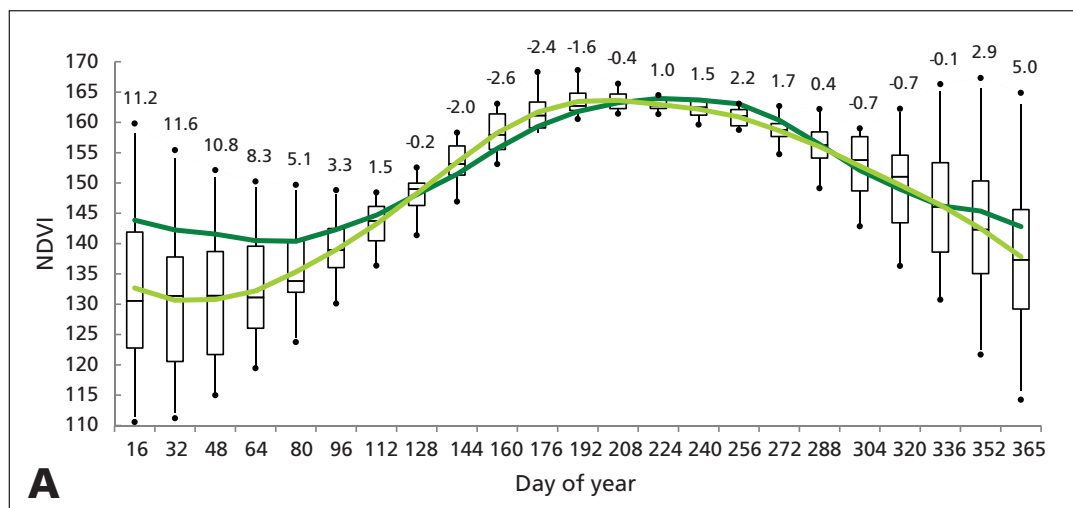


Figure 3.15-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green, Timpanogos Cave NM. Numbers above box plots are the difference between 10-year average and 2009 NDVI for each 16-day period.



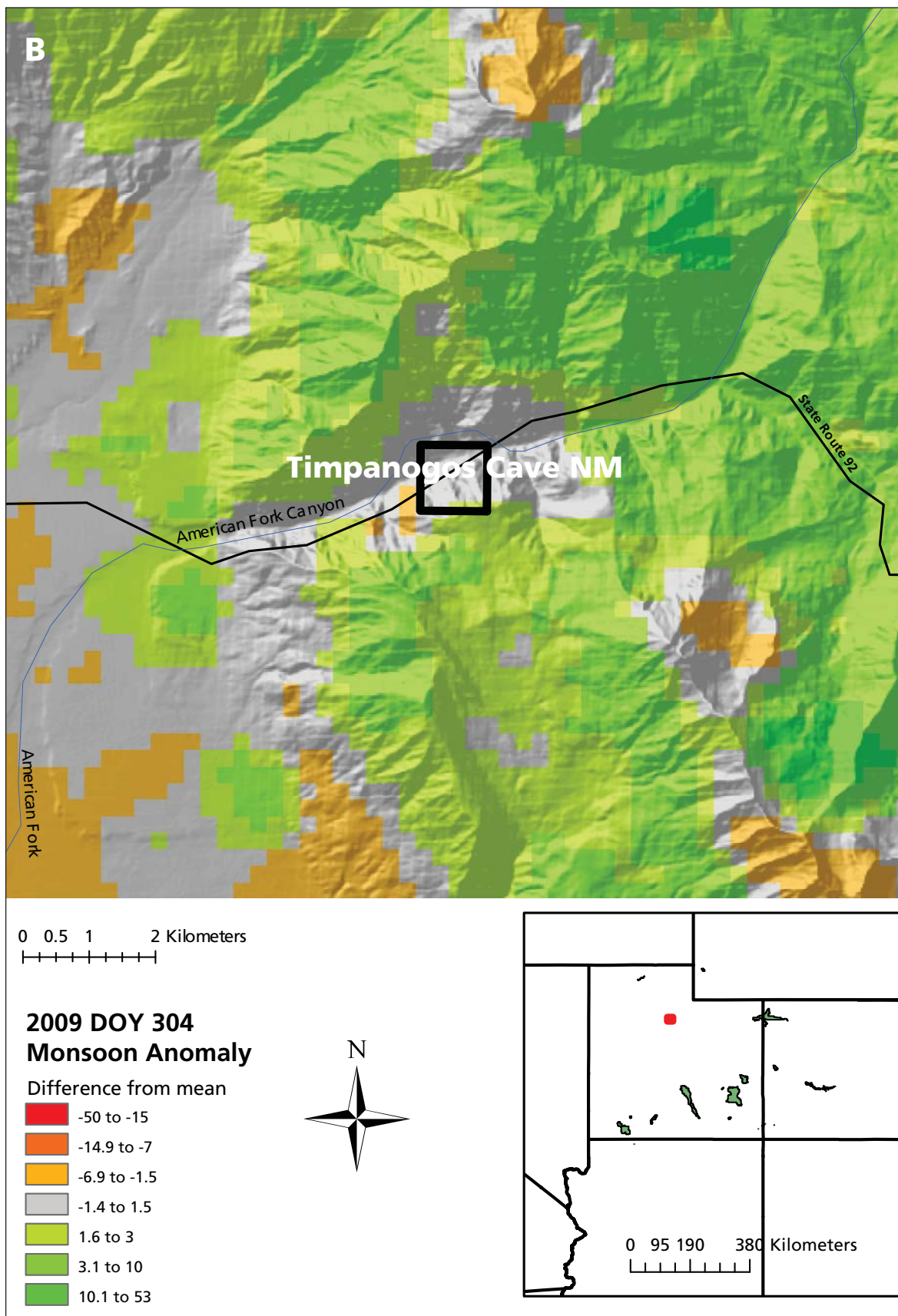


Figure 3.15-3. (b) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Timpanogos Cave NM.

Table 3.15-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Timpanogos Cave NM.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	72	226	363	291	3036	45.57
2001	77	208	388	311	3341	36.54
2002	107	262	409	303	3337	28.53
2003	145	234	347	202	2142	35.40
2004	65	200	344	280	2868	44.21
2005	98	234	382	285	2876	38.01
2006	96	208	317	221	2396	37.55
2007	53	222	373	319	3319	32.67
2008	120	226	368	248	2778	28.59
<i>correlation</i>	0.08	-0.16	-0.29	-0.25	-0.24	-0.45
<i>slope</i>	0.88	-1.10	-2.90	-3.77	-37.43	-0.98
<i>p-val slope</i>	0.83	0.67	0.45	0.51	0.53	0.23
<i>intercept</i>	-1662	2437	6185	7835	77916	2003
<i>p-val intercept</i>	0.84	0.64	0.42	0.50	0.51	0.22

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

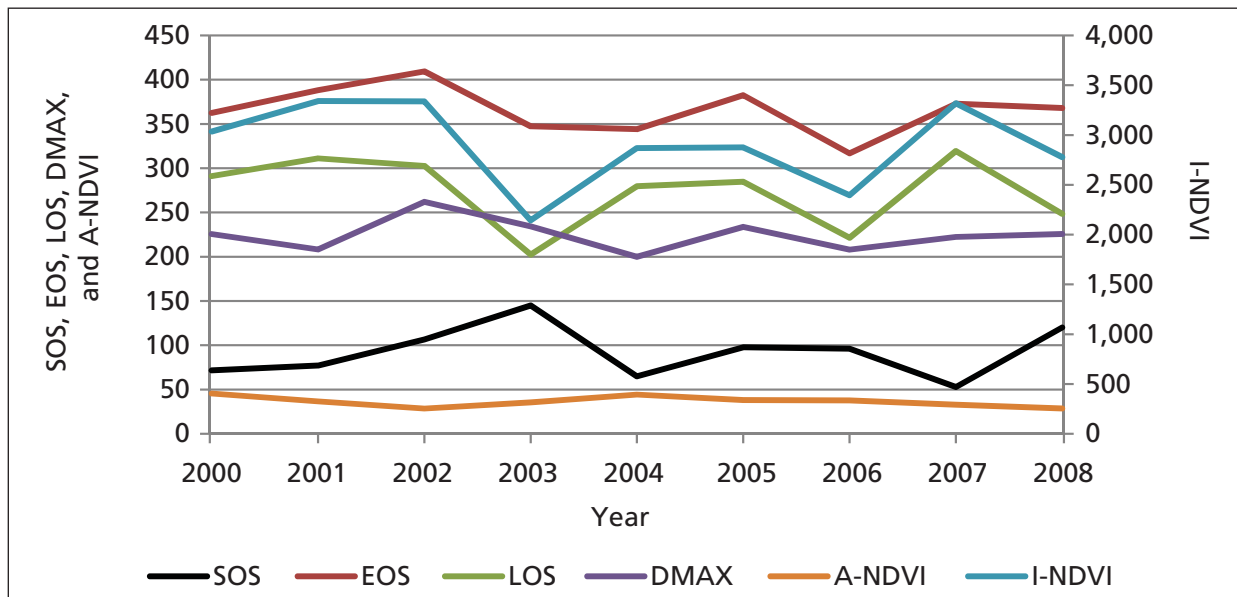


Figure 3.15-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Timpanogos Cave NM. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.15.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Timpanogos Cave NM (Figure 3.15-5a) was highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of the year when snow cover is unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves indicate that years 2004 and 2007 had the most extensive and persistent snow cover (Figure 3.15-5b) and that less park area was snow-covered for less time in 2009 than in the past 10 years (Figure 3.15-5c).

Although water content cannot be directly inferred from snow cover, they are related. The earliest snowmelt occurred in 2000 and 2004, at DOY 104 (April 14), while the latest snowmelt occurred in 2005, at DOY 160 (June 9). It is interesting to note that 2005 also had the latest SOS

in the record, but ranked fourth in productivity as measured by I-NDVI. Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both. The 10-year average snow-free period in the park, defined here as less than 5% coverage, occurred between DOYs 122 (May 2) and 278 (October 5). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.15-3).

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. A weak positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.06$) for the nine years of record (Figure 3.15-6). Stronger relationships may occur at other spatial scales where snowmelt/SOS coupling may be more mechanistic. However, air and soil temperatures are also important to SOS and are expected to contribute to variability in this relationship.

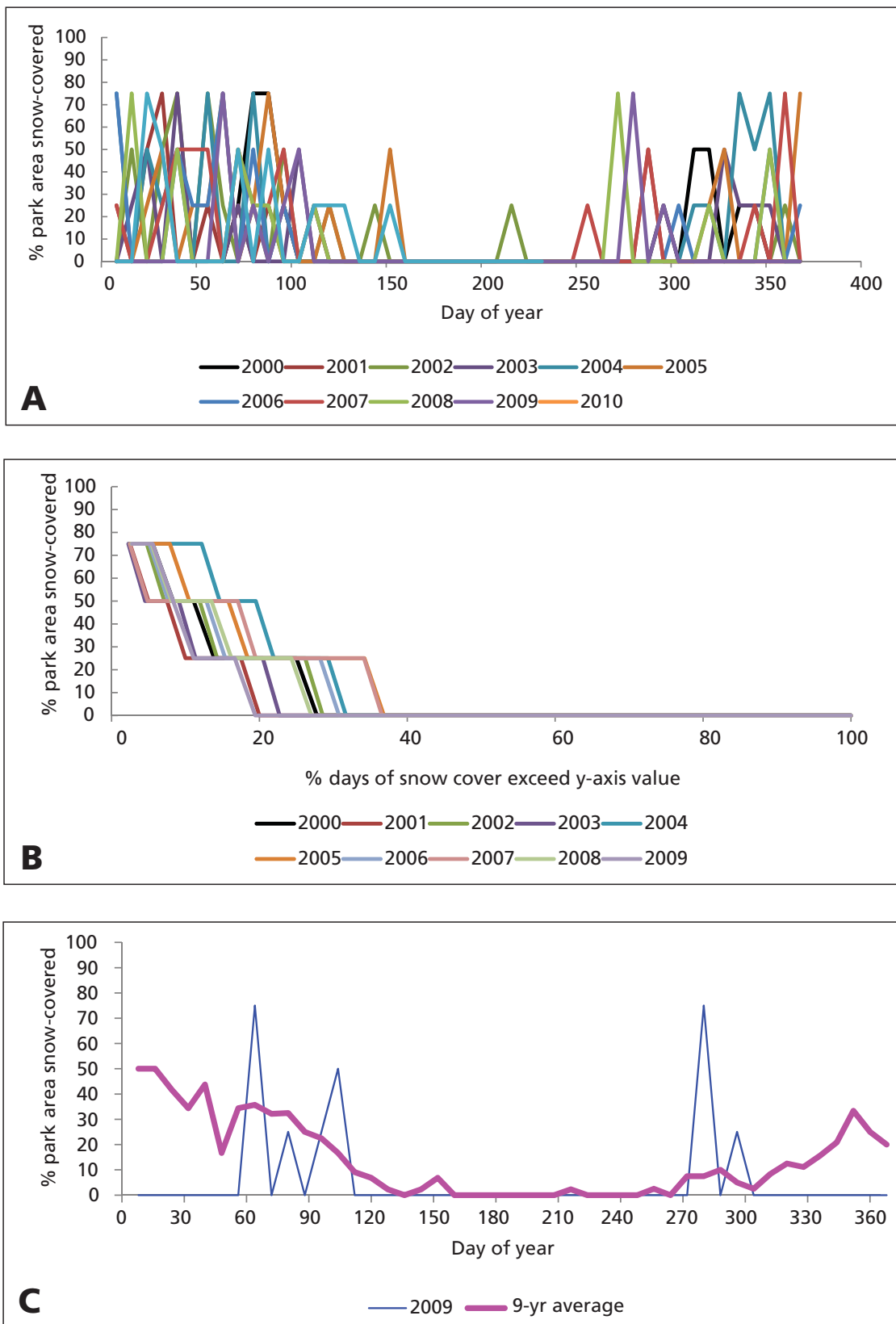


Figure 3.15-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Timpanogos Cave NM.

Table 3.15-3. Timing and duration of snow cover, Timpanogos Cave NM.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	4/13/2000	10/14/2000	104	288	184	181
2001	4/22/2001	10/7/2001	112	280	168	197
2002	6/2/2002	7/28/2002	152	208	56	309
2003	4/24/2003	11/2/2003	112	304	192	173
2004	4/16/2004	11/2/2004	104	304	200	165
2005	6/12/2005	11/11/2005	160	312	152	213
2006	5/4/2006	10/27/2006	120	296	176	189
2007	5/5/2007	9/10/2007	120	248	128	237
2008	5/5/2008	9/26/2008	120	264	144	221
2009	4/28/2009	10/5/2009	112	272	160	205
<i>correlation</i>			0.05	-0.04	-0.05	0.05
<i>slope</i>			0.29	-0.44	-0.73	0.73
<i>p-val slope</i>			0.90	0.91	0.88	0.88
<i>intercept</i>			-462	1152	1614	-1249
<i>p-val intercept</i>			0.92	0.88	0.87	0.90

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

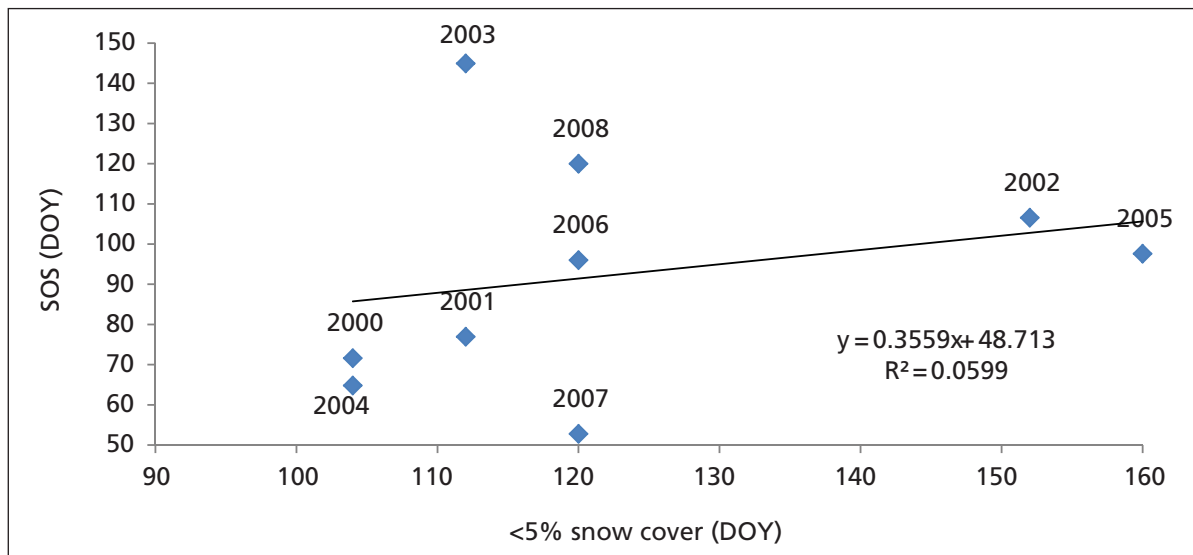


Figure 3.15-6. Relationship between snowmelt DOY and SOS, Timpanogos Cave NM.

3.16 Zion National Park

3.16.1 Historical NDVI conditions

The 10-year continuous record of parkwide mean NDVI, determined on 16-day intervals, illustrated a high degree of both within- and between-year variability in NDVI response to environmental conditions (Figure 3.16-1a). In the 10-year time series, several years (2002 and 2007–2009) were clearly different from most other years. Although Zion NP is influenced by monsoon weather patterns, the monsoon vegetation response at the park scale is more of a “shoulder” than a peak in most years. When annual curves are stacked (Figure 3.16-1b), a more direct year-to-year comparison is possible. Viewed this way, the stacked annual curves illustrate differences in significant growth periods between years that are partly driven by precipitation magnitude and timing (Figure 3.16-1c). The importance of “effective” precipitation that recharges soil moisture prior to important plant phenological stages is clearly shown by the low productivity and strongly bi-modal signature of 2002, in contrast to the high productivity and uni-modal response in 2004 (Figure 3.16-1a). The differences in precipitation abundance and distribution (Figure 3.16-1a, c) may explain this disparity. In 2005, soil moisture storage from the preceding winter period, plus spring precipitation before DOY 128 (May 8), resulted in a large spring peak NDVI. Contrasting with this pattern was 2002, when recharged winter soil moisture was utilized but not replenished after DOY 60 (March 1), resulting in a much smaller NDVI response in spring of that year. Winter soil-moisture recharge, plus spring moisture before and during spring growth, is critically important to early season native vegetation on the Colorado Plateau because it is generally the most reliable (Comstock and Ehleringer 1992), and plant adaptation has evolved to take advantage of this seasonal precipitation.

In June 2006, the Kolob Fire burned approximately 4,255 ha (10,516 acres), and in July 2007, the Dakota Hills fire burned 2,384 ha (5,891 acres) in Zion NP. Together, these fires seem to have affected enough area (11.1% of the park) to impact the parkwide NDVI average every year since (Figure 3.16-1a). The depressed summer peaks after 2006 are interpreted as a reduction in growing season productivity that gradually increased with time, while the depressed winter troughs may be the result of a loss of evergreen cover (pinion/juniper) in the 2007 Dakota Hills fire.

This interpretation is speculative, as similar dips in winter NDVI in heavy snow years have been observed in other NCPN park units (BRCA, BLCA) that did not experience substantial vegetation change. In those cases, it was determined that winter dips were more likely due to the interaction of NDVI trends before snowfall and after snowmelt that forced the smoothing algorithm to interpolate unusually low winter NDVI when NDVI was masked in winter.

Although timing and consistency of precipitation events are clearly important to plant growth, descriptive statistics help to quantify general observations apparent in the annual curves. Year 2002 had the narrowest range in annual maximum and minimum NDVI (7.0) and the lowest maximum NDVI value (138.4) in the record (Table 3.16-1). Immediately preceding the Kolob Fire, the largest maximum value on record was observed in 2006 (NDVI 143.4). The average annual maximum NDVI after the fire was 5.3% less (2.0 NDVI units) than before the fire. The minimum value in 2008 was 3.4% lower than the minimum value in 2007, possibly due to pinion/juniper mortality associated with the Dakota Hills fire. A more focused analysis of just the burned portion of the park and adjacent areas, using ancillary data collected from ground-based fire research, may help further explain some of these observations.

Weather data from the Zion Headquarters NWS Coop station were used to interpret NDVI variation (Figure 3.16-1c, 3.16-2a, b). Although the station data do not represent precipitation conditions uniformly over the entire park, they are informative in evaluating extreme years, when the station generally tracks regional extremes. As previously noted, year 2002 had the narrowest range in NDVI and one of the lowest median NDVIs in the 10-year record (Table 3.16-1, Figure 3.16-2a). This corresponds to the lowest cumulative annual precipitation observed at the station for the same period and, perhaps more importantly, corresponds to one of the lowest cumulative winter soil-moisture recharge periods in the 10-year record (Figure 3.16-1a), preceding spring 2002. Year 2005 received the most cumulative precipitation, but had a higher peak, again indicating the importance of precipitation timing in determining vegetation response. Additional precipitation data for more areas of the park could help further refine the relationship between precipitation magnitude and timing with vegetation response.

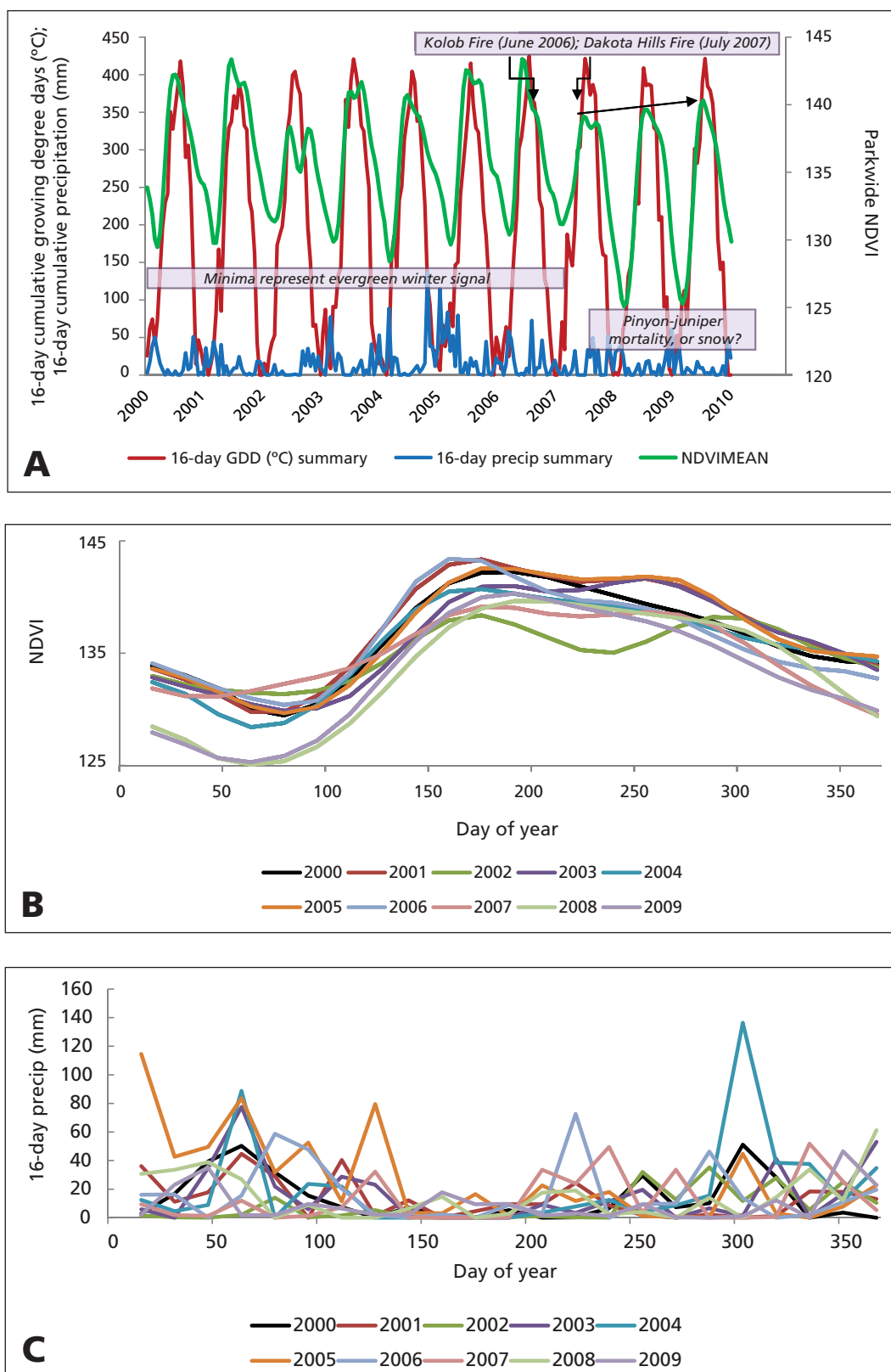


Figure 3.16-1. (a) 10-year parkwide average NDVI time series on 16-day intervals, plotted with 16-day cumulative precipitation and growing degree days from data collected at weather station; (b) Annual NDVI curves stacked for inter-annual comparison; (c) Stacked cumulative precipitation curves for inter-annual comparison, Zion NP.

Table 3.16-1. Annual descriptive statistics for parkwide average NDVI, Zion NP.

Year	Scaled NDVI					Sum
	Mean	Median	Max	Min	Range	
2000	136.35	135.85	142.24	129.46	12.77	3136.12
2001	137.21	137.25	143.36	129.77	13.59	3155.94
2002	135.03	135.28	138.36	131.36	7.01	3105.64
2003	136.24	136.69	141.69	129.87	11.82	3133.61
2004	135.65	136.17	140.72	128.41	12.31	3119.86
2005	136.87	136.23	142.56	129.65	12.91	3147.97
2006	136.26	135.29	143.38	130.39	13.00	3133.98
2007	134.99	135.00	139.13	129.49	9.65	3104.74
2008	133.42	134.69	139.64	125.08	14.55	3068.74
2009	133.20	132.88	140.32	125.28	15.05	3063.66

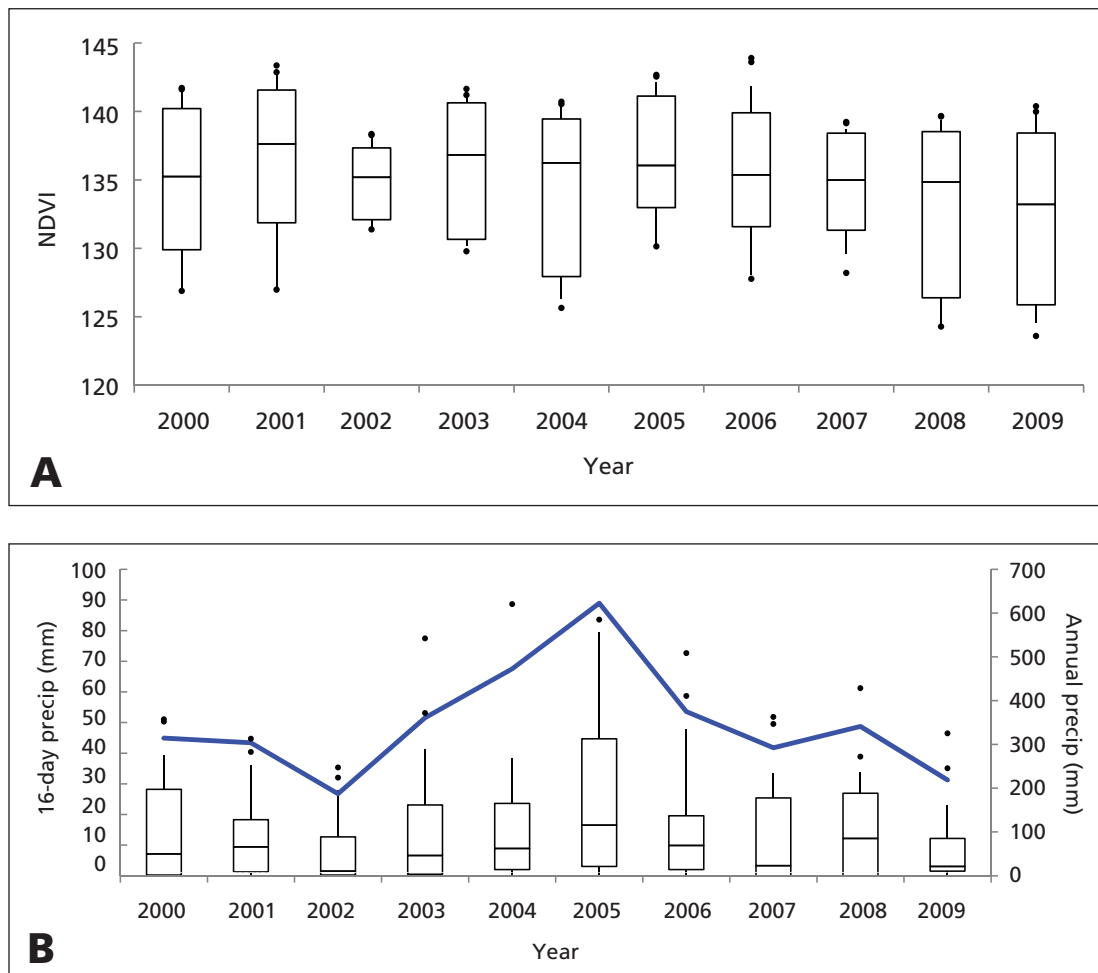


Figure 3.16-2. (a) Annual box plots of NDVI for inter-annual comparison of range, extremes, and central tendency; (b) Annual 16-day cumulative precipitation box plots, with cumulative annual precipitation as blue line, Zion NP.

3.16.2 Recent NDVI conditions

The NDVI curve for 2009 was lower than the historical average at every 16-day interval (Figure 3.16-3a) and 1.7% below average for the year, whereas cumulative precipitation for 2009 was 37.3% below average. The early season NDVI curve was well below average in spite of above-average early spring soil-moisture recharge (Figure 3.16-3b). This may be due to the lingering effects of evergreen removal caused by the Dakota Hills fire that depressed parkwide average NDVI in 2009 relative to the long-term average, or it may be due to snow effects, as winter 2008–2009 was a heavy snow year. Later in 2009, the effect of a failed monsoon was apparent starting at approximately DOY 240 (August 28), when the 2009 NDVI began to steadily drop below the long-term mean of previous years. Data from the Zion Headquarters weather station indicated very little precipitation after DOY 208 (July 27), causing the earliest senescence in the 10-year NDVI record (Figure 3.16-3a).

Monsoon NDVI was below average for extensive areas in Zion NP in 2009, a pattern not limited to any particular geographic location or elevation (Figure 3.16-3c). Below-average NDVI in 2009 was still apparent after the Kolob, Dakota Hills, and Cliff fires. Differential recovery, likely related to burn intensity, was also apparent as differences in anomaly within the burn perimeters. Isolated areas of above-average NDVI occurred in patchy distributions in extreme northern portions of the park. On DOY 304 (October 31), most areas in Zion NP were within -6.9 to -1.5 NDVI units, or between -13.2 and -2.8%, of the long-term average.

3.16.3 Phenology

Over the nine-year historical record, the ranges of SOS, EOS, LOS, and DMAX were 22, 83, 93 and 65 days, respectively. The most productive year, based on I-NDVI, was 2004, while the least productive was 2006 (Table 3.16-2). The productivity rankings are somewhat counterintuitive, considering the relative position of curves for those years compared to 2002 and 2005 in the stacked series (Figure 3.16-1b). Length of growing season, more than peak NDVI magnitude, appears to be the primary determinant of annual productivity rankings. Year 2004 had the longest growing season (301 days), while 2006 had the

shortest (209 days), at 92 days less than 2004. The importance of growing-season length in determining annual productivity is further illustrated by year 2006, which had the largest maximum peak NDVI (143.38; Table 3.16-1) but the lowest productivity (2077). This is true regardless of the reason for growing-season length, be it differences in soil moisture, temperatures suitable for growth, or fires that truncate growing seasons.

There were no statistically significant linear trends (p -value < 0.1) in the phenology metrics, but there was an interesting inflection point in the 2006 phenology (Figure 3.16-4), in which the metrics for EOS, LOS, and I-NDVI were lower than in most preceding years (Figure 3.16-2b), presumably due to the influence of the Kolob fire. The earlier peak (DMAX = DOY 173; June 22) may have reflected a truncated growing season caused by the fire, which started on June 24. The DMAX is a Timesat-derived estimate based on the NDVI curve, which is remarkably close to the day when the fire actually started. Although the Kolob area that burned contained much senescent cheatgrass and pinion/juniper woodland, the park-averaged NDVI was affected by this loss of cover. Consistent with the June 24 timing of the Kolob fire ignition, it is expected that EOS, LOS, and I-NDVI would be affected by late-season change in cover, while SOS would remain unaffected and amplitude little affected, considering the proximity of ignition date with annual peak NDVI. It is not clear why similar effects on phenology were not apparent in 2007, after the Dakota Hills fire; it is possible that parkwide effect on NDVI was mitigated because a smaller area burned and because more consistent precipitation in 2007 supported longer growing-season conditions elsewhere in the park that year, which may have compensated for depressed NDVI in the burned area.

The 10-year MODIS record is too short to determine trends in phenology with confidence, given the observed annual variability and spatial heterogeneity averaged in the parkwide analysis. Presently, the annual phenology metrics do not clearly indicate trends (Table 3.16-2, Figure 3.16-4). A longer data record and more robust statistical techniques may provide early warning of broad-scale change in the future, if it occurs. It is promising for this monitoring that changes in parkwide average NDVI were easily observed after 11.1% of the park area burned.

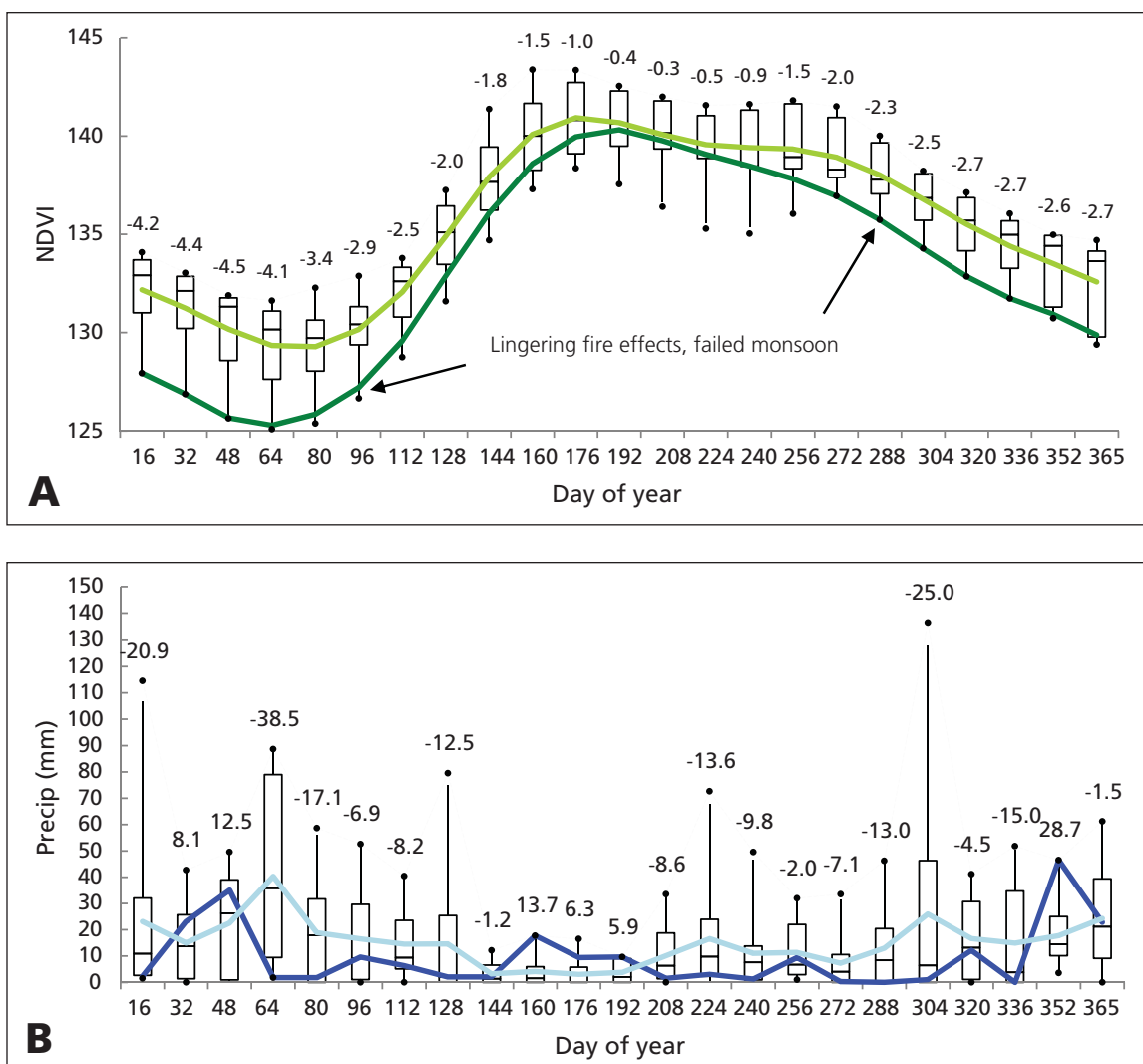


Figure 3.16-3. (a) Day of year NDVI box plots for historical record, with year 2009 annual curve superimposed as a solid dark green line and 10-year average in light green; (b) Day of year cumulative 16-day box plots for historical record, with year 2009 annual curve superimposed as a solid dark blue line and 10-year average in light blue, Zion NP. Numbers above box plots are the difference between 10-year average and 2009 precipitation for each 16-day period.

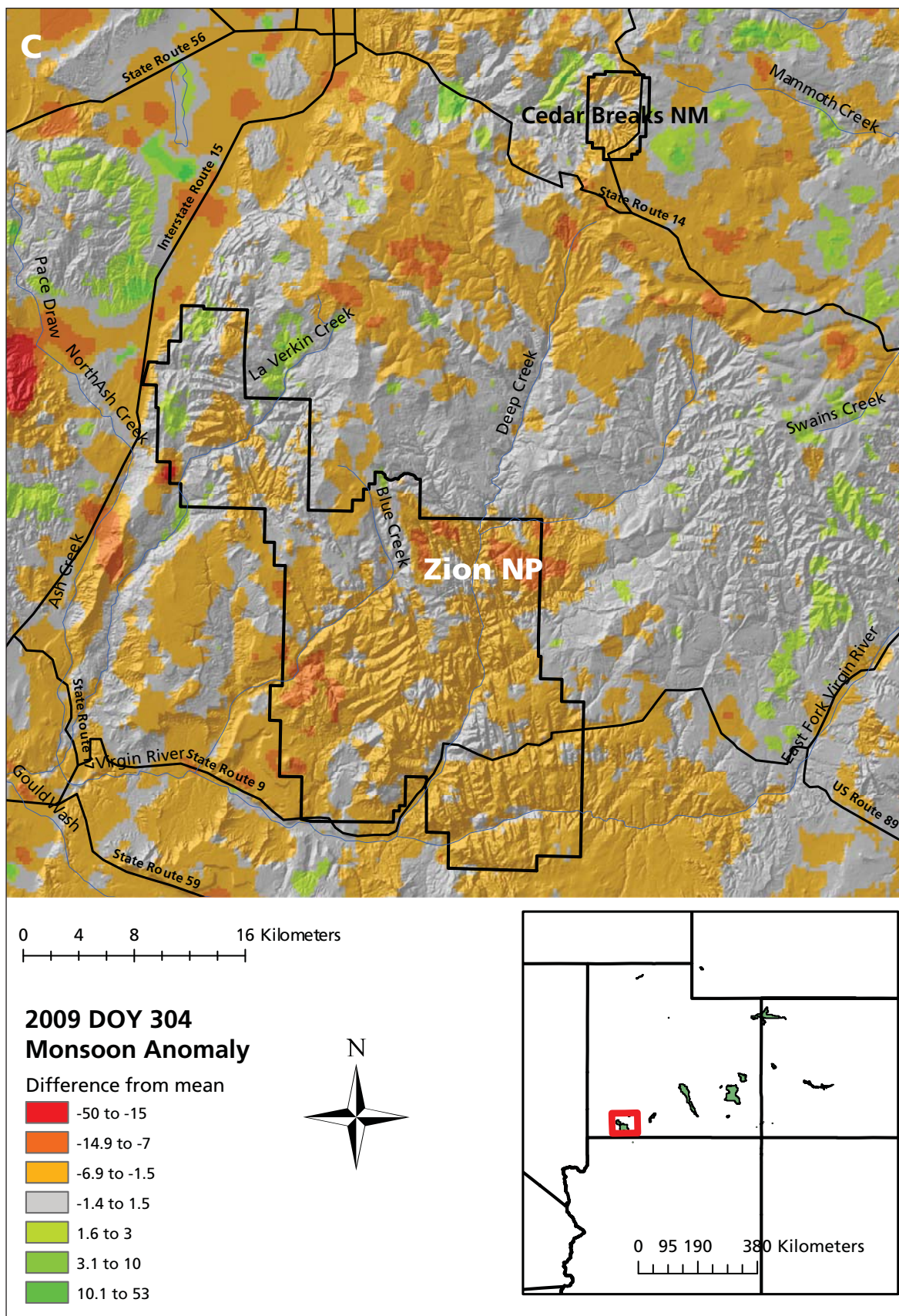


Figure 3.16-3. (c) Regional 2009 anomaly, mapped as 2009 NDVI minus historical average on DOY 304 (October 31), Zion NP.

Table 3.16-2. Phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Zion NP.

Year	DOY			LOS (Days)	I-NDVI	A-NDVI
	SOS	DMAX	EOS			
2000	112	199	396	284	2744	12.60
2001	108	208	361	253	2499	12.69
2002	117	238	401	284	2710	7.64
2003	122	227	393	270	2611	12.34
2004	103	202	405	301	2867	11.62
2005	115	219	394	278	2627	12.52
2006	114	173	322	209	2077	12.55
2007	101	226	382	281	2575	10.99
2008	112	232	374	263	2565	14.47
<i>correlation</i>	-0.23	0.10	-0.31	-0.25	-0.36	0.30
<i>slope</i>	-0.57	0.76	-3.00	-2.42	-28.97	0.21
<i>p-val slope</i>	0.55	0.79	0.41	0.52	0.34	0.43
<i>intercept</i>	1256	-1315	6387	5122	60635	-402
<i>p-val intercept</i>	0.52	0.82	0.38	0.50	0.32	0.44

Metrics were computed with TimeSat using the Savitsky-Golay fitted function and growing season start and end dates as 25% of the maximum amplitude. Statistics derived from linear regression with year as independent variable and phenology metric as dependent variable.

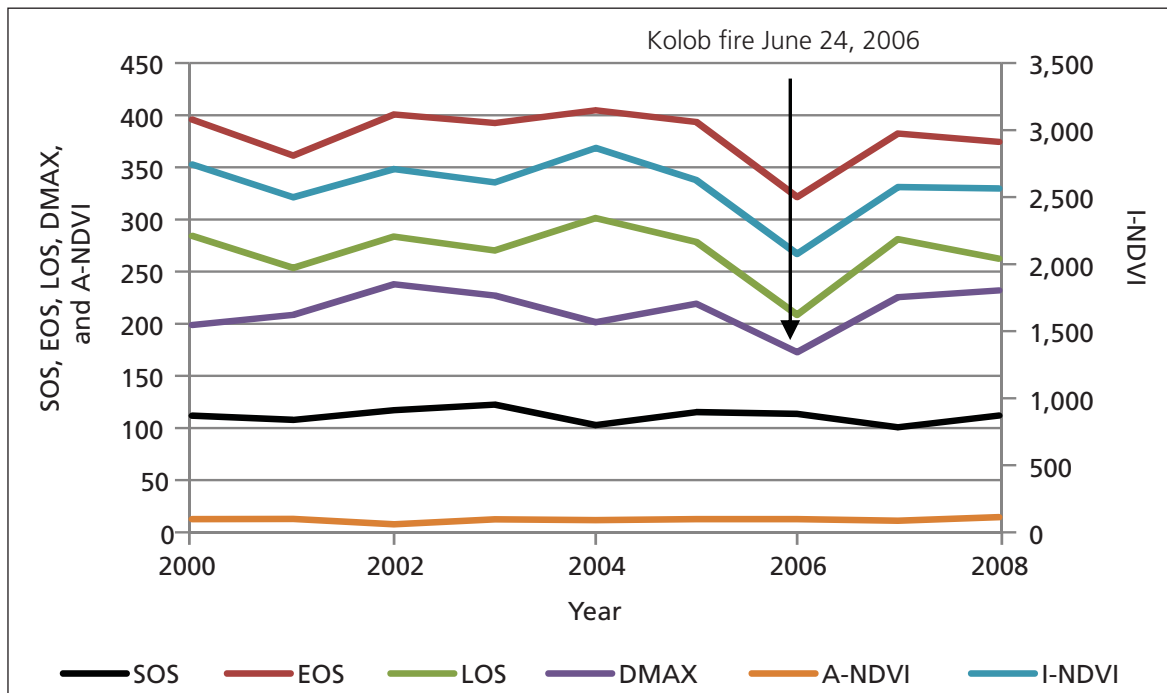


Figure 3.16-4. Annual phenology metrics for SOS, EOS, LOS, DMAX, I-NDVI, and A-NDVI, Zion NP. Metrics were computed with TimeSat for a uni-modal growing season using the Savitsky-Golay fitted function and growing season SOS and EOS as 25% of A-NDVI.

3.16.4 Historical and recent conditions of snow-cover extent

Seasonal snow coverage for Zion NP (Figure 3.16-5a) is highly variable within and between years due to variation in regional weather patterns and abrupt changes in snow-cover extent caused by short-lived “dustings.” There is also noise present, as indicated by occasional spikes during times of year when snow cover is exceedingly unlikely (e.g., between DOYs 150 and 250). Cumulative exceedance frequency curves show that 2001, 2008, and 2009 had the most extensive and persistent snow cover (Figure 3.16-5b). Years 2008 and 2009 had the lowest winter NDVI. Although water content cannot be directly inferred from snow cover, they are related. For example 2002 had one of the earliest snowmelt dates (DOY 88, Table 3.16-3) and one of the least productive spring seasons as measured by NDVI (Figure 3.16-1a). The cumulative exceedance frequency curve for 2002 also indicates that it was a year of less extensive and persistent snow cover. Early snowmelt could be the result of warmer temperatures, less winter snow accumulation, or both. Coupling these data with NRCS Snotel and USGS streamflow data in the watershed could help answer that question.

Because snow is both a physical and thermal barrier against SOS, one might expect there to be a direct relationship between the two, with longer snow cover corresponding to delayed SOS. Earlier snowmelt could result in an earlier SOS, but

snow cover is not the only factor driving SOS, as shown by 2002, which had the earliest snowmelt date but ranked seventh in the record for SOS. Air and soil temperatures are also important to SOS. A weak positive relationship at the parkwide scale exists between snowmelt DOY and SOS ($R^2 = 0.21$) for the period of analysis (Figure 3.16-6). Stronger relationships may occur if analysis is restricted to finer spatial scales and higher elevations where snowmelt/SOS coupling may be more mechanistic.

More of Zion NP was snow-covered in 2009 than in the previous nine years (Figure 3.16-5). However, the available moisture from melting snow in spring 2009, plus rain later in the spring, was not sufficient to raise 2009 productivity to the long-term average (Figure 3.16-1a) because of the suppressed NDVI signal after 2006 (caused by two large fires). In general, years with relatively little snow cover peak earlier but have lower peak NDVI, presumably because less soil moisture is available to support plant growth for longer (see Figure 3.16-1a, 2002 and 2007, for example).

The 10-year average snow-free period in Zion NP, defined here as less than 5% coverage, occurred between DOYs 106 (April 16) and 308 (November 4). There were no statistically significant trends in snow-cover metrics at the park scale for the period of record (Table 3.16-3).

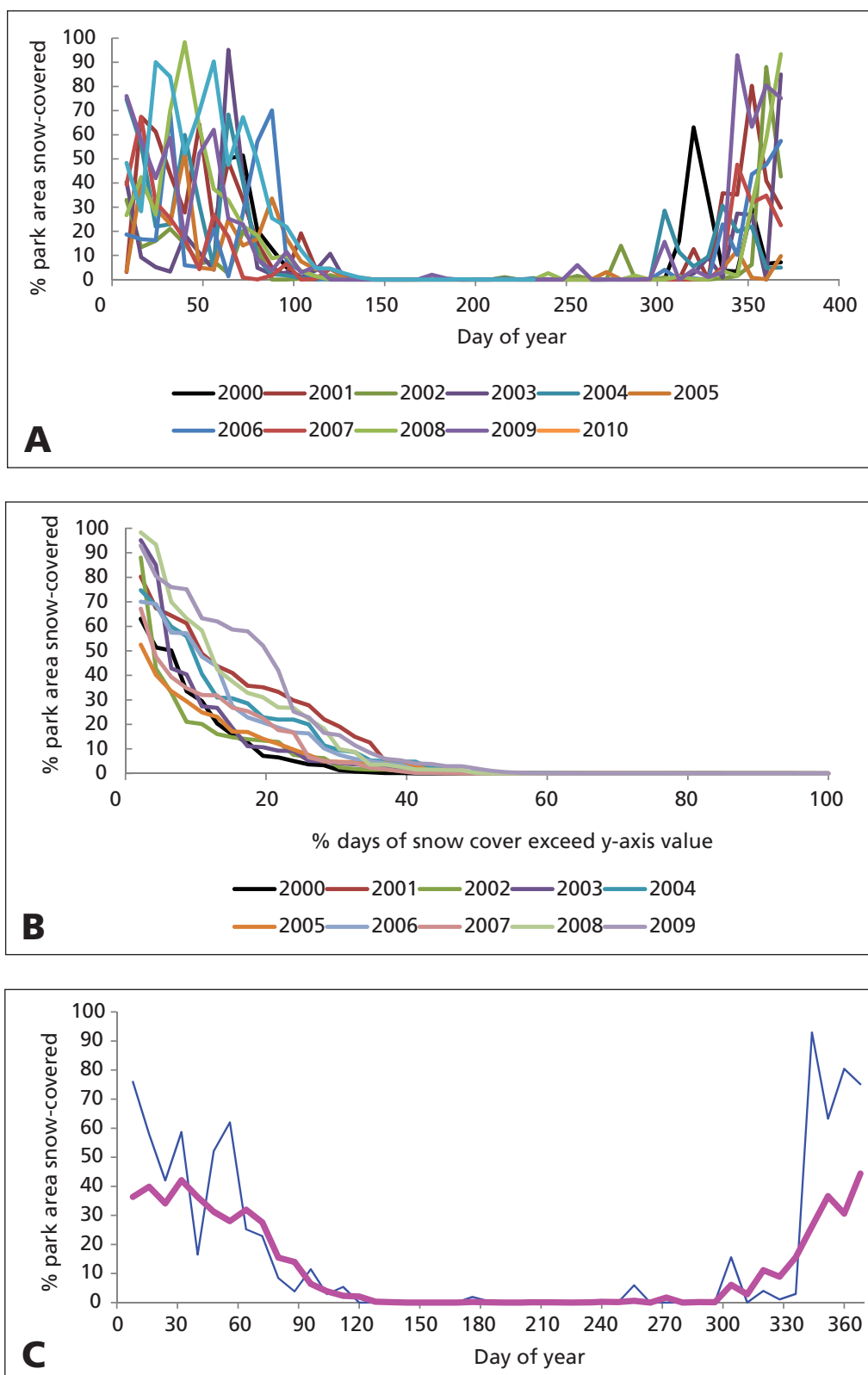


Figure 3.16-5. (a) Time series of parkwide snow-cover extent for 10+ years of snow-cover imagery; (b) annual frequency of days that exceeded a given percent coverage; (c) Snow-cover extent, 2000–2009 (pink), with 2009 snow-cover extent (blue), Zion NP.

Table 3.16-3. Timing and duration of snow cover, Zion NP.

Year	Snow off	Snow on	DOY <5% cover	DOY >5% cover	Days snow-free	Days snow-covered
2000	4/13/2000	10/30/2000	112	304	200	165
2001	4/22/2001	11/8/2001	112	312	200	165
2002	3/30/2002	9/30/2002	88	272	184	181
2003	5/10/2003	11/18/2003	128	320	192	173
2004	3/31/2004	10/25/2004	88	296	208	157
2005	4/25/2005	12/5/2005	112	336	224	141
2006	4/18/2006	11/28/2006	104	328	224	141
2007	4/19/2007	11/29/2007	104	328	224	141
2008	4/19/2008	12/15/2008	104	344	240	125
2009	5/6/2009	9/11/2009	120	248	128	237
<i>correlation</i>			0.18	0.04	-0.03	0.03
<i>slope</i>			0.73	0.39	-0.34	0.34
<i>p-val slope</i>			0.63	0.91	0.93	0.93
<i>intercept</i>			-1351	-469	883	-518
<i>p-val intercept</i>			0.65	0.95	0.91	0.95

Statistics were derived from linear regression with year as independent variable and DOY or days as dependent variable.

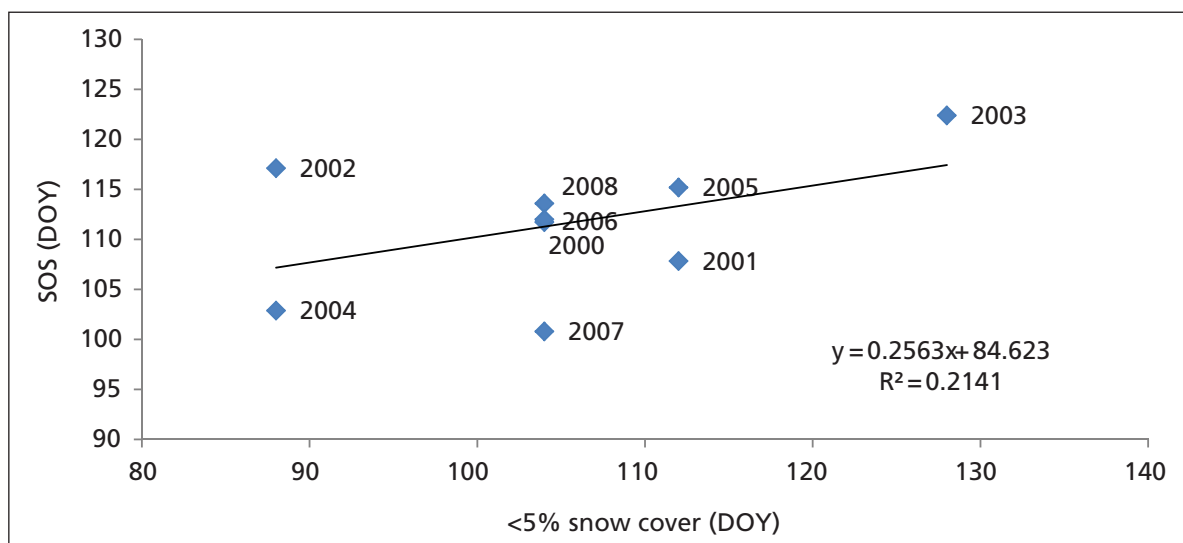


Figure 3.16-6. Relationship between snowmelt DOY and SOS, Zion NP.

4 Discussion

This work represents the first attempt to evaluate vegetation condition using MODIS satellite products for national parks on the Northern Colorado Plateau. It combined measures of vegetation condition with snow extent and weather station data to aid interpretation of causal relationships that will help managers to understand fundamental physical drivers and biological response at landscape scales.

Important insights into vegetation condition and response on the Colorado Plateau have been gained through this analysis of 16 NCPN parks representing enormous variation in size, elevation, latitude, precipitation regime, geology, and soils. Most of these insights and relationships were expected, but they can now be quantified for use in management applications, such as scenario planning, that may require an understanding of processes at broad spatial scales beyond park boundaries and over long temporal scales. Additionally, these analyses provide a broad context for understanding processes occurring at finer spatial scales, such as those measured by other vital signs protocols. As a starting point for further work in land condition monitoring, several conclusions can be drawn at this stage that lead to potential management applications.

4.1 Generalizations

The data and analysis presented in this report support several generalized conclusions:

- 1) Using the Timesat algorithms, annual productivity is more strongly correlated with length of growing season than either maximum NDVI or annual NDVI sum in these parks.
- 2) Some years showed a north/south latitudinal gradient in productivity across the Colorado Plateau that may correspond with monsoon storm tracks (Dinosaur NM).
- 3) Cumulative precipitation and vegetation productivity in 2009 were below the 10-year average for most NCPN parks except for the northern group (Fossil Butte NM, Golden Spike NHS, and Timpanogos Cave NM), where productivity was above the 10-year average.
- 4) Even distribution of precipitation through time is a more important determinant of productivity than cumulative annual precipitation (Arches NP, Bryce Canyon NP, Capitol Reef NP).
- 5) Winter soil-moisture recharge *and* spring precipitation are required for abundant spring growth in lower-elevation parks (Arches NP, Canyonlands NP, Capitol Reef).
- 6) There may be a direct relationship between snow extent and start of season at higher elevations (Cedar Breaks NM, Black Canyon of the Gunnison NP).
- 7) At park scales, interannual variability in phenology metrics is large relative to trends that may be climate-related for the 10-year MODIS record (Golden Spike NHS, Hovenweep NM).
- 8) Smaller analysis scales dramatically increase variability of NDVI signal in low-productivity environments (Pipe Spring NM, Timpanogos Cave NM, Golden Spike NHS).
- 9) Anomaly mapping is an effective tool for determining extent and severity of fire and subsequent recovery processes (Bryce Canyon NP, Zion NP) and may be sensitive enough to monitor other kinds of disturbance, such as beetle kill in pine forests, noxious weed invasions, and tamarisk defoliation in riparian areas (Cedar Breaks NM, Golden Spike NHS, Canyonlands NP).
- 10) Seasonality is generally bi-modal at lower elevations and latitudes (Capitol Reef NP, Canyonlands NP, Arches NP, Colorado NM) and uni-modal at higher elevations and latitudes (Cedar Breaks NM, Fossil Butte NM, Curecanti NRA) on the Colorado Plateau. Depending on elevation and vegetation, some parks may have areas that are both bi-modal and uni-modal (Canyonlands NP, Capitol Reef NP, Zion NP).

4.2 Potential management applications

Park managers may use the data and analysis presented in this report in numerous ways. For instance:

- 1) After the relationships between precipitation timing, temperature, and vegetation response are refined via lagged regression at plot scale near weather stations and regionally with gridded weather data, these relationships may be used in scenario planning for climate change.
- 2) Spatial and temporal patterns of vegetation productivity may be determined across landscapes of interest. (Park scales are not typically the best scales for analysis.)
- 3) Species (mammal, bird, plants) population distributions may be evaluated spatially and temporally with vegetation condition to answer a variety of questions, including whether productive vegetation years correlate with productive years for species of interest.
- 4) Fire severity and recovery may be evaluated by examining time-series NDVI for burned polygons.
- 5) NDVI may be correlated with biomass for fire management planning purposes.
- 6) Relationships between NDVI and fire effects plot data may be determined.
- 7) Grazing effects may be investigated by comparing grazed and ungrazed ecosites.
- 8) Beetle-kill timing, expansion, and severity may be evaluated in riparian areas along big rivers and in high-elevation pine forests.
- 9) Exotic weed infestation may be tracked based on phenology.
- 10) Watershed-scale vegetation condition may be correlated with stream and spring hydrology.
- 11) Relationships between snowmelt, weather, and dust may be determined at regional scales using gridded climate data and air quality station data.
- 12) Changes in phenology metrics may be tracked and used to interpret upland vital signs results as monitoring continues.

4.3 Trends

Few statistically significant trends in time were apparent in the phenology and snowmelt data, and those that were detected may have been the product of “step-trends” in which, for instance, early years of low value and later years of high value clump together. This kind of scenario is expected within the context of the quasi-periodic climate cycles that drive vegetation response and snow-cover extent. A powerful and globally important driver of weather cycles is the El Niño/Southern Oscillation (ENSO), which demonstrates periodic cycles that can affect continental weather (Wolter and Timlin 2011). A time-series longer than the 10-year MODIS record would be necessary to characterize trends in cycles that have interannual variability. For these reasons, the temporal trends in the annual phenology metrics should be viewed more as a demonstration of capability that may be more definitive in the future, with a longer record of observation.

The strong relationships between climate variables and NDVI are clear in many of the figures presented in this report. Spatial trends across landscapes, and relationships between climate variables and NDVI and snow extent, may hold promise for park managers by quantitatively demonstrating the quantitative relationship between ecosystem drivers and response. These lines of inquiry will likely be informative at multiple scales and can be investigated immediately.

Continued monitoring using the relatively short, 10-year MODIS data products over a longer period of time and at different spatial extents may show trends, if they occur. MODIS certainly is capable of quantifying short-term variability and change, which are important to resource managers. However, data products from the Landsat or AVHRR (Advanced Very High Resolution Radiometer) programs afford a much longer period of record for trend assessments and may provide insight to trends not yet apparent using the shorter MODIS data record. Combining results from multiple viewing platforms may provide the best insight into trends that may persist within variable and cyclic patterns.

4.4 Challenges

4.4.1 Scale

Low-productivity environments at low and high elevations pose a serious problem in remote sens-

ing of vegetation condition. The weak vegetation signal relative to background, combined with inherent issues of measurement sensitivity from a satellite platform, result in temporal variation of the signal that may not be caused by vegetation changes. Spatial and temporal averaging can mitigate this issue to some degree, but performing spatial averaging on pixels that are already coarse may result in analysis extents that are broader than those of management interest, and may compound extant issues by including contrasting landscapes. More work in this area is needed to determine appropriate spatial scales for analysis (Thoma et al. 2008). Discussion with park staff and further analyses can help refine the optimum balance between target heterogeneity and analysis extent.

4.4.2 Phenology

Phenology metrics from satellite sensors are derived from algorithms that attempt to define when significant vegetation change takes place (de Beurs and Henebry 2010; Eklundh and Jönsson 2009). Their performance has been evaluated for different regions and they vary widely in their results (White et al. 2009). The Timesat methodology employed in this report is one of many, and others could be evaluated for use on the Colorado Plateau. There may be justification for using different algorithms for different landscapes on the Plateau, as some respond more realistically to seasonality or phenology observed in ground-based observations than others. Amplitude thresholds for SOS and EOS can be selected independently and arbitrarily, or can be refined in the future if ground phenology observations are made to provide a reference.

Similarly, there may be opportunities to improve the snow “phenology” algorithm and metrics by coupling satellite observations of snow-cover extent with snow depth and water content from point-based observations and regional models.

4.4.3 Image products, processing, and continuity

The image products analyzed in this report (MOD13Q1 for NDVI and MOD10A1 for snow-cover extent) are the result of team efforts to systematically ensure delivery of quality-controlled imagery usable in scientific investigations. There are, however, alternative image products that could be used, such as the MODIS Enhanced Vegetation Index (EVI), which is similar to NDVI

except that EVI uses blue-band reflectance, which may minimize background effects in arid environments and signal saturation in highly productive environments (Huete et al. 2002; Chen et al. 2006).

Image processing followed the unpublished draft USGS protocol developed for the NCPN and Southern Colorado Plateau Network. However, there are other image-processing techniques that handle winter snow cover conditions in NDVI imagery by using thermal bands to mask winter conditions, rather than optical bands that sense snow (Carroll et al. 2004; Gao et al. 2008). Use of these products could be investigated.

As with most monitoring programs, there are trade-offs between refinements in methodology and delivery of useful information. Because the mission of the NPS Inventory and Monitoring Program is to deliver the best available science for management applications, rather than the “best possible science” in the pure sense, it was considered reasonable to provide analysis at the park scale at this first stage of reporting. In the future, different spatial scales may be chosen for analysis, depending on management needs. As satellites and sensors degrade over time, new sensors will be launched to extend Earth-observation capability into the future. However, there will always be improvements in sensor technology, image processing, and algorithms used to analyze data that will require careful attention to continuity. With this caveat in mind, it will be possible to “merge” results from different sensors forward and—just as importantly—backward in time to improve our ability to detect change when and where it occurs.

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