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Trend and climatic sensitivity of vegetation phenology in semiarid and arid ecosystems in the US Great Basin during 1982–2011

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Abstract

We quantified the temporal trend and climatic sensitivity of vegetation phenology in dryland ecosystems in the US Great Basin during 1982–2011. Our results indicated that vegetation greenness in the Great Basin increased significantly during the study period, and this positive trend occurred in autumn but not spring and summer. Spatially, increases in vegetation greenness were more apparent in the northwestern, southeastern, and eastern Great Basin but less apparent in the central and southwestern Great Basin. In addition, the start of growing season (SOS) was not advanced while the end of growing season (EOS) was delayed significantly at a rate of 3.0 days per decade during the study period. The significant delay in EOS and lack of earlier leaf onset caused growing season length (GSL) to increase at a rate of 3.0 days per decade during 1982–2011. Interestingly, we found that the variation of mean vegetation greenness in the period of March to November (SSA) was not significantly correlated with its mean surface air temperature but was strongly correlated with its total precipitation. Seasonally, the variation of mean vegetation greenness in spring, summer, and autumn was mainly attributable to changes in pre-season precipitation in winter and spring. Nevertheless, climate warming played a strong role in extending GSL that in turn resulted in the upward trend in mean vegetation greenness during 1982–2011. Overall, our results suggested that changes in wintertime and springtime precipitation played a stronger role than temperature in affecting the interannual variability of vegetation greenness while climate warming was mainly responsible for the 30-year upward trend in the magnitudes of mean vegetation greenness in the dryland ecosystems during 1982–2011.

1 Introduction

Shifts in plant phenology (e.g., greenness and spring leaf onset) resulting from anthropogenic climate change can affect the cycling of carbon, water, and energy between the

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biosphere and atmosphere (Wu and Liu, 2013), the availability of biotic (e.g., forests) and abiotic (e.g., water) resources (White and Nemani, 2011), and the best practices for managing these resources for production of fiber and food to sustain human life (Butt et al., 2011). Quantifying the spatiotemporal dynamics of plants phenology – such as long-term trend in vegetation greenness, the start of growing season (SOS), end of growing season (EOS), and growing season length (GSL) – and their climatic sensitivity can enable us to assess climate change impacts on terrestrial vegetation dynamics (Soudani et al., 2011) and ecosystem biogeochemistry (Brown et al., 2010). Consequent information in turn has important implications for more accurate prediction of terrestrial water, carbon, and nutrient cycles in Earth system, climate, and ecosystem models (e.g., Piao et al., 2011).

Existing phenological studies mostly focus on regions with low evergreen cover such as temperate deciduous forests (e.g., Nagai et al., 2010) or where terrestrial ecosystems may be particularly sensitive to climate warming such as boreal and arctic regions (e.g., Zhang et al., 2011). A few studies have focused on quantifying plant phenological responses in semiarid and arid (hereafter dryland) ecosystems to climate variability and recent climate warming (e.g., Bradley and Mustard, 2008; Zhang et al., 2010; Fensholt et al., 2011). Although terrestrial carbon sequestration was considered to be relatively low in dryland ecosystems, these ecosystems cover almost 40 % of Earth's land area (UNDP/UNSO, 1997) and account for nearly 20 % of the global soil carbon pool (Field et al., 1998; Lal, 2004). They also may be buffering anthropogenic CO₂ rise more than expected (Jasoni et al., 2005; Wohlfahrt et al., 2008) and particularly sensitive to both climatic variation and increasing atmospheric CO₂ concentrations (Notaro et al., 2011). Hence, quantification of the responses of dryland plant phenology to climate variability at the regional scale is needed to improve forecasting of shifts in ecosystem functioning and consequences for ecosystem services that drylands provide.

Furthermore, climate warming has been widely accepted as the major driver responsible for the general increase in vegetation greenness, the earlier SOS, the delayed EOS, and the extension of GSL that have occurred in the Northern Hemisphere

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during the past few decades (e.g., Piao et al., 2011; Hmimina et al., 2013). These findings, though, mainly apply to mesic ecosystems where water is often not limiting for vegetation growth. In dryland ecosystems, water is scarce and the availability of water strongly controls plant seed germination, growth, and reproduction (e.g., Bradley and Mustard, 2005). Although some studies indicated that precipitation plays an important role in affecting vegetation greenness (e.g., Wu and Liu, 2013) and SOS (e.g., Cong et al., 2013) in temperate deserts, it is still unclear if the role of precipitation is as strong as or even stronger than that of temperature in controlling some aspects of plant phenological dynamics in dryland ecosystems. Improved understanding of the role of precipitation in affecting or controlling plant phenology in dryland ecosystems is critical for accurate quantification of terrestrial carbon, water, and plant community dynamics under changing climatic conditions.

Therefore, the objectives of this study were to utilize the dryland ecosystems at lower elevation zones of the US Great Basin (Fig. 1) to (i) quantify long-term trends in mean vegetation greenness (represented by Normalized Difference Vegetation Index (NDVI)), SOS, EOS, and GSL in the dryland ecosystems that may have occurred during the most recent 30 years of climate warming, and (ii) explore the spatial variation and climatic sensitivity of vegetation phenology in the study region. To meet these objectives, we utilized satellite-based NDVI data because they enable us to quantify the synoptic and landscape pattern of vegetation phenology (White et al., 2009) as well as its long-term temporal dynamics (Studer et al., 2007). Time series of weather records (temperatures and precipitation) were used to analyze climatic sensitivities of vegetation phenology in the study region.

2 Materials and methods

2.1 Study region

The Great Basin is located in the western US and encompasses the majority of Nevada (NV), western Utah (UT), and parts of California (CA), Oregon (OR), Idaho (ID), Montana (MT), and Arizona (AZ) (Fig. 1a). It is bordered by the Sierra Nevada Range on the west, the Rocky Mountains on the east, the Columbia Plateau to the north, and the Mojave and Sonoran deserts to the south. The hydrographically defined Great Basin includes the northern Mojave Desert (Grayson, 2011). Lying in the rain shadow of the Sierra Nevada mountain range, the Great Basin is the driest region in the US and experiences extremes of weather and climate that are not normally found elsewhere in the US (Houghton et al., 1975). Most precipitation falls in the winter. Climate conditions inside the Great Basin vary by elevation and latitude, and most of the Basin experiences a semiarid or arid climate with warm summers and cold winters.

Land cover types in the Great Basin are diverse because of topographic and local climatic heterogeneity. The predominant flora in the Great Basin consist of shrubs such as *Artemesia tridentata* (sagebrush), *Ericameria nauseosa* (rabbit brush), *Sarcobatus vermiculatus* (greasewood); grasses such as *Achnatherum hymenoides* (Indian rice grass), *Bouteloua curtipendula* (Sideoats grama); evergreen trees such as *Pinus monophylla* (pinyon pine) and *Juniperus osteosperma* (Utah juniper); as well as invasive species including *Bromus tectorum* (cheatgrass). In contrast to shrubs and grasses that are mostly present in valleys, evergreens are mainly located in mountain ranges and at higher elevations. Because evergreen forests have little or even no visible leaf seasonal cycle (Botta et al., 2000), they were excluded from this study (see below).

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2.2 Satellite-based vegetation indices and data processing

We used the global inventory monitoring and modeling studies (GIMMS) NDVI data to examine the long-term trends in vegetation greenness and phenology. The GIMMS NDVI data used in this study were derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) series satellites (NOAA 7, 9, 11, and 14) and span from January 1982 to December 2011 (Tucker et al., 2005). These data are at bi-weekly temporal and 8 km spatial resolution. The GIMMS NDVI data were corrected to remove known non-vegetation effects caused by sensor degradation, clouds, and stratospheric aerosols loading from volcanic eruptions (Tucker et al., 2005). The GIMMS NDVI data have been widely used to quantify long-term trends in vegetation phenology and its relationships to climatic variability at global and continental scales (e.g., Brown et al., 2010; Zhang et al., 2010; Cong et al., 2013). Given snow cover can affect NDVI values, our analysis excluded winter (December, January and February) and only considered the period of March to November (i.e., spring, summer and autumn and hereafter SSA).

To accurately quantify how vegetation phenology in the Great Basin may have changed and responded to climate change during the study period, we refined our study areas based on the Global Land Cover Facility (GLCF) 8 km land cover data (Hansen et al., 2000) and the National Land Cover Database (NLCD) 2001 (Homer et al., 2007). We first excluded areas where evergreen trees predominated in both GLCF and NLCD 2001. In addition, we excluded lakes, urban areas, and cultivated lands defined in either GLCF or NLCD 2001, the phenology of which depends largely on management practices (i.e., irrigation) and crop types. As a result, only lands where shrubs/grasses were predominant in both GLCF and NLCD 2001 (Fig. S1 in Supplement) were considered. Finally, we excluded areas located at relatively high elevation (> 2100 m), and only selected those at lower elevation (< 2100 m; areas where over 85% of shrubs and grasses are located according to GLCF data) for analysis (Fig. S1). Figure 1b shows the distribution of NDVI points considered in this study.

2.3 Weather data and processing

We generally followed the same procedure of acquiring and processing weather data as described in Tang and Arnone (2013). Briefly, we collected time series of daily minimum and maximum temperatures as well as total precipitation from 126 weather stations that are or were historically located within the Great Basin. These stations included the Cooperative Observer Program Stations (COOP), the Remote Automated Weather Stations (RAWS), the SNOwpack TELemetry (SNOTEL) weather stations, and Nevada Test Site (NTS) stations (Fig. 1a). The selection of 126 stations was based on two criteria: first, selected stations had to have at least 24 years of records (80 % of coverage) for each of 12 months during the period of interest in this study; second, selected stations had to be located near selected NDVI points (Fig. 1b). Stations located inside developed areas (e.g., residential), and cultivated land or near urban areas/cities were excluded to maximize the accuracy of climatic sensitivity analysis of vegetation phenology.

In addition, for each of the selected stations during the period of interest, daily weather records that exceeded the long-term (1982–2011) mean of all available records from that station by four standard deviations (for temperature) or greater than 500 mm (for precipitation) were manually checked or removed on a case-by-case basis (Tang and Arnone, 2013). We plotted and visually compared derived time series of monthly minimum and maximum temperatures at each station with those from neighboring stations to further check data inhomogeneity (e.g., Peterson et al., 1998). Daily mean temperature for each station and each day was calculated as the mean of recorded daily minimum and maximum temperatures. Based on these daily values, we calculated mean temperatures for each month, season, and SSA. We used daily total precipitation values from each station to calculate precipitation sums for each month, season and SSA at each of the selected stations.

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2.4 Characterization of temporal dynamics and climatic sensitivities of plant phenology

To quantify long-term trends in vegetation greenness, SOS, EOS, and GSL, we first interpolated the bi-weekly series GIMMS NDVI data for all points considered in this study into daily time-step values using a cubic spline interpolation approach. Based on interpolated daily NDVI values, we followed the midpoint-pixel method (White et al., 2009) to define SOS, EOS, and GSL for each NDVI point (Fig. 1b). Instead of using a global threshold, the midpoint-pixel approach uses a locally tuned NDVI threshold to define SOS. This metric has been demonstrated (e.g., White et al., 2009) and also initially tested (see below for detail) to be suitable for semiarid and arid regions. In the midpoint-pixel approach, the state of the ecosystem is indexed by transforming the NDVI to a 0 to 1 $NDVI_{ratio}$ as:

$$NDVI_{ratio} = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (1)$$

where NDVI is the interpolated daily NDVI value in a year; and $NDVI_{max}$ and $NDVI_{min}$ are the maximum and minimum of the NDVI curve. Thus, SOS can be defined as the day of year when a $NDVI_{ratio}$ of 0.5 is exceeded because the 0.5 value is often considered to correspond to timing of the most rapid increase in NDVI or to the initial leafing of the overstory canopy (White et al., 2009). In our study, we defined SOS as the date in a year when the daily $NDVI_{ratio}$ becomes greater than 0.5 for six consecutive days in ascending order, and EOS as the date in a year when the daily $NDVI_{ratio}$ becomes less than 0.5 for six consecutive days in descending order. Annual GSL was calculated as the difference between EOS and SOS. Our initial comparison of SOS based on the midpoint-pixel method with that based on observed breaking leaf buds data (USA National Phenology Network (USA-NPN), 2010) for the study region justified the suitability of this metric in the study region (Fig. S2).

We used the nonparametric Kendall's tau (τ) based slope estimator (Sen, 1968) to compute long-term trends in four phenological indices: vegetation greenness, SOS,

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EOS, and GSL – largely because this method does not assume a distribution for residuals and is insensitive to the effect of outliers in time-series data. The two-tailed P values at the 95 % (significant) or 90 % (marginal significant) confidence levels were used to test the significance of trends. We followed the same procedure described in Tang and Arnone (2013) to calculate a single value for each phenological index for the entire Basin. Briefly, we first divided the basin into $1.34^\circ \times 1.34^\circ$ boxes to make a total of 37 boxes, each of which (except one) contained at least one weather station (Fig. 1a). We calculated anomalies for each index for each month, season, and SSA at each location (e.g., a NDVI point) against its 30-year arithmetic mean, respectively. We then averaged all anomalies within a box to obtain the box anomaly for each index for each month, season, and SSA. Finally, the resultant box anomalies for each index are averaged to obtain its Basin-wide average. The goal of using this approach was to minimize effects of clustered points on the Basin-wide averaged values for each month, season, and SSA. The above approaches also were applied to temperature and precipitation indices.

We analyzed the sensitivity of vegetation phenology to changes in temperature and precipitation through the univariate linear regression approach largely because temperature and precipitation correlate/interact with each other. The Akaike Information Criterion (AIC; Akaike, 1974) was used to determine the goodness fit of a univariate linear regression model. In addition, we used the metric proposed by Lindeman, Merenda and Gold (LMG; Grömping, 2006) to quantify the relative importance of temperature and precipitation in controlling vegetation phenology in the study region. The LMG metric considers both the direct effects of an independent variable (e.g., temperature) on a dependent variable (e.g., greenness) and its indirect effects adjusted by other independent variables (e.g., precipitation) in a multivariate regression model and thus is suitable for analyzing the contribution of variation in temperature or precipitation to variations in vegetation phenology.

3 Results

3.1 Long-term trends in vegetation greenness and corresponding climatic conditions

When averaged for the period of March to November (i.e., SSA), both mean NDVI and mean surface air temperature in SSA in the dryland ecosystems increased significantly during the period 1982–2011 (Fig. 2a and b) while total precipitation in SSA showed no significant trend during the study period (Fig. 2c). The rate of increase was about 5×10^{-4} ($p < 0.04$) units per year in NDVI and 0.2°C ($p < 0.09$) per decade in temperature during 1982–2011. Although mean NDVI in SSA increased during the 1982–2011 period, this long-term positive trend contained shorter periods of increases or decreases in NDVI (Fig. 2a). For example, mean NDVI in SSA decreased significantly ($p < 0.01$) from 1986 to 1992 and then increased significantly ($p < 0.01$) from 1992 to 1998 (Fig. 2a). Similarly, the long-term positive trend in mean surface air temperature and no trend in total precipitation in SSA also comprised shorter periods of increases or decreases (Fig. 2b and c).

Seasonally, seasonal mean vegetation greenness in autumn (Fig. 3c) increased significantly ($p < 0.01$) while greenness in spring and summer (Fig. 3a and b) had no significant ($p > 0.13$) trend during the 1982–2011 period. Seasonal mean temperature in spring and autumn (Fig. 3d and f) showed no significant ($p > 0.19$) trend while seasonal mean temperature in summer (Fig. 3e) increased significantly ($p < 0.02$) during the period 1982–2011. Compared to seasonal mean temperatures, seasonal total precipitation in spring, summer and autumn had no significant trend ($p > 0.13$) from 1982 to 2011 (Fig. 3g, h and i).

The seasonality of NDVI, temperature, and precipitation also varied at different time intervals during 1982–2011. For example, mean springtime NDVI decreased from 1986 to 1992 (Fig. 3a) whereas mean autumn NDVI increased from 1992 to 1998 (Fig. 3c). In addition, although summertime NDVI showed no significant trend during the period

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during 1982–2011 (Fig. 4c), and most of these points were concentrated in the southern and southwestern Great Basin (Fig. 4c) and near the eastern side of the Sierra Nevada mountains. Autumn mean NDVI increased in 31 % of areas during the years 1982–2011 and these increases mostly occurred in the northwestern, eastern, and southeastern Great Basin (Fig. 4d). As in other seasons, there still were points where autumn vegetation greenness decreased significantly during the 1982–2011 period, but these points were less than 9 % of the total points considered in our study (Fig. 4d) and mostly concentrated near the eastern side of the Sierra Nevada Mountains.

3.3 Variation of SOS, EOS, and GSL in the Great Basin

Based on the GIMMS NDVI data, the values of the start of growing season (SOS) in the dryland ecosystems showed no significant ($p = 0.59$) trend during 1982–2011 (Fig. 5a), indicating that spring leaf onset was not significantly advanced during the study period. In contrast, the end of growing season (EOS) increased significantly at a rate of 3.0 ($p < 0.002$) days per decade during 1982–2011 (Fig. 5b), suggesting that the timing of leaf senescence in the dryland ecosystems was delayed significantly during these years. The non-significant trend toward earlier leaf onset and a significant delay in leaf senescence extended the growing season length (GSL) at a rate of 3.0 ($p < 0.05$) days per decade in the dryland ecosystems during 1982–2011 (Fig. 5c).

In addition to these 30 year long-term trends, we observed significant interannual variations in these phenological indicators. For example, the SOS varied on average from 90 to 111 Julian days, EOS varied from 271 to 295 Julian days, and GSL varied from 164 to 196 days. Also, the timing of leaf out and leaf senescence, as well as GSL, did not change monotonically during the 30 year observation period. Shorter-term (decadal or sub-decadal) trends were evident. For example, SOS decreased significantly during the 1982–1990 period while increased significantly during the 1994–2011 period (Fig. 5a).

sonal mean temperature in autumn during the study period. As a result, GSL was positively correlated with mean spring temperature, although such correlation was only marginally significant ($p < 0.10$) at the 90% confidence level. Overall, we found that SOS and GSL in the dryland ecosystems were strongly correlated with mean surface air temperature in SSA (Table 2). When mean surface air temperature increased by 1°C, GSL was extended about 5 days per decade (Table 2).

4 Discussion

4.1 Long-term trends in vegetation greenness in the Great Basin

The increase in mean vegetation greenness in SSA we observed during 1982–2011 in the dryland ecosystems in the Great Basin was consistent with reported trends for other similar ecosystems worldwide. Fensholt et al. (2011) suggested that semiarid areas across the globe experienced an increase in vegetation greenness of about 0.015 NDVI units on average during 1981–2007. Zhang et al. (2010) indicated that growing season NDVI in grasslands in southwestern North America increased from 1982 to 2007. In arid environments of China, an increase in monthly average NDVI measured during the growing season also was observed during 1982–1999 (Piao et al., 2011). These trans-northern-hemispheric findings may have resulted from worldwide warming that has occurred during the last few decades (e.g., Zeng et al., 2011; Menzel et al., 2011). In fact, although mean NDVI in SSA was not significantly correlated with mean surface air temperature, the warming trend we observed (Fig. 2b) was the major driver responsible for the significant extension of GSL (Fig. 8a), which in turn resulted in the 30 year positive trend in mean NDVI values (Fig. 8b) we measured in the dryland ecosystems in the US Great Basin.

Our results, however, contrast with those of Zhang et al. (2010) who reported both a negative trend in NDVI from 1982 to 2007 in shrublands in southwestern North America, as well as an oscillation in NDVI with increases observed from 1982 to 1993 and

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stronger decreases from 1993 to 2007. These apparent discrepancies may be attributed to differences in the spatial extent of the study regions (the Great Basin vs. southwestern North America) and suggest that dryland ecosystems in more northern regions of the arid western US may respond differently to warming trends than those distributed in more southern regions of the arid US as indicated in our study (e.g., Fig. S3a). Such regional differences are actually common (e.g., Jeong et al., 2011) and may be attributed to latitudinal differences in solar radiation and climate condition such as temperature distribution (it decreases as latitude increases, Fig. S4a).

The increases we observed in autumn NDVI in dryland ecosystems in the Great Basin may be a result of the interaction between precipitation and temperature variation in SSA. The multivariate regression analyses suggested that precipitation in winter and autumn as well as mean surface air temperature in SSA are responsible (at the 98 % confidence level) for the increase in seasonal mean NDVI in autumn (Table 3). Increases in surface air temperature in SSA (Fig. 2b) extended GSL (Fig. 8a) while increasing precipitation can ameliorate soil moisture condition. This combination seemed to have stimulated vegetation growth in autumn during the period 1982–2011 (Fig. 3c). In contrast, the no-trend in summertime mean NDVI resulted from increase in summertime mean temperature (Fig. 3e) while precipitation in summer had no positive trend (Fig. 3h). This combination of conditions may have led to greater limitations (e.g., increased heat stress and deteriorated soil moisture) on plant growth in summer. The no-trend in mean springtime NDVI may have resulted from the variation of seasonal mean temperature in spring, which did not increase significantly during the study period (Fig. 3d). Overall, the significant/non-significant relationship between mean NDVI and total precipitation/mean surface air temperature in SSA (Fig. 6) suggested that changes in precipitation played a more important role in controlling the interannual variability of mean vegetation greenness at lower elevation zones of the US Great Basin.

4.2 Spatial heterogeneity of trends in vegetation greenness in the Great Basin

The increase in the temporal positive trend in NDVI as latitude and longitude increase (longitude is negative, Fig. S3) was a result of temperature and precipitation gradients along the latitudinal and longitudinal directions (Fig. S4). In the northern Great Basin, temperature was lower compared to other regions and typically limits vegetation growth in spring. Thus, it was not surprising that the warming trends that we found appeared to benefit vegetation growth more at higher latitudes than it did at lower latitudes in the Great Basin, especially in spring and autumn (Fig. S4a). Zhu et al. (2011) also found that the spatial pattern of vegetation phenology in North America depended strongly on latitude. In addition, the more spatial uniformity in the temporal positive trends we observed in autumn (Fig. 4d) may have occurred as a result of precipitation generated by large-scale frontal systems, which generally start from October and can create relatively uniform water additions to the entire region during the autumn (Weiss et al., 2004).

In the absence of these large regional inputs of precipitation, we expected that the temporal trend in NDVI could be spatially more variable across the Great Basin (Bradley and Mustard, 2008; Atkinson et al., 2011) than we actually observed (i.e., most points in Fig. 4a are green showing significantly positive trends). The phenological cycle of leaf onset and senescence and effect of climate on vegetation greenness are vegetation- and location-dependent (Atkinson et al., 2011). In the western US, topography strongly modulates temperature and precipitation (Hamlet et al., 2007), and local-scale processes – such as cold air drainage flow or the trapping of cold dense air masses by relief – can cause surface climate conditions to vary through space (Daly et al., 2010; Pepin et al., 2011). Because of the spatial heterogeneity of precipitation timing and magnitude and because historical trends in temperature at local scale also varied across the Great Basin (Tang and Arnone, 2013), not all points showed significant positive or negative trends in vegetation greenness during 1982–2011 (Fig. 4). Bradley and Mustard (2008) indicated that trends in vegetation greenness in mountainous areas can

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ited. The insensitivity of EOS in the Great Basin to autumn warming (Fig. 3c) might involve interactive effects of temperature and soil water availability that signal plants to senesce in a way that differs from temperate and boreal forests as demonstrated by the multivariate regression analysis (Table 3, the three regressors for autumn NDVI are all marginally significant at the 90 % confidence level). In fact, the synoptic rainfall events in autumn in these dryland ecosystems can increase the variability of NDVI (Fig. S5), and thus likely alter the timing of leaf senescence under warming condition.

4.4 Climatic sensitivities of vegetation phenology in the Great Basin

Previous studies demonstrated that changes in plant phenology in the mid- and high-latitudes of the Northern Hemisphere were primarily linked with temperature variations due to the adaptive responses of vegetation to climate variability (e.g., Piao et al., 2011; Hmimina et al., 2013), and thus earlier leaf onset in these regions was believed to result mainly from spring warming (e.g., Kaduk and Los, 2011; Piao et al., 2011). These findings were in accordance with our observed significant relationship between SOS and spring temperature (Table 2). Our findings of non-significant relationships of EOS to autumn temperature agreed well with some previously reported data. Menzel et al. (2011) reported that the correlation between leaf color change in fall and temperature trends for 14 European countries was weak and non-significant. As mentioned above, this non-significant relationship between EOS and autumn temperature also may be attributed to the sensitivity of vegetation growth in dryland ecosystems to synoptic rainfall events (Fig. S5). Nevertheless, our results suggested that regional warming is the main driver responsible for the extension of GSL (Table 3 and Fig. 8a).

Changes in precipitation also played a strong role in controlling the interannual variability of vegetation greenness on an annual basis (the calculated AIC values are smaller for precipitation and larger for temperature; Fig. 6). On a seasonal basis, the calculated AIC values (Table 1) still suggested that precipitation in winter, spring, and summer can better explain the interannual variability of seasonal mean vegetation greenness in spring, summer, and autumn. The underlying reason is that water

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availability strongly constrains biotic activity in dryland ecosystems, including plant seed germination, growth, and reproduction, the emergence of leaf-out, and GSL (e.g., Hadley and Szarek, 1981; Bradley and Mustard, 2005). Because plants in dryland ecosystems are mostly deeply rooted, increases in pre-season precipitation, therefore, are likely to increase soil water content in deep soil layers through soil infiltration, and thus benefit vegetation growth in next season. The relative importance analyses further indicated that the interannual variability of mean greenness in SSA was largely affected by the variation of precipitation instead of temperature (Table 3), and the interannual variability of seasonal greenness in spring, summer, and autumn was attributed mainly to the variation of precipitation (especially winter precipitation) rather than temperature (Table 3).

4.5 Non-climatic factors that may influence vegetation phenology in the Great Basin

Although other factors – such as changes in biological soil crust (Ustin et al., 2009), shifts in land covers at landscape-scales, and invasion of exotic species (e.g., Cheatgrass; Bradley and Mustard, 2008) – can affect vegetation phenology in the dryland ecosystems, we are lack of precise information about the spatiotemporal distribution of these factors in the study region. Therefore, additional study is necessary to examine how these factors, especially the invasion and expansion of invasive species, may have already affected the temporal dynamics and climatic sensitivity of vegetation phenology we observed in this study. In addition, although our analysis excluded winter and although snowing may still occur sometimes in early spring or in late fall in parts of the Great Basin, it often accumulates only in high elevational areas. As a result, the effects of snow on NDVI values were minimal because we focused on vegetation phenology in low elevational areas. For example, in the southern and southeastern Great Basin (Fig. 4) where snow rarely occurs in spring and autumn, there were large amounts of points showing a significant positive trend in vegetation greenness during 1982–2011.

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This can justify the robustness of our results given the overall climate warming trend across the Great Basin in the last few decades (Tang and Arnone, 2013).

5 Summary

Based on GIMMS NDVI data and from a regional perspective, our results suggested that changes in total precipitation rather than mean surface air temperature in SSA is the major factor controlling the interannual variability of mean vegetation greenness in dryland ecosystems of the US Great Basin. On a seasonal basis, pre-season precipitation in winter and spring contributed more to the interannual variability of seasonal mean greenness in spring, summer, and autumn. Nevertheless, climate warming is mainly responsible for the extension of GSL, which in turn resulted in the 30 year positive trend in mean vegetation greenness in the dryland ecosystems. Overall, our results suggest that both precipitation and temperature played an important but different role in affecting vegetation phenology in the dryland ecosystems in the US Great Basin.

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Table 1. Relationship of vegetation greenness to seasonal mean temperature (SMT), total precipitation (STP), and pre-season precipitation (PSP).

Seasons	SMT		STP		PSP		AIC		
	Slope	$p <$	Slope	$p <$	Slope	$p <$	SMT	STP/PSP	STP/PSP
Spring	0.002	0.30	1.1×10^{-4}	0.15	1.1×10^{-4}	0.18	-162	-167 _s	-163 _w
Summer	-0.010	0.01	1.2×10^{-4}	0.16	3.4×10^{-4}	0.001	-154	-164 _s	-154 _w
Autumn	0.003	0.29	-5.6×10^{-5}	0.23	8.3×10^{-6}	0.86	-188	-190 _w	-189 _a

AIC refers to the Akaike Information Criterion. The smaller the AIC value is, the better a univariate linear regression model fits. The subscripts “w”, “s”, “a” represent winter, spring, and autumn, respectively.

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Table 2. Relationships of SOS, EOS and GSL to temperatures (T).

Indices	Spring T		Autumn T		SSA T	
	Slope	$p <$	Slope	$p <$	Slope	$p <$
SOS	-2.7	0.001	x	x	-5.0	0.01
EOS	x	x	0.7	0.43	0.2	0.87
GSL	1.8	0.10	0.6	0.68	5.2	0.02

x indicates that the relationship analysis was not considered.; SSA represents the period of March to November (spring, summer and autumn).

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Table 3. The relative importance of annual/seasonal mean temperature (T) and precipitation (P) to the variation of annual/seasonal mean NDVI based on multivariate regression analyses.

Best multivariate regression model ^a	Statistics		LMG ^a for Regressors (R) ^b			
	R^2	$p <$	R_1 (%)	R_2 (%)	R_3 (%)	R_4 (%)
$SSA_N = SSA_T + SSA_P + SSA_T \times ANN_P$	0.22	0.09	8	75	17	
$MAM_N = MAM_T + DJF_P + MAM_P$	0.31	0.02	42	19	39	
$JJA_N = JJA_T + DJF_P + MAM_P + JJA_T \times DJF_P$	0.59	0.001	25	29	31	15
$SON_N = DJF_P + SON_P + SSA_T$	0.23	0.07	63	20	17	

^a These models were selected based on adjusted- R square and p values.

The subscripts “N”, “T”, and “P” in each model represent NDVI, temperature, and precipitation, respectively. “SSA”, “MAM”, “JJA” and “SON” represents the period of March to November, spring, summer and autumn, respectively.

LMG^a refers to the averaging over orderings of importance proposed by Lindeman, Merenda and Gold (LMG; Grömping, 2006).

^b The order of regressors corresponds to the order of those variables listed in multivariate regression model.

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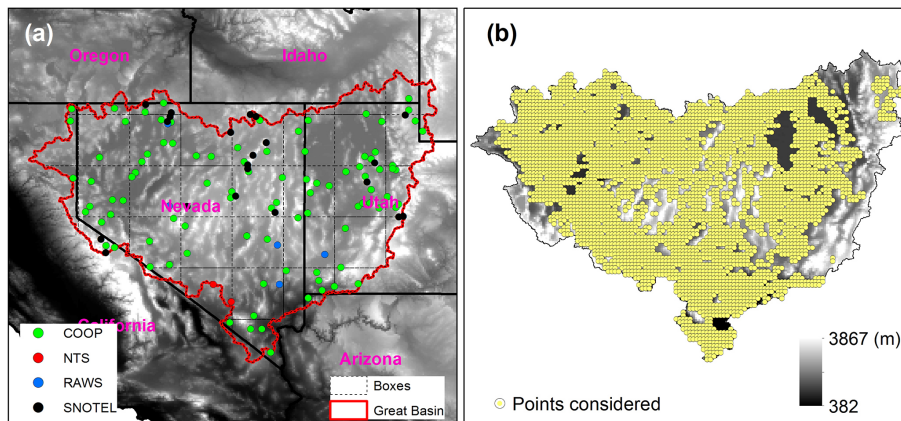


Figure 1. (a) The hydrological Great Basin in the western US and the distribution of weather stations used in this study. (b) The distribution of NDVI points considered in this study.

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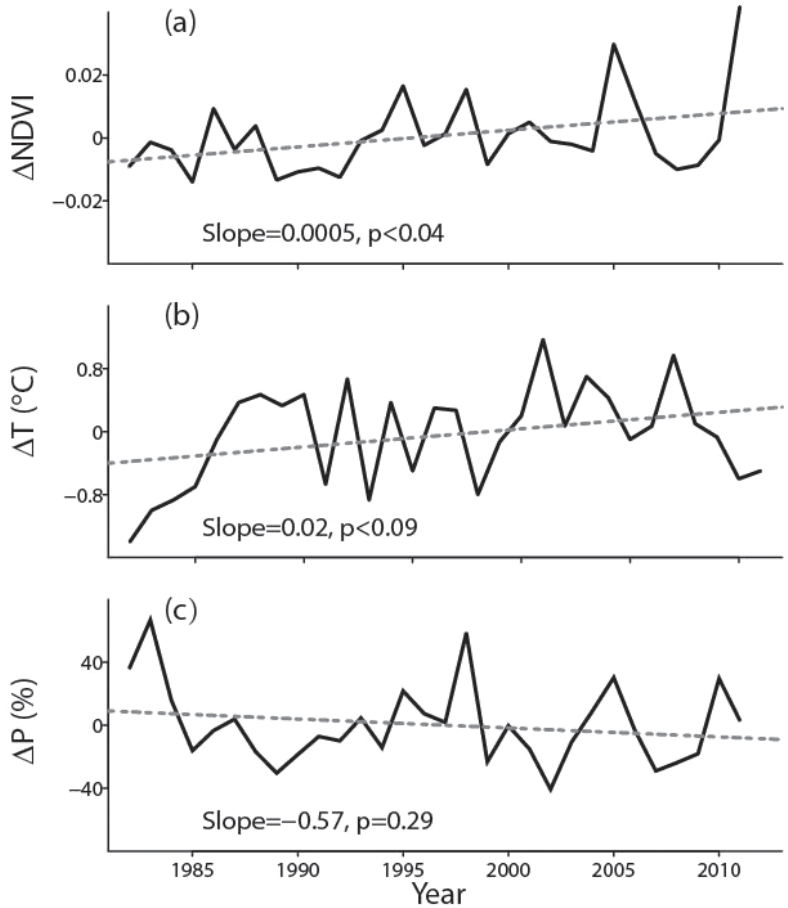


Figure 2. The temporal trends in **(a)** mean vegetation greenness, **(b)** mean surface air temperature, and **(c)** total precipitation in the period of March to November in the Great Basin during 1982–2011.

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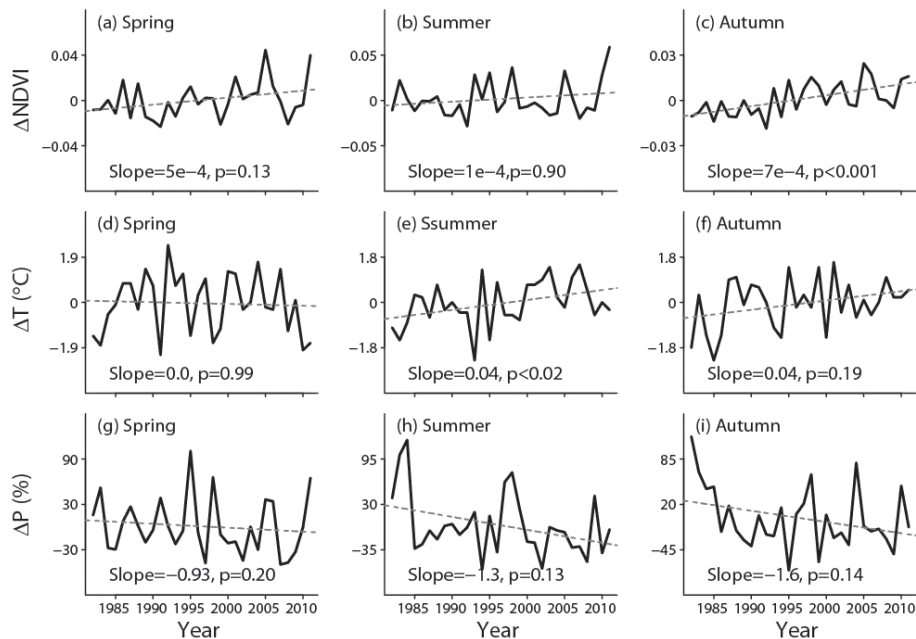


Figure 3. The temporal trends in (a–c) seasonal mean vegetation greenness, (d–f) seasonal mean temperature, and (g–i) seasonal total precipitation in the Great Basin during 1982–2011.

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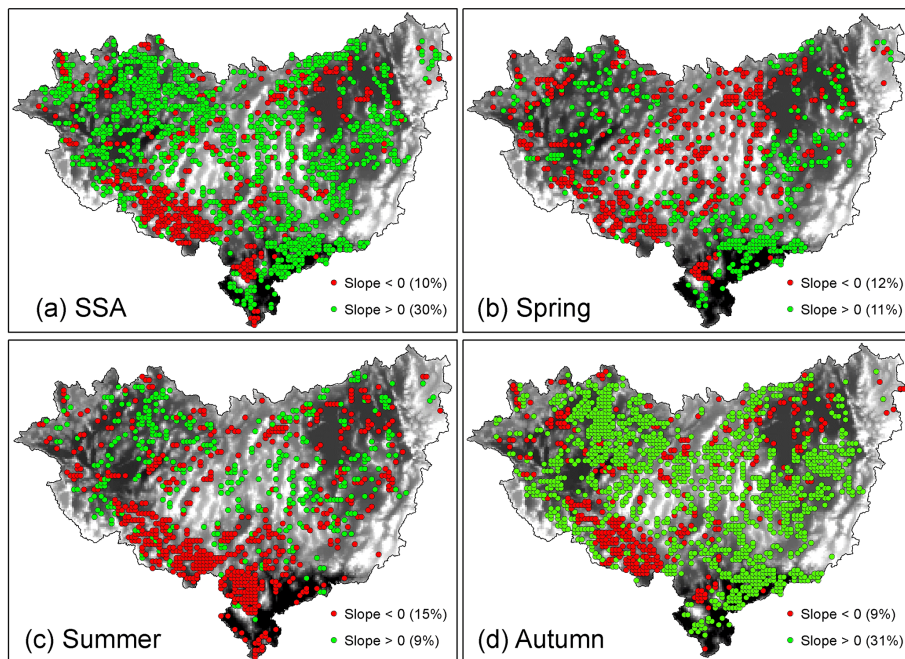


Figure 4. The spatial patterns of temporal trends in mean vegetation greenness in **(a)** SSA (the period of March to November), **(b)** spring, **(c)** summer, and **(d)** autumn in the Great Basin. The percentages were calculated against the total of points considered in this study.

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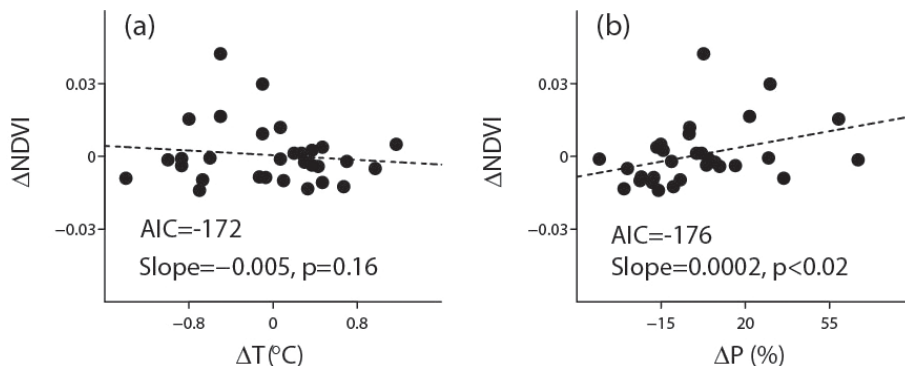


Figure 6. (a) The relationship between mean vegetation greenness and mean surface air temperature in SSA (the period of March to November); (b) the relationship between mean vegetation greenness and total precipitation in SSA. AIC refers to the Akaike Information Criterion.

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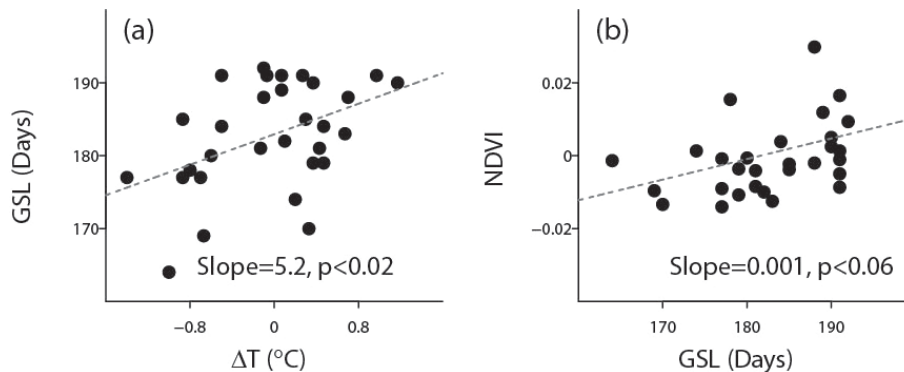


Figure 8. (a) The relationship between mean surface air temperature in SSA (the period of March to November) and the grown season length (GSL); (b) the relationship between GSL and mean vegetation greenness in SSA.

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