Assessing Impact of Seasonal Precipitation and Temperature on Vegetation Dynamics in Semiarid Rangelands

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Abstract

Vegetation dynamics are affected by many climatic factors and have been successfully monitored through satellite remote sensing over the past twenty years. In this study, the Normalized Difference Vegetation Index (NDVI), derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite was selected as an indicator of vegetation dynamics. Monthly MODIS composite NDVI at 1-km resolution was acquired throughout the 2004-2009 growing seasons (e.g., April - September) and used to quantify a relationship with seasonal precipitation and temperature. Both precipitation and temperature, primary factors affecting vegetation growth in semiarid rangelands, were derived from the Surface Observation Gridding System (SOGS) and local weather station datasets. Interannual and seasonal fluctuations of precipitation and temperature were analyzed and the impact of precipitation and temperature on vegetation dynamics examined. Results indicated that NDVI values observed in June and July had strong correlation with accumulated precipitation ($R^2 > 0.75$), while NDVI values observed in May, August, and September were only moderately related with accumulated precipitation ($R^2 \geq 0.45$). The role of ambient temperature was also apparent, especially early in the growing season. Specifically, early growing season temperatures significantly affected plant phenology and subsequently, correlations between NDVI and accumulated precipitation.

Keywords: Rangelands, precipitation, temperature, vegetation indices, remote sensing, Idaho

INTRODUCTION

Interannual and seasonal vegetation dynamics are key driving variables for modeling and monitoring terrestrial ecosystems. In the past twenty years, satellite remote sensing has enhanced our ability to monitor vegetation dynamics at various spatial and temporal scales (Goward and Prince 1995; Zhang et al. 2003; Anyamba and Tucker 2005; Chen et al. 2010). In particular, the Normalized Difference Vegetation Index (NDVI), which leverages the ratio of reflectance in the red band of a sensor to that of the near infra-red band, has proven an effective indicator of plant growth, vegetation cover, biomass production, and phenology (Rouse et al. 1973; Huete and Jackson 1987; Carlson and Ripley 1997; Beck et al. 2006; Bradley et al. 2007; Martínez and Gilabert 2009).

The vegetation of semiarid environments is well adapted to highly variable conditions of rainfall and temperature (Rodríguez-Iturbe and Porporato 2004; D'odorico and Porporato 2006), and seasonal precipitation and temperature fluctuations are the primary factors which affect vegetation dynamics and plant growth these ecosystems (Sneva 1977; Neilson et al. 1992). Jobbágy and Sala (2000) analyzed the relationship between aboveground net primary production (ANPP) and seasonal precipitation and demonstrated that spring precipitation was closely related to summer grass ANPP in semiarid Patagonian steppe. Similarly, Nasri and Doescher (1995) indicated a specific amount of heat was required for vegetation to develop from one growth stage to another in the semiarid rangelands of Idaho. To quantify this effect, growing degree days (GDD) are calculated to measure heat accumulation each day and used as an index of vegetation maturity in many studies (Botkin et al. 1972; McMaster and Wilhelm 1997; Hassan et al. 2007).

Several studies have demonstrated a close relationship between temporal variations of NDVI, temperature, and precipitation (Goetz 1997; Myneni et al. 1997; Foody 2003). Malo and Nicholson (1990) concluded a strong linear relationship between NDVI and rainfall exists when rainfall accumulations were between 150mm and 1000mm. Davenport and Nicholson (1993) presented a log-linear relationship between NDVI and precipitation in cases where annual precipitation was below 1000mm and monthly precipitation did not exceed 200mm. Similarly, Wang et al. (2003) concluded there was a positive correlation between temperature and NDVI both early and late in the growing season, and that temperature was negatively correlated with NDVI during the middle of the growing season. There are many reasons for the observed variable relationships between NDVI, temperature, and precipitation, and much of the variability is likely attributable to region- and site- specific conditions (e.g., soil, and vegetation types) (Du Plessis 1999).

Approximately 45 percent of Idaho is considered rangeland, and many of these areas are categorized as a semiarid sagebrush-steppe ecosystem (http://www.cnr.uidaho.edu/west/). Investigating the correlation between NDVI, temperature, and precipitation will aid in an understanding of the influence of weather on vegetation dynamics in semiarid rangelands. In this study, monthly maximum NDVI derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) were used to generate time-series layers of vegetation dynamics from 2004 to 2009. Precipitation and temperature were obtained from the Surface Observation Gridding System (SOGS) dataset (Weber et al. 2010). Finally, temporal responses of NDVI to precipitation and temperature were examined.

MATERIALS AND METHODS

Study area

The Big Desert is an area of sagebrush-steppe rangelands in southeastern Idaho approximately 71 km southeast of Pocatello, Idaho (43° 14' 27.88" N 113° 4' 18.68" W) (Fig. 1). The Big Desert is managed by the Bureau of Land Management (BLM). The Big Desert receives 0.23 m of precipitation annually (primarily in the spring) and the elevation of the study area ranges from 1349-2297 m above sea level. The Big Desert exhibits a high proportion of bare ground (bare ground typically exceeds 17%), and is classified as a Wyoming big sagebrush/blue bunch wheatgrass habitat type. The dominant plant species include big sagebrush (*Artemisia tridentata*) with various native and non-native grasses and forbs.

Monthly NDVI layers

Collection 5 MODIS NDVI (MOD13A3) monthly products were selected to cover the 6-year time frame of this study (i.e., from 2004 to 2009). The MODIS NDVI algorithm is calculated on a per-pixel basis and the ingests of all 16-day 1-kilometer products for that month (Huete et al. 2002). In this study, NDVI was acquired throughout the growing season (i.e., from April to September) for the entire Big Desert study area. All imagery was projected into Idaho Transverse Mercator, NAD 83 and NDVI values were screened to reject all data of insufficient quality through MODIS NDVI quality control (QC) layers.

Monthly precipitation and temperature data collection

Daily precipitation and minimum temperature data provided by the SOGS dataset were selected for the 2004-2009 growing seasons (April - September). Daily precipitation and temperature were accumulated into monthly aggregations, corresponding to the same time periods of the NDVI data. Like MODIS NDVI layers, SOGS precipitation and temperature layers have a spatial resolution of 1km x 1km pixels, and each of these raster layers were similarly projected into Idaho Transverse Mercator, NAD 83. Following this, the interannual comparisons of minimum temperature were summarized using the SOGS dataset. Similarly, GDD were calculated using a weather dataset provided by the United States Bureau of Reclamation (USBR) AgriMet Program (http://www.usbr.gov/pn/agrimet/). Because no Agrimet sites were available within the Big Desert study area, stations near the perimeter of the study area were selected. Weather patterns at these sites exhibit nearly identical trends compared to those observed in the Big Desert and for this reason are assumed to be ideally suited to this project. Weather datasets from 2004 to 2009 were selected for analysis and comparison across all years of this study.

Analysis of relationships between precipitation, temperature, and NDVI

Results of field surveys conducted in 2007 and 2008 were used to assist in sample site selection and a total of 32 sites were selected across the Big Desert study area. The selected sites were dominated by grasses and considered homogeneous areas. The "Spatial analyst" tool within ESRI’s ArcGIS 10 was used to extract monthly NDVI, monthly precipitation, and monthly temperature values at each sample site [n=32]. Using these data, mean values of monthly NDVI, monthly precipitation, and monthly temperature for all sample sites were calculated. In addition, periodic accumulated precipitation (PAP) values for each month were calculated (e.g., $\mathrm{PAP}_{\mathrm{May}}$ [accumulated precipitation from April to May]; $\mathrm{PAP}_{\mathrm{June}}$ [accumulated precipitation from April to June]) (Fig. 2). Mean monthly NDVI and PAP data were exported to SPSS (V17.0) for correlation analysis between NDVI and PAP. Similarly, correlation analysis between NDVI and GDD was performed.

RESULTS AND DISSCUSSION

Interannual correlation between NDVI and PAP (Fig. 3), along with respective coefficients of determination indicate NDVI was strongly correlated with PAP in July ($R^2 > 0.75$) (Fig.3c) and moderately well correlated in May ($R^2 = 0.59$), August ($R^2 = 0.68$), and September ($R^2 = 0.45$) (Fig. 3a, d, e). NDVI was weakly correlated with PAP in June ($R^2 = 0.15$) (Fig. 3b).

Monthly coefficients of determination between NDVI and PAP were compared and a general increasing trend through July (i.e., between May and July R^2 increased from 0.59 to 0.75) was observed with a subsequent decrease observed after July(i.e., between July and September R^2 decreased from 0.75 to 0.45). This change in trend may be attributed to the variation in temporal responses by vegetation to precipitation and temperature. In semiarid rangelands, grasses require abundant water for growth and start to grow only after temperatures are within an appropriate range (e.g., the germination temperature of cheatgrass [*Bromus tectorum*] is approximately 5°C and germination is inhibited by temperatures above 30 °C [Evans and Young 1972; Harris and Goebel 1976]). Between April and early May, sufficient precipitation and heat are required for optimal vegetation growth. Between June and July, critical ambient temperatures have been reached and precipitation becomes the primary factor affecting grass growth. As a result, strong coefficients of determination were seen between NDVI and PAP. Later in the summer (e.g., August), high temperatures and reduced precipitation hastens the desiccation of grasses. As a result, the correlation between NDVI and PAP begins to decline.

The coefficient of determination between NDVI and PAP in June was only 0.15. This initially appears to disagree with otherwise increasing trend expected and described above. It is noted, however that observations for June 2008 (Fig. 3b) deviated substantially from the trend line and we conclude that the 2008 June relationship between NDVI and PAP might be abnormal and likely influenced by other factors (e.g., lower temperatures).

In order to assess how temperature affected plant growth in 2008, the role of ambient temperature on NDVI was similarly examined (Fig. 4). It was noted that the minimum temperature in April and May 2008 were -4.6 °C and 1.9 °C respectively. These temperatures were substantially lower than that observed in corresponding months for all other years of this study. These lower temperatures early in the 2008 growing season likely affected the initial growth of grasses and we conclude that grass phenology was delayed in 2008.

To further assess temperature effects on grass development from emergence to maturity, GDD were further analyzed (Fig. 5). It was noted that annual grasses such as cheatgrass emerged in late April or early May (Julian day: ~ 120) in both 2004 and 2007 while initial growth was delayed until the middle of May (Julian day: ~ 135) in 2008. GDD analysis indicated that annual grasses germinated at or around the middle of May in 2005, 2006, 2008, and 2009. However, after the middle of May GDD values in 2006 and 2009 increased abruptly relative to that observed in 2008, contributing to much higher minimum temperatures in 2006 and 2009. Interannual comparisons of minimum temperature coupled with GDD analysis suggested that 2008 was an overall cooler year relative to the other years during key portions of the growing season. This cooler weather pattern slowed early season grass growth in 2008 resulting in a first flush of growth in June, hence the anomolously high NDVI values observed in June 2008 (Fig. 5). In 2004-2007, and 2009, NDVI reached its peak in May whereas peak NDVI did not occur until June in 2008. This variation in vegetation development made the relationship between NDVI and PAP appear abnormal in June 2008.

A re-analysis of these data using only 2004-2007 and 2009 datasets (i.e., omitting 2008 data) assessing the correlation between NDVI and PAP, resulted in a marked increase in the coefficient of determination to 0.78 (Fig. 3f).

This study illustrates that temperature is an important factor for grass development and has various effects on grass growth at specific times of the growing season. Grasses exhibited a different phenology curve when temperatures were cooler or warmer than average especially during the early growing season. Warmer temperatures may accelerate plant growth, while cooler temperatures will delay growth. We conclude that interactions between temperature and precipitation synergistically determine vegetation dynamics in semiarid rangelands. In addition, we believe the interactions between temperature, precipitation and vegetation dynamics are very complex and currently it is very difficult to represent the relationship of temperature, precipitation and vegetation dynamics using a direct formulation model.

MANAGEMENT IMPLICATIONS

This study examined an NDVI time series from 2004 through 2009 in the semiarid rangelands of Idaho. NDVI was used as an indicator of vegetation dynamic to help understand climatic influences on vegetation, and the temporal responses of NDVI to precipitation and temperature. NDVI was well good correlated with PAP between May and July ($R^2 > 0.5$) when temperatures were optimal for early season growth. Correlations between NDVI and PAP began to decrease in August as high temperatures hastened the desiccation of plants. Temperatures during the early growing season had a significant effect on plant growth and appeared to affect the overall plant phenology for each year. Plant response to temperature and precipitation are very complex and it is difficult to use temperature, precipitation, and NDVI together in a multivariate correlation analysis. This study analyzed the relationship between precipitation and NDVI and the relationship between temperature and NDVI discretely, representing an incremental step toward building a better understanding of these relationships and our ability to predict vegetation dynamics in response to differences in seasonal and interannual precipitation and temperature. Future work will seek to conduct a more systematic analysis to form a mechanistic understanding of the interactions between temperature, precipitation, and vegetation dynamics.

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Figure captions

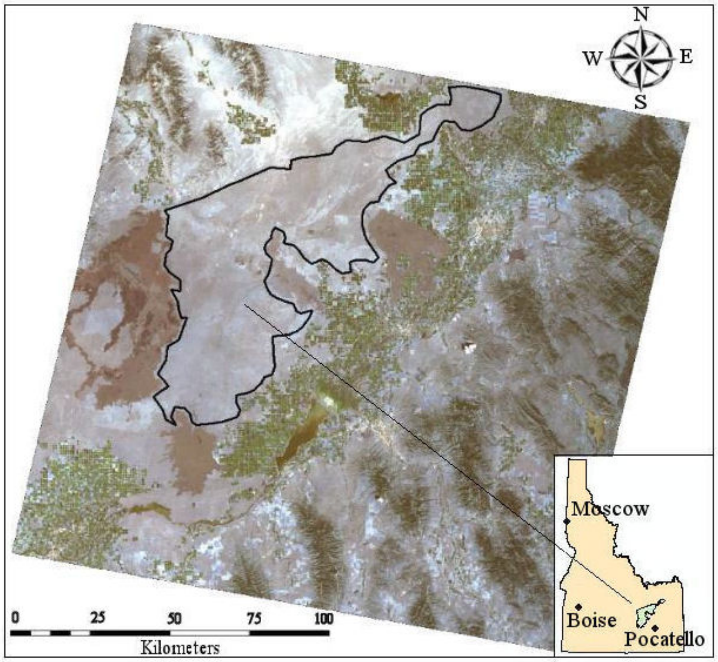
Fig. 1. Location and general characteristics of the Big Desert in southeastern, Idaho. The true color composite of Landsat-5 TM: band3=red, band2=green, band1=blue.

Fig. 2. Time period of periodic accumulated precipitation (PAP) used in this study.

Fig. 3. Fig. 3. Correlations between monthly NDVI values and periodic accumulated precipitation (PAP) for each growing season. Note: PAP of growing seasons are given along the horizontal (x) axis and mean NDVI values of each month were indicated along the vertical (y) axis.

Fig. 4. Interannual comparisons of minimum temperature using SOGS dataset.

Fig. 5. Comparisons of growing degree days (GDD) on 2004, 2005, 2006, 2007, 2008 and 2009.



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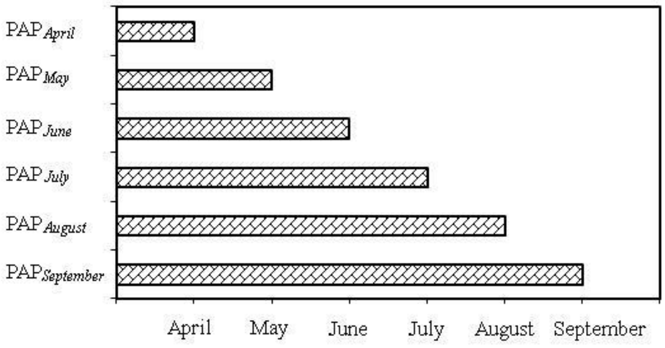

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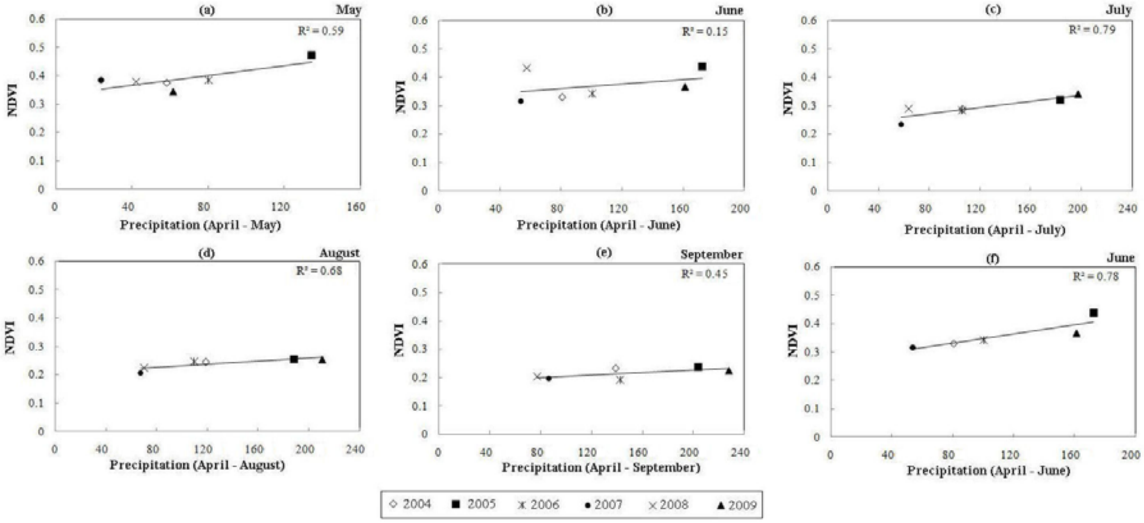

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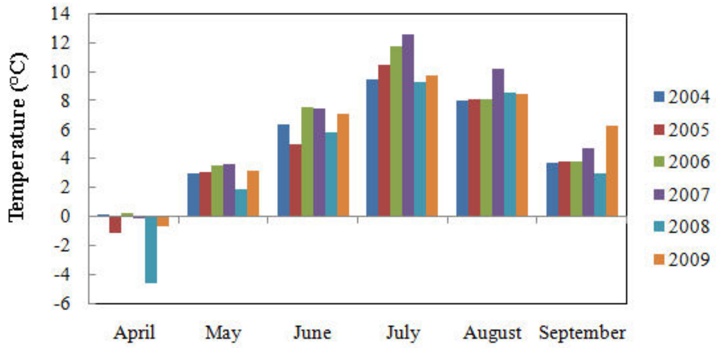

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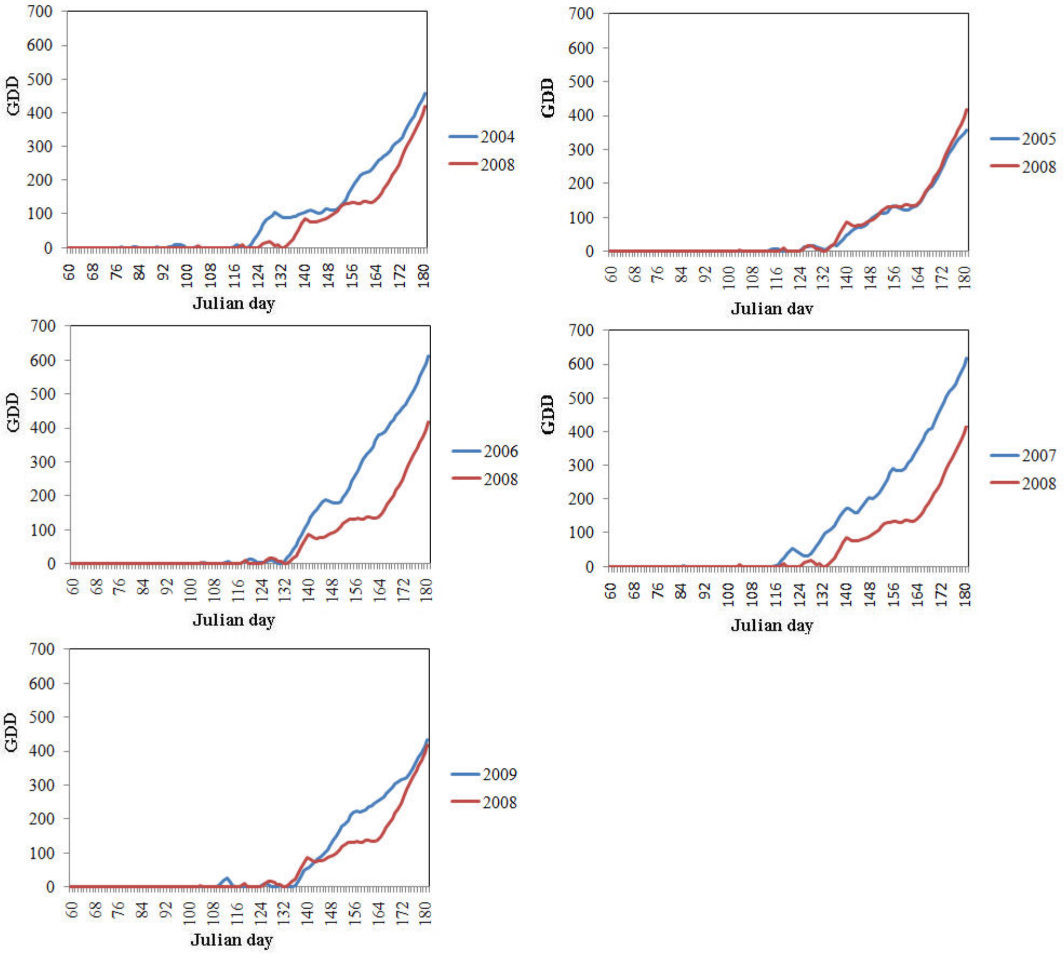

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