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The effect of precipitation on vegetation cover over three landscape units in a protected semi-arid grassland: Temporal dynamics and suitable climatic index

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ABSTRACT

The principal drivers that effectively determine the vitality of semi-arid grassland ecosystems are the amount and timing of precipitation. In contrast to well-established relationships between precipitation and some vegetation biophysical properties such as vegetation productivity and biomass, the effect of precipitation on percent vegetation cover in semi-arid grasslands are poorly understood. The percent green vegetation cover is an important indicator of ecosystem health, especially in a protected semi-arid grassland where dead material dominates vegetation canopy. Consequently, this study used field data, high spatial resolution SPOT satellite images, and low spatial but high temporal resolution AVHRR images to (1) analyze temporal variations in maximum percent green vegetation cover over three landscape units in a protected grassland from 1988 to 2007, and (2) investigate the performance of three commonly used climatic moisture indexes (accumulated precipitation – P; climate moisture index – CMI; and the modified Palmer drought severity index – MPDSI) in estimating percent vegetation cover. The results revealed moderate to strong links between percent vegetation cover and climate conditions in three landscape units. The selected indices were able to explain a relatively high proportion of variation in percent vegetation cover in the upland/sloped grassland ($R^2 = 0.41$ for P, 0.45 for CMI, and 0.53 for MPDSI), low variation in the riparian shrub ($R^2 = 0.25$ for P, 0.28 for CMI, and 0.32 for MPDSI), and even lower variation in the valley grassland ($R^2 = 0.09$ for P, 0.14 for CMI, and 0.21 for MPDI). In comparison with accumulated precipitation, the CMI and MPDSI which considered water availability, were able to explain a much higher variation in percent vegetation cover over the three grassland landscape units. The results from this work provide new insight into the effects of precipitation/climatic factors upon different landscape units and further aid to establish a more complete picture in this field.

1. Introduction

Temporal and spatial changes in plant traits such as percent vegetation cover, leaf area index, or biomass have been a central concern of grassland ecology (Zhang and Guo, 2008). The need for information on change patterns of plant traits in grassland prairies has increased as current environmental changes intensify. Semi-arid grasslands with short growing seasons and limited vegetation cover are particularly sensitive to environmental changes (He et al., 2009; Sauchyn, 2010). A slight change in climate during the growing season has the potential to change vegetation production, modify ecosystem composition, and change vegetation cover characteristics in this type of vegetation ecosystem (Stow et al., 2004). The semi-arid mixed grasslands in Canada are expected to be among the most sensitive to a changing climate, especially to changes in precipitation because the amount and timing of precipitation are the principal drivers that effectively determine the vitality of these ecosystems (Li and Guo, 2012; McGinn, 2010). Historic climate trends suggest a 1–4 mm decrease in rain per year in the mixed grassland prairie in Southern Saskatchewan, Canada (Sauchyn, 2010). In contrast to well-established relationships between climate conditions and vegetation productivity (e.g. Andales et al., 2006; Wu and Chen, 2012), biomass (e.g., Derner et al., 2011; Li and Guo, 2012; Liang et al., 2003; Yang et al., 2009), and phenology (e.g. Archibald and Scholes, 2007), the effect of precipitation on percent green vegetation cover has rarely been quantified (Derner et al., 2008).

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The amount of green vegetation varies substantially from year to year due in part to precipitation in a semi-arid grassland. To evaluate the effect of changes in precipitation on vegetation growth over time, some studies have simply used accumulated precipitation, while others developed climatic indices that can be calculated based on documented climate data. A few commonly used indices include the Palmer drought severity index (PDSI) and moisture anomaly index (*Z*-index) (Palmer, 1965), the crop moisture index (CMI) (Palmer, 1968), and the standardized precipitation index (SPI) (McKee et al., 1993). The strengths and limitations of these indices have been evaluated and discussed in previous studies (e.g. Heim, 2002; Keyantash and Dracup, 2002; Mishra and Singh, 2010). In Canadian grassland prairies, Hogg (1997) used the CMI to reproduce the distribution of vegetation for the period of 1951–1980; Akinremi et al. (1996) found that the PDSI is not suitable for characterizing drought on the Canadian prairies and thus proposed a modified PDSI (MPDSI) with improved performance; and Quiring and Papakyriakou (2003) evaluated the performance of four indices and concluded that the CMI is more appropriate for Canadian prairies applications.

The studies that examined the effect of precipitation on Canadian prairie vegetation (e.g. Akinremi et al., 1996; Quiring, 2004; Sun et al., 2011) have focused on large geographical areas which provided a comprehensive view of spatial and temporal patterns of moisture variability and its impacts on vegetation (Quiring and Papakyriakou, 2003). However, these studies were conducted either over agriculture land or on geographical areas dominated by agricultural land. The net effect of precipitation on vegetation in these areas could be modified by human activities such as irrigation or other management practices. The conclusions in these studies may not adequately characterize the effect of water availability on natural vegetation ecosystems and thus determine which index would be suitable to detect the effect of water availability on undisturbed grasslands. In order to provide a more comprehensive assessment of climate conditions and their effect on natural vegetation health, this study examined the effect of precipitation on green vegetation in a natural protected grassland ecosystem.

Differentiated by different micro-environmental characteristics such as topography, three dominant landscape units exist in the mixed grassland and they are (1) upland/sloped grassland, (2) valley grassland, and (3) riparian shrubs (Michalsky and Ellis, 1994; Zhang and Guo, 2008). The responses of vegetation in different landscape units to precipitation can vary. For example, the upland/sloped grassland can vary significantly in response to water availability during the growing season, while riparian shrub may be invariant under the same environment (Derner et al., 2008). Therefore, the ability to predict changes in individual landscape unit is critical for accurate environmental change research.

Remote sensing has been used to provide a deeper understanding of grassland vegetation temporal dynamics in a wide range of ecological applications due to its ability to deliver observations at many spatial scales, over large areas and with regular revisit intervals (Hunt et al., 2003). Due to their long historic archive (since the early 1980s) and near-real time ecosystem monitoring across broad areas, time series AVHRR data are commonly used to demonstrate the substantial effect of climate on dynamics of vegetation structure, primary productivity and growing season length. However, the low spatial resolution of AVHRR data (i.e. 1 km) makes it difficult to correlate them with field measurements collected at a much smaller scale (e.g. 0.1 km). The interpretations from AVHRR data sets would be suspect if not supported by reliable field data. The mismatch between broad-scale AHVRR data and local-scale field data might be resolved through linking a few available high spatial resolution images such as SPOT4 & 5 with AVHRR. The empirical models can be used to relate the local-scale field data to spectral indices calculated from high spatial resolution remote sensing data (e.g. SPOT 4/5), and further related to low spatial resolution remote sensing data (e.g. AVHRR).

The best known spectral index is the Normalized Difference Vegetation Index (NDVI) that combines the red and near infrared bands, and can be integrated overtime, to estimate green vegetation biophysical properties. Green vegetation parameters such as green biomass, leaf area index, or vegetation cover are important indicators of grassland health which can be used to monitor land condition and to identify processes of land degradation in a semi-arid grassland (Zhang and Guo, 2008). Studies usually use leaf area index as an indicator of green vegetation health because it can be easily measured using optical sensors in the field. However, due to long-term grassland conservation, a large amount of dead material (including standing dead and litter) occurs in the vegetation canopy in the study area. Remote sensing spectral indices, which are sensitive to green and healthy vegetation, may be not well correlated with leaf area index for the canopy which was dominated by dead material. Instead, percent green vegetation cover is an easier vegetation parameter to be estimated in the field, and it should also have a better connection to remote sensing data than the commonly used leaf area index.

Consequently, this study examined temporal dynamics of percent green vegetation cover during the peak growing season over three landscape units in a protected grassland ecosystem for a period of 20 years from 1988 to 2007using field measurements, 20-m SPOT 4 images, 1-km AHVRR images, and climate data. Specifically, this study addressed the following questions: (1) to what extent can the annual variability of peak green vegetation cover be accounted for by precipitation variation in each landscape unit? And (2) what is a suitable index to detect the effect of precipitation on vegetation over different landscape unit? Answers to these questions will provide timely and quantitative information about the effect of precipitation on biophysical properties of a mixed grassland prairie to better inform decision making at the management level.

2. Methodology

2.1. Study area

The study area is located at Grassland National Park (GNP, 49°15′N, 107°249′W), southern Saskatchewan, Canada (Fig. 1). The park was established in 1988 to conserve and protect a portion of the natural region defined as a semi-arid, mixed grass prairie ecosystem. The average temperatures for May, June, July, and August (1937–2004) are 11 °C, 15.8 °C, 18.3 °C, and 17.7 °C, respectively. Compared with temperature, precipitation values show a similar trend but with larger variations. Average precipitation values for May, June, July, and August are 39.4, 64.3, 46.0, and 30.7 mm, respectively, with the usual full growing season concentrated in the period with highest precipitation (June and July) (Zhang, 2006). However, although the maximum monthly temperature is consistently in July each year, the highest amount of monthly precipitation for each year can appear in any month from May to September (Zhang, 2006). Upland/sloped soils on till are dominantly loamy, orthic brown chernozems with local swales supporting brown vertisols where clay has accumulated. Valley soils on alluvium are a complex of fine saline regosols, solonetz, and chernozems on upper terraces, while lower terraces adjacent to streams are loamy humic regosols (Parks Canada, 2006). The study area has three main landscape units including upland/sloped grassland, valley grassland, and riparian shrub with characteristic