Manuscript Number: JAE13-22R2

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

Article Type: Research Paper

Keywords: Grassland Landscape Units, Precipitation, Semi-arid Grassland, Climatic Index, AVHRR NDVI, SPOT 4 Image

Corresponding Author: Prof. Yuhong He, Ph.D.

Corresponding Author's Institution: University of Toronto

First Author: Yuhong He, Ph.D.

Order of Authors: Yuhong He, Ph.D.

Abstract: The principal drivers that effectively determine the vitality of semi-arid grassland ecosystems are the amount and timing of precipitation. 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 vegetation cover in a protected grassland over three plant functional groups 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. Our results revealed fairly strong links between percent vegetation cover and climate conditions in three landscape units over the 20 years. The selected indices are able to explain a relatively high variation in percent vegetation cover in the upland landscape. In comparison with accumulated precipitation, the CMI and MPDSI which consider water availability, are able to explain a much higher variation in percent vegetation cover over the three landscape units.

1
2
3
4 1 The effect of precipitation on vegetation cover over three landscape units in a protected
5
6 2 semi-arid grassland: temporal dynamics and suitable climatic index
7
8
9
10 3 Yuhong He
11 4
12 5 ^a Department of Geography, University of Toronto Mississauga, 3359 Mississauga Road North,
13 6 Mississauga, Ontario, Canada, L5L 1C6
14 7
15 8 Author for correspondence: yuhong.he@utoronto.ca, phone: 1-905-569-5679; fax: 905-828-5273
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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.

Keywords

Grassland Landscape Units, Precipitation, Semi-arid Grassland, Climatic Index, AVHRR NDVI, SPOT 4 Image

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 (Sauchyn, 2010, He et al., 2009). 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; MaGinn, 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).

The amount of green vegetation vary 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; Akinermi 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 Papakryiakou (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 Parakyriakow, 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 AVHRR 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

1
2
3
4 101 calculated from high spatial resolution remote sensing data (e.g. SPOT 4/5), and further related
5
6 102 to low spatial resolution remote sensing data (e.g. AVHRR).
7
8
9

10 103 The best known spectral index is the Normalized Difference Vegetation Index (NDVI)
11
12 104 that combines the red and near infrared bands, and can be integrated over time, to estimate green
13
14 105 vegetation biophysical properties. Green vegetation parameters such as green biomass, leaf area
15
16 106 index, or vegetation cover are important indicators of grassland health which can be used to
17
18 107 monitor land condition and to identify processes of land degradation in a semi-arid grassland
19
20 108 (Zhang and Guo, 2008). Studies usually use leaf area index as an indicator of green vegetation
21
22 109 health because it can be easily measured using optical sensors in the field. However, due to long
23
24 110 term grassland conservation, a large amount of dead material (including standing dead and litter)
25
26 111 occurs in the vegetation canopy in the study area. Remote sensing spectral indices, which are
27
28 112 sensitive to green and healthy vegetation, may be not well correlated with leaf area index for the
29
30 113 canopy which was dominated by dead material. Instead, percent green vegetation cover is an
31
32 114 easier vegetation parameter to be estimated in the field, and it should also have a better
33
34 115 connection to remote sensing data than the commonly used leaf area index.
35
36
37
38
39
40
41
42

43 116 Consequently, this study examined temporal dynamics of percent green vegetation cover
44
45 117 during the peak growing season over three landscape units in a protected grassland ecosystem for
46
47 118 a period of 20 years from 1988 to 2007 using field measurements, 20-m SPOT 4 images, 1-km
48
49 119 AHVRR images, and climate data. Specifically, this study addressed the following questions: 1)
50
51 120 to what extent can the annual variability of peak green vegetation cover be accounted for by
52
53 121 precipitation variation in each landscape unit? And 2) what is a suitable index to detect the effect
54
55 122 of precipitation on vegetation over different landscape unit? Answers to these questions will
56
57
58
59
60
61
62
63
64
65

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 °0' W), southern Saskatchewan, Canada (Figure 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 et al., 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 differences in vegetation cover between each landscape unit (Parks Canada, 2006).

Insert figure 1 approximately here

2.2 Approach Overview

Our approach for investigating the effect of precipitation on percent vegetation cover over the peak growing season (the end of June to early July, described in Zhang, 2006) from 1988 to 2007 consists of three major steps. First, 2005 and 2006 SPOT 4 images were used to establish the empirical model between SPOT derived NDVI and field collected percent vegetation cover for each landscape unit during the peak growing season. To derive percent vegetation cover over 20 years, the regression model between AVHRR NDVI and downscaled SPOT NDVI in the year of 2005 and 2006 was used to calibrate 20-year AVHRR NDVI, so that the percent vegetation cover data can be derived from SPOT-calibrated AVHRR NDVI products. In the final step, climate data were used to calculate climatic indices which were then correlated to derived temporal percent vegetation cover for each landscape unit. A flowchart of these steps is provided in Figure 2.

Insert figure 2 approximately here

2.2.1 Field Data

Field measurements were taken at the peak growing season in 2005 and 2006 in the west block of the GNP (Figure 1). In total, 64 randomly selected sampling sites distributed over valley (14), upland/sloped (24) and riparian areas (26) were visited for the vegetation cover and species composition data. At each of the sites, field sampling was conducted along two 100 m transects that ran perpendicular in the north-south and west-east directions, intersecting in the centre to form a cross. The georeferenced coordinates for each of the cross centres were determined using a handheld global positioning system (GPS). Along each of the 100 m transects, canopy cover was collected at 10-m intervals using a 0.5 m x 0.5 m quadrat. The percent cover of green

vegetation, litter, moss, lichen, bare ground, and standing dead, as well as species composition, were collected from within each quadrat. Percent vegetation cover was visually estimated to the nearest 5% for cover values ranging from 10% to 90%, and to the nearest 1% for cover values less than 10% and greater than 90% (Davidson and Csillag, 2003).

In this study, to allow for the comparison between field plots (100 x 100 m²) and satellite data, the AVHRR data were resampled from their native resolution (~ 1 km) to the 100 m grid using a bilinear interpolation approach. Each 100 x 100 m AVHRR site was then assigned to a landscape unit based upon DEM data. Consequently, 19 sites of upland/sloped grasslands, 13 sites of valley grasslands, and 21 sites of riparian zone were chosen for further analysis.

2.2.2 Remote Sensing Data and Processing

Two SPOT 4 HRV images (Path 37, Row 26) for the study area were acquired on June 22, 2005 and June 28, 2006 (approximately mid-point during the ground truth data collection). The satellite images were geometrically corrected using PCI Geomatica V.10.1 software. An accuracy of 0.3 RMS or better (representing approximately 6 meters or less error on the earth's surface) was ensured in the geometric correction process. Topography distortions were corrected using a Digital Elevation Model (DEM), obtained from the GNP's GIS database. Since this study involved analysis of a biophysical parameter (i.e. percent green vegetation cover) derived from the images, it was necessary to perform atmospheric correction to convert digital numbers to radiance and, in turn, radiance to reflectance values. The atmospheric correction was completed using the ATCOR 2 module within PCI Geomatica V.10.1 software. In order to establish percent vegetation cover prediction model (the details are provided in 2.2.4), the 2005 and 2006

SPOT NDVI data were calculated and extracted from study sites. The SPOT images would be sufficient for this purpose as a 100x100 m field site can cover 5x5 pixels in a SPOT 4 image.

The AVHRR NDVI surface data from the raw 10-day AVHRR composite images (July 1 to July 10) were obtained from Manitoba Remote Sensing Centre 10-day composite images and in total there are 20 AVHRR NDVI maps for the entire park from 1988 to 2007. The data were processed by the second generation of the Geocoding and Compositing System (GEOCOMP-n), which was designed to produce systematic, map-compatible, multi-date composite images over large areas with reduced or no cloud content (Adair, et al., 2002). The imagery were atmospherically corrected using ATCOR2 in PCI Geomatica software. Mean NDVI data from each landscape unit were used in the later analysis.

2.2.3 Climate Data and Processing

Daily temperature and precipitation data for this study were downloaded from two nearby weather stations (Val Marie southeast station and Mankota station) through Environment Canada's data archive¹. The station Val Marie southeast is located in the southwest of the study area and the station Mankota in the southeast of the study area (Figure 1). The data from Val Marie station are available only since 1993, and the Mankota station observations covered the entire study period (1988-2007) (Figure 1). The current work focuses upon the role of the year-to-year variation of study area-averaged precipitation. Therefore the Mankota rainfall observations are used to represent the averaging rainfall condition in the entire study area for 1988-1992, and the average precipitation from the two stations are used for the rest (1993-2007). Such a treatment could be efficient and acceptable for the current work since (i) although the

¹ http://www.msc-smc.ec.gc.ca/climate/products_services/cdcd_iso_e.cfm

stations are sparse and may contain sampling problem, they still represent the benchmark estimation for the average rainfall in the study region; (ii) the accumulated rainfall between the start of the growing season to the maximum growing season is the focus of the study. The spatial variability of rainfall is less pronounced for the accumulated rainfall during the study period in the region. The accumulated rainfall does not show significant biases ($p < 0.05$) between two stations. In addition, the two station data show a good correlation ($r = 0.7$), indicating that the precipitation has a consistent variability at the two stations overall; and (iii) this study looks at the three landscape units (upland grassland, valley grassland, and riparian shrub). Each one is widely distributed in the study region. Hence, overall the spatial variability of the rainfall, if any, is supposed to have similar effects upon the three landscape units, therefore will not cause considerable impact on the conclusions of the study.

The daily precipitation data for the weather stations were accumulated from the start of growing season (May 1st, determined by Zhang, 2006) to the peak growing season (July 1st - July 10th). Temperature data were averaged during the period from daily mean temperature data. As mentioned in the introduction, the few studies that investigated drought hazard for Canadian prairies found the CMI (Hogg, 1996) and MPDSI (Akinermi et al., 1996) are suitable to study Canadian prairies. I thus compared accumulated precipitation with these two indices for detecting the effect of climate conditions on vegetation. The two indices were usually calculated at a fixed temporal scale (annually or monthly). However, it is commonly accepted that the response of vegetation to water availability is a multiscalar phenomenon. We thus modified the indices (equation 1 & 2) to make them capable of detecting water availability at different time scales. The following formula is applied for the calculation of the two indices:

$$CMI = \overline{P - PET} = (\sum_{i=1}^n (P_i - PET_i)) / n \quad (1)$$

$$MPDSI = \frac{\overline{P - PET}}{\sigma(P)} = \frac{(\sum_{i=1}^n (P_i - PET_i)) / n}{\sqrt{(\sum_{i=1}^n [(P_i) - (\sum_{i=1}^n (P_i)) / n]^2) / n}} \quad (2)$$

Where n is the study period and it is 70 days (from the start of growing season to the peak growing season) in this study, i is day sequence, P is daily precipitation data and PET is potential evapotranspiration. A number of equations (e.g. the Thornthwaite equation, the Penman-Monteith equation, the Hargreaves equation) exist to model PET based on available climate data, and this work used the Thornthwaite equation (Thornthwaite, 1948) since it requires only two variables: mean temperature values and the average number of daylight hours during the study period.

2.2.4 Data analysis

Regression analysis was used to establish the percent vegetation cover prediction model based on SPOT NDVI data and field percent vegetation cover data. Cross validation of the regression models was carried out using the random leave-group-out algorithm (one third of the samples, i.e. 17 observations per group), also known as repeated random sub-sampling validation (Vapnik, 1995). Specifically, each regression model was established using a model-fit dataset with 36 observations and this model was then evaluated using a validation dataset with 17 observations. The model efficiency was determined using the coefficient of determination (R^2) and root mean squared error (RMSE).

The SPOT-calibrated AHVRR NDVI data are needed for estimating percent vegetation cover over 20 years. To accomplish this step, a regression was used to establish a SPOT-

AVHRR calibration model. Specifically, randomly selected 44 AVHRR NDVI values from 2005 and 2006 respectively were correlated to the downscaled 1-km SPOT 4 NDVI data. The R^2 values and the slope of the regression models between SPOT and AVHRR data for each year and both years are used to determine the efficiency of the calibration models.

The SPOT-calibrated AVHRR NDVI time series were then used to derive percent vegetation cover for each of the landscape units. The effects of precipitation on vegetation were examined through correlating percent vegetation cover with climatic indices (accumulated precipitation, the CMI, and the MPDSI). The coefficients of determination (R^2) were calculated for NDVI and climate variables over 20 years to determine how much variation in percent vegetation cover could be explained by climate data for each landscape unit.

3. Results

Based on field measurements it is found that in the years 2005 and 2006, mean percent vegetation cover of the shrub was 37.2% with a large variation (standard deviation = 12.5%), the upland/sloped grass was 17.9% with a low variation (standard deviation = 3.2%), and the valley grass was 10.8% with an even lower standard deviation of 2.5% (Table 1).

Insert Table 1 approximately here

In terms of species composition, the upland/sloped landscape unit was dominated by northern wheatgrass (*Elymus lanceolatus*), blue grama (*Bouteloua gracilis*), June grass (*Koeleria macrantha*) and western wheatgrass (*Pascopyrum smithii*). Valley landscape unit were patchy (Figure 1), reflecting varied salinity and microtopography. Dominant species in the valley

grassland landscape unit was salt grasses (*Distichlis stricta*, *Puccinella nuttallii*); bluegrasses (*Poa sandbergii*, *P. compressa*), and cactus (*Opuntia* spp.). The riparian shrub landscape unit was dominated by western snowberry (*Symphoricarpos occidentalis*), prairie rose (*Rosa acicularis*) and sagebrush (*Artemisia cana*).

The repeated random sub-sampling validation provided the best vegetation prediction model with a 5.37% RMSE (Figure 3). 79% of percent vegetation cover was explained by SPOT NDVI using the model.

Insert figure 3 approximately here

Insert figure 4 approximately here

SPOT-AVHRR calibration models are shown in Figure 4. The results indicated a good consistency between SPOT and AVHRR in both 2005 and 2006. The slopes are close to one in both the 2005 and 2006 regression models indicating that there was no underestimation or overestimation, in spite of higher NDVI data in 2005 and lower NDVI data in 2006. We thus used data from both years to establish the regression model between SPOT and AVHRR (Figure 3) and this regression model (Equation 3) was used to calibrate AVHRR NDVI time series.

$$\text{SPOT-calibrated NDVI} = 1.17 \times \text{AVHRR NDVI} - 0.03 \quad (3)$$

Insert figure 5 approximately here

Percent vegetation cover in the peak growing season was derived from AVHRR data and is shown in Figure 5a for the three landscape units. Throughout the years, vegetation cover was always higher in the shrub unit, followed by the upland/sloped grassland and then the valley grassland. The lowest vegetation cover for the three landscape units appeared in the years 1990,

1992, 2001 and 2006, corresponding to the lower precipitation during these years. The highest percent vegetation cover was found in 1989, 1991, 1994, 1999, and 2002, corresponding well with high levels of precipitation in those years. However, it was also found that the vegetation cover in 1988 and 1997 were relatively low, while precipitation was not as low as would have been expected considering the vegetation response. Higher temperatures experienced in these two years may have caused an increase in plant evapotranspiration which exacerbated water deficiency in the soil resulting in a lower vegetation cover.

Insert figure 6 approximately here

The regressions between percent vegetation cover and climate indices over the 20 years are shown in Figure 6. The accumulated precipitation (Figure 6 a, b, c), the CMI (Figure 6 d, e, f) and the MPDSI (Figure 6 g, h, i) was able to explain higher variations in percent vegetation cover in the upland/sloped grassland ($R^2 = 0.41$ for accumulated precipitation, 0.45 for the CMI, and 0.53 for the MPDSI), low variations in shrub unit ($R^2 = 0.25$ for accumulated precipitation, 0.28 for the CMI, and 0.32 for the MPDSI), and much lower in valley grass ($R^2 = 0.09$ for accumulated precipitation, 0.14 for the CMI, and 0.21 for the MPDSI). Compared with using only precipitation data, the CMI and the MPDSI were found to be able to explain a higher variation in percent vegetation cover. This is especially obvious when using the MPDSI to detect the effect of water availability on the valley grass – no significant relationship ($p = 0.17$ in Figure 6 b) was found between percent vegetation cover and accumulated precipitation or the CMI ($p = 0.09$ in Figure 6 e), while a significant relationship was observed between percent vegetation cover and the MPDSI ($p < 0.05$ in Figure 6 h).

4. Conclusions and Discussion

This study revealed moderate to strong links (Figure 6) between percent vegetation cover and precipitation over three landscape units in the protected semi-arid grass prairie region of Canada. The results are not surprising since soil water availability is critical to plant survival, development, and ultimate productivity, and precipitation is a major natural source of soil moisture in the semi-arid grasslands (He et al., 2007). Accumulated precipitation and two modified indices are significantly correlated with percent vegetation cover over upland/sloped grass and shrub landscape units, indicating that these indices have the capacity to quantify the effect of water availability on the plants in these areas. In comparison with accumulated precipitation, the CMI and MPDSI explained more of the total variation in percent vegetation cover, likely because the index takes into account the important process of evaporation. These results are in agreement with a similar study in which evapotranspiration-based indices performed better than precipitation-based indices in monitoring agricultural droughts (Narasimhan and Srinivasan, 2005).

The MPDSI was able to explain much more of the total variation in percent vegetation cover over the three landscape units, reflecting the fact that the index considered both water availability (P-PET) and the variations in water availability ($\sigma(P)$) during the analyzed period. Percent vegetation cover in natural grasslands is not only dependent upon accumulated precipitation, but also upon vegetation/soil evapotranspiration and upon how the precipitation varied during the period. This result also demonstrated the importance of applying the appropriate index to investigate the effect of climate conditions on semi-arid grassland vegetation traits. For this and similar areas, it is preferable to use the MPDSI to identify and monitor the response of vegetation to a changing climate. A multi-index drought model which

combines the strengths of various drought indices may be explored in the future for the natural grasslands as it was recently demonstrated to be able to provide better agricultural drought risk assessment on the Canadian prairies (Sun et al, 2011).

The higher correlations between climatic indices and percent vegetation cover in upland/sloped grass landscape unit are reasonable as water plays a crucial role in plant growth in this landscape unit. Compared with the upland/sloped grass, the shrub showed lower response to short term changes in climate. This result is consistent with a similar study (Zhang, 2006) in which the author found that climate would have significant influences on shrub growth only in an extremely dry year. It is also widely accepted that shallowly rooted grasses rely on soil moisture primarily from summer rainfall events, while deep-rooted shrubs would favor deep soil moisture (Pennington and Collins, 2007). Further, in the valley grassland, we failed to see significant correlations between percent vegetation cover and accumulated precipitation or the CMI and a weak but significant correlation between percent vegetation cover and the MPDSI. The lack of response by the valley grassland unit may be partially resulting from having only 13 sites compared to 20 and 19 sites for the other two landscape units. To further check if the smaller sampling size leads to the lack of response by the valley unit, the responses of the other two units using the same size (i.e. only considering 13 sites out of the 20/21 sites) were also examined and the results showed that their responses were still more pronounced than the valley unit.

It is worth noting that percent vegetation cover decreased in the years with moderate precipitation but high temperature, suggesting that a decline in water availability caused by a combination of reduced precipitation and increased evapotranspiration may have led to a loss of percent vegetation cover. Based on predicted future climate scenarios it can be expected that the

1
2
3
4 360 mixed grassland prairies become warmer with an increase in variable precipitation such as
5
6 361 extreme storms (Sauchyn, 2010). Such a change in climate could thus induce a decrease in
7
8
9 362 percent vegetation cover and further lead to a dramatic reduction in productivity (Parton et al.,
10
11 363 1995). In addition, a decrease in vegetation cover could increase soil erosion rates – likely an
12
13 364 irreversible process. Long-term studies integrating field and remote sensing data are
14
15
16 365 recommended to more definitively establish the mechanisms behind the observed changes in
17
18 366 percent vegetation cover and its associated effects.
19
20
21

22 367 Climate conditions, especially precipitation, were found to play an important role in
23
24 368 vegetation growth. However, only 21- 53% of the variation in vegetation cover was explained
25
26
27 369 across three different landscape units, indicating that other factors had contributed to the
28
29 370 variation seen in vegetation growth. Previous studies have discovered that other environmental
30
31 371 factors such as topography (e.g. He et al., 2007), soil properties (e.g. Zhang, 2006), and wildlife
32
33 372 grazing (e.g. Landsberg et al., 2009) also contribute to vegetation variation. In our study area,
34
35
36 373 these factors, together with climate may interact and affect vegetation growth in a complex
37
38
39 374 manner.
40
41
42

43 375 This study focused upon the role of the year-to-year variation of study area-averaged
44
45 376 precipitation on vegetation. Given precipitation spatial variation can be significant as a
46
47
48 377 consequence of local variation in the intensity and path of convective thunderstorms, vegetation
49
50 378 percent cover data from each randomly selected site were averaged to represent averaging
51
52 379 condition of the landscape unit across the park, which was further related to area-averaged
53
54
55 380 rainfall data from two weather stations. At this moment, *in-situ* measurement (rain gauge) from
56
57 381 the weather stations is still considered as a benchmark for the area-averaged rainfall in various
58
59
60 382 research fields (e.g. meteorology and hydrology). However, the “averaging” condition may not
61
62
63
64
65

1
2
3
4 383 fully reflect the effect of precipitation on spatial pattern of vegetation and thus result in relatively
5
6 384 lower/uneven vegetation responses.
7
8
9

10 385 The effect of the spatial variability of the rainfall on vegetation is not assessed in this
11
12 386 work since only two series of weather data are available. The other option is to retrieve rainfall
13
14
15 387 data using satellite technologies (visible/near-infrared, passive microwave, and active sensors),
16
17 388 but the satellite products have their own problems. Microwave sensors onboard polar-orbiting
18
19
20 389 satellites can directly detect precipitation hydrometeors and the overlying cloud layer, but
21
22 390 generally have relatively coarse spatial (~20 km) and temporal (1-2 visits per day) sampling
23
24
25 391 frequency. The visible/ near-infrared measurements from geostationary satellites can offer a
26
27 392 much higher time resolution (hourly or finer), but have a poor physical connection to
28
29
30 393 precipitation since rainfall rates are estimated from the cloud-top temperatures. Ground-based
31
32 394 radars can provide high spatial (a few km²) and temporal resolution (~ 6 min) precipitation
33
34 395 estimation, but suffer from several known sources of uncertainty such as reflectivity calibration,
35
36
37 396 inappropriate Z-R relation, range degradation, and bright band contamination. To resolve the
38
39 397 spatial variability of the precipitation field, the most efficient way could be using the grid data
40
41
42 398 from an assimilation system, e.g. the Canadian Precipitation Analysis (CaPA), that merges the
43
44 399 gauge, radar, satellite, and model forecast. Currently, the CaPA resolution (~15 km) is still too
45
46
47 400 coarse for this type of work. When finer-resolution precipitation data become available, the role
48
49 401 of the spatial variability of precipitation will be further investigated.
50
51

52 402 Although the SPOT- percent cover regression model and the SPOT-AVHRR calibration
53
54
55 403 model were acceptable, the R² values in the SPOT- percent cover models and a slope of 1.17 in
56
57
58 404 the calibration model (Figure 4) indicated that the use of remote sensing to estimate percent
59
60 405 vegetation cover from satellite data sources are subject to uncertainty, leading to the propagation
61
62
63
64
65

of the error existing in the regression of percent vegetation cover-climate indices. Further research using more field data and multi-sensor remote sensing images may address these issues.

In summary, this work examined the responses of three different landscape units to precipitation based upon their year to year variations. The purpose is to provide new insight into the effects of precipitation/climatic factors upon different landscape units and to establish a more complete picture in this field. The findings from this work could be of value for the prediction, model studies and other field comparisons in the future. For example, the identified relations between vegetation cover and climatic index can be used to estimate the future vegetation cover, based upon a climate projection, i.e. the potential effect of climate change on the vegetation cover. The results also can provide guidance/reference for model studies and other field observations.

Acknowledgement

The support of the NSERC Discovery Grant RGPIN-386183 to Dr. Yuhong He is gratefully acknowledged. The author truly appreciates Dr. Xulin Guo for sharing her research data.

Reference:

- Adair, M., Cihlar, J., Park, B., Fedosejevs, G., Erickson, A., et al., 2002. GeoComp - n, an advanced system for generating products from coarse- and mediumresolution optical satellite data. Part 1: System characterization. Canadian Journal of Remote Sensing. 28, 1-20.
- Akinremi, O.O., McGinn, S.M., Barr, A.G., 1996. Evaluation of the Palmer Drought Index on the Canadian Prairies. Journal of Climate. 9, 897-905.

- Andales, A.A., Derner, J.D., Ahuja, L.R., Hart, R.H., 2006. Strategic and tactical prediction of forage production in northern mixed-grass prairie. *Rangeland Ecology and Management*. 59, 576-584.
- Archibald, S. and Scholes, R.J., 2007. Leaf green-up in a semi-arid African savanna -separating tree and grass responses to environmental cues. *Journal of Vegetation Science*, 18, 583–594. doi: 10.1111/j.1654-1103.2007.tb02572.x
- Daubenmire, R.F., 1959. A canopy coverage method of vegetational analysis. *Northwest Sci.* 35, 43–64.
- Davidson, A. and Csillag, F., 2003. A comparison of three approaches for predicting C4 species cover of northern mixed grass prairie. *Remote Sensing of Environment*. 86, 70-82.
- Derner, J.D., Hess, B.W., Olson, R.A. and Schuman, G.E., 2008. Functional group and species responses to precipitation in three semi-arid rangeland ecosystems. *Arid Lands Research and Management*. 22, 81-92.
- Derner, J.D., Hickman, K.R., Polley, H.W., 2011. Decreasing precipitation variability does not elicit major aboveground biomass or plant diversity responses in a mesic rangeland. *Rangeland Ecology Management*. 64, 352–357.
- Gitay, H., Noble, I.R. 1997. What are functional types and how should we seek them? In: Smith TM, Shugart HH, Woodward FI (eds) *Plant Functional Types. Their Relavance to Ecosystem Properties and Global Change*. Cambridge University Press, Cambridge, pp 3-19
- Guo, X., Zhang, C., Wilmshurst, J., Sissons, R., 2005. Monitoring grassland health with remote sensing approaches. *Prairie Perspectives*. 8, 11–22.
- He, Y., X. Guo, B.C. Si., 2007. Detecting grassland spatial variation by a wavelet approach. *International Journal of Remote Sensing*. 28, 1527 – 1545.

- 1
- 2
- 3
- 4 451 He, Y., X. Guo, and J. Wilmshurst. 2006. Studying mixed grassland ecosystems I: suitable
- 5
- 6 452 hyperspectral vegetation indices. *Canadian Journal of Remote Sensing*. 32(2), 98-107.
- 7
- 8
- 9 453 He, Y., X. Guo, and J. Wilmshurst. 2009. Reflectance measures of grassland biophysical
- 10
- 11 454 structure. *International Journal of Remote Sensing*. 30 (10), 2509-2521.
- 12
- 13
- 14 455 Heim, R. R., 2002. A review of twentieth-century drought indices used in the United States. *Bull.*
- 15
- 16 456 *Amer. Meteor. Soc.* 83, 1149–1165.
- 17
- 18 457 Hogg, E.H. 1997. Temporal scaling of moisture and the forest-grassland boundary in western
- 19
- 20
- 21 458 Canada. *Agricultural and Forest Meteorology*. 84, 115–122.
- 22
- 23 459 Hunt, E. R., Jr., Everitt, J. H., Ritchie, J. C., Moran, M. S., Booth, D. T., Anderson, G.L., Clark,
- 24
- 25
- 26 460 P. E., and Seyfried, M. S., 2003. Applications and research using remote sensing for
- 27
- 28 461 rangeland management, *Photogrammetric Engineering & Remote Sensing*. 69: 675-693.
- 29
- 30
- 31 462 Keyantash, J., and J. Dracup, 2002. The quantification of drought: An evaluation of drought
- 32
- 33 463 indices. *Bull. Amer. Meteor. Soc.*, 83, 1167–1180.
- 34
- 35
- 36 464 Li, Z., Guo, X., 2012. Detecting climate effects on vegetation in northern mixed prairie using
- 37
- 38 465 NOAA AVHRR 1-km time-series NDVI Data. *Remote Sensing*, 4(1), 120-134.
- 39
- 40
- 41 466 Liang, E. Y., Vennetier, M. Lin, J. X., and Shao, X. M. 2003. Relationships between tree
- 42
- 43 467 increment, climate and above-ground biomass of grass: A case study in the typical steppe,
- 44
- 45 468 North China. *Acta Oecological*, 24, 87–94.
- 46
- 47
- 48 469 McGinn, S.M. 2010. Weather and climate patterns in Canada’s prairie grasslands. In *Arthropods*
- 49
- 50 470 *of Canadian Grasslands, Vol. 1: Ecology and Interactions in Grassland Habitats*. Edited
- 51
- 52
- 53 471 by J.D. Shorthouse and K.D. Floate. *Biological Survey of Canada, Ottawa, Ontario*. pp.
- 54
- 55 472 105–119.
- 56
- 57
- 58
- 59
- 60
- 61
- 62
- 63
- 64
- 65

- McKee, T. B. N., J. Doesken, and J. Kleist, 1993. The relationship of drought frequency and duration to time scales. *Proc. Eight Conf. on Applied Climatology*. Anaheim, CA, Amer. Meteor. Soc., 179–184.
- Mishra, A.K., and V. P. Singh, 2010. A review of drought concepts. *J. Hydrol.*, 391, 202–216
- Michalsky, S.J., Ellis, R.A. 1994. *Vegetation of Grasslands National Park*. D.A. Westworth and Associates Ltd. Calgary AB.
- Narasimhan, B., and R. Srinivasan. 2005. Development and evaluation of soil moisture deficit index and evapotranspiration deficit index for agricultural drought monitoring. *Agricultural and Forest Meteorology*, 133, 69-88.
- Palmer, W.C. 1965. Meteorological drought, Res. Pap. 45, 58 pp., U. S. Weather Bur., Washington, D. C.
- Palmer, W.C. 1968. Keeping track of crop moisture conditions, nationwide: the Crop Moisture Index. *Weatherwise*, 21, 156–161
- Parks Canada 2006. *Restoring Grazing-Induced Heterogeneity in Grasslands National Park of Canada: Large-Scale Experiment and Long-term Monitoring Plan*. Grasslands National Park of Canada.
- Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Schimel, D.S., Hall, D.O., and SCOPEGRAM Group Members, 1995. Impact of climate change on grassland production and soil carbon worldwide. *Global Change Biology*, 1, 13-22.
- Pennington D.D., Collins, S.L. 2007. Response of an aridland ecosystem to interannual climate variability and prolonged drought. *Landscape Ecol.* 22, 897–910.
- Quiring, S.M. and Papakyriakou, T.N. 2003. An Evaluation of Agricultural Drought Indices for the Canadian Prairies. *Agricultural and Forest Meteorology*, 118, 49-62.

- Sauchyn, D.J. 2010. Prairie Climate Trends and Variability. Chapter 3 In Sauchyn, D.J., Diaz, H. and Kulshreshtha, S. (editors) The New Normal: The Canadian Prairies in a Changing Climate. CPRC Press, Regina, SK.
- Stow, D.A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrich, F., Houston, S. et al. 2004. Remote sensing of vegetation and land-cover change in arctic tundra ecosystems. *Remote Sensing of Environment*, 89, 281-308.
- Sun, L., Mitchell, S.W., Davidson, A. 2011. Multiple drought indices for agricultural drought risk assessment on the Canadian prairies. *Int J Climatol*. doi:10.1002/joc.2385
- Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. *Geographical Review*, 38, 55–94. doi:10.2307/210739
- Vapnik, V., 1995. *The Nature of Statistical Learning Theory*. Springer-Verlag.
- Wu, C., J.M. Chen. 2012. The use of precipitation intensity in estimating gross primary production in four northern grassland. 82: 11-18.
- Yang Y.H., Fang, J.Y., Li, C.J., 2009. Aboveground biomass in Tibetan grassland. *Journal of Arid Environments*. 73: 91-95.
- Zhang, C., 2006 *Monitoring Biological Heterogeneity in a Northern Mixed Prairie Using Hierarchical Remote Sensing Methods* (PhD thesis, University of Saskatchewan, Saskatchewan)
- Zhang, C. and Guo, X., 2008. Monitoring northern mixed grassland health using broadband satellite imagery. *International Journal of Remote Sensing*, 29, 2257-2271

Table 1 Descriptive statistics of percent vegetation cover and a list of dominant species in the three landscape units

	Descriptive statistics		Dominant species
	Percent cover		
Upland/sloped grassland	Percent cover	17.9%	<ul style="list-style-type: none"> • needle-and-thread (<i>Stipa comata</i> Trin. & Rupr) • blue grama (<i>Bouteloua gracilis</i>) • western wheatgrass (<i>Pascopyrum smithii</i>)
	Standard Deviation	3.2%	
	Minimum - Maximum	13.2% -25.1%	
Valley grassland	Percent cover	10.8%	<ul style="list-style-type: none"> • salt grasses (<i>Distichlis stricta</i>, <i>Puccinella nuttallii</i>) • western wheatgrass and northern wheatgrass (<i>Agropyron dasystachym</i>) • cactus (<i>Opuntia</i> spp.)
	Standard Deviation	2.5%	
	Minimum - Maximum	7.3% -13.0%	
Riparian shrub	Percent cover	37.2%	<ul style="list-style-type: none"> • western snowberry (<i>Symphoricarpos occidentalis</i>) • prairie rose (<i>Rosa acicularis</i>) • sagebrush (<i>Artemisia cana</i>)
	Standard Deviation	12.5%	
	Minimum - Maximum	15.5% - 57.8%	

Figure Captions:

Figure 1. Study area located at the West Block of Grasslands National Park, Canada. Picture (a) bottom left is showing valley grasses, (b) for upland/sloped grasses, and (c) is for riparian shrubs.

Figure 2. A flowchart of the overall approach for modeling percent vegetation cover based on ground data, SPOT images, and AVHRR time series which is then used to relate the derived percent vegetation cover to precipitation data.

Figure 3. The best percent vegetation cover prediction model determined through the repeated random sub-sampling validation.

Figure 4. The relationship between SPOT NDVI and AVHRR NDVI in 2005 and 2006

Figure 5. Percent vegetation cover for three landscape units (a) and accumulated June precipitation and mean temperature (b) from 1988 to 2007

Figure 6. The relationship between percent vegetation cover during the peak growing season and accumulated precipitation over three landscape units (a for upland/sloped grass, b for valley grass, and c for riparian shrub) from 1988 to 2007, between percent vegetation cover and the CMI (d for upland/sloped grass, e for valley grass, and f for riparian shrub), and between percent vegetation cover and the MPDSI (g for upland/sloped grass, h for valley grass, and i for riparian shrub).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6