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Topographic Effects on Vegetation Biomass in Semiarid Mixed Grassland under Climate Change Using AVHRR NDVI Data

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Authors' contributions

This work was carried out in collaboration between both authors. Author ZL designed the study, performed the statistical analysis, and wrote the first draft of the manuscript. Author XG as the academic supervisor of author ZL provided direction on this research and comments on the drafted manuscript. Both authors read and approved the final manuscript.

Short Research Article

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ABSTRACT

The topography effects on vegetation biomass under climate change impact have been ignored in prairie regions as it is not as significant as in mountain areas. This paper aims to investigate the topographic effects on vegetation biomass under climate change in semiarid Canadian mixed grass prairie. The study site is Grasslands National Park (GNP) and the study period is from 1985 to 2007. Data used include dry green biomass data sampled from June to July of 2003 to 2005, 10-day Advanced Very High Resolution Radiometer (AVHRR) 1km Normalized Difference Vegetation Index (NDVI) composites of 1985 to 2007, and Global Digital Elevation Model derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER GDEM) data with 90 m resolution. To achieve the objective, the applicability of AVHRR NDVI data being a proxy of vegetation biomass was investigated. Then, the range and standard deviation (SD) of each individual vegetation patch in both valley and upland grasslands were calculated. In addition, the variation trend of valley and upland vegetation was analyzed respectively using the Mann-Kendall (M-K) test and the Sen's slope. The results indicate that the inter-annual variation of vegetation biomass at GNP can be fairly well represented by AVHRR 1 km NDVI data. Although some patches in valley grassland have similar NDVI range and SD values as those in upland grassland, the others have much smaller range and SD

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values than the highest range (0.154) and SD (0.045) of upland grassland. The M-K test and Sen's slope analyses indicate that NDVI had an increase trend with a larger slope (0.0005) in upland and a smaller slope (0.0002) in valley grassland. It is concluded that climatic variation has more effects on upland grassland than valley grassland in GNP. Topography effects in prairie regions should not be ignored.

Keywords: Topographic effect; climate change; vegetation; semiarid mixed grass prairie; AVHRR NDVI product; mann-kendall test.

1. INTRODUCTION

Grasslands are ecologically important as they provide multiple habitats for diverse wildlife [1], and economically essential for achieving high agricultural productivity as they hold the largest grazing capacity in the world [2]. Unfortunately, grasslands are experiencing a worldwide degradation in recent decades due to climate change and anthropological activities [3]. Under such circumstances, evaluation on climate change impacts on grassland ecosystems is essential for coming up with suitable management plans to adapt to climate change [4].

The impacts of climate change on grassland vegetation have been assessed in numerous studies. These climate impacts were generally assessed based on either modeling (simulation) or empirical relationships between vegetation indices derived from satellite imagery and climate variables. According to modeling, the older and traditional limestone grasslands were more resistant to the simulated climate change than the younger, productive, and disturbed limestone grasslands in UK [5]. Climate change generally increases net primary production in temperate and tropical grasslands globally, except in cold desert steppe regions [6]. The humid grassland [7] and mixed-grass prairie of USA [8] were also under the influence of climate change. In addition to modeling, there is considerable research conducted using vegetation indices especially Normalized Difference Vegetation Index (NDVI), the ratio of the difference and the sum of near-infrared (NIR) and red reflectance, as an indicator of vegetation [9]. NDVI have demonstrated good linear relationships with environmental variables, such as temperature and precipitation, under various environmental circumstances [10]. NDVI data have been used to study vegetation response to climate change at a range of time and spatial scales [9,11-13], and explore variation trends of vegetation [14-16] under climate change. For example, climate change impacts on temperate grasslands [17], Alpine grasslands [e.g., 18,19], northern Great Plains [20,21], Canadian mixed prairie [22], and Sahel region of Africa [23] have been assessed using NDVI time series data. These studies are beneficial to future research in terms of the methods used and to their local ecosystem management in terms of adaptations to climate change. However, in these studies, topographic effects on vegetation under climatic change were ignored as they are not as significant as in mountainous regions where ecosystems are likely more vulnerable under climate change [24]. According to the Hurley Pasture Modeling results, lowland grasslands in southern Britain likely had different response to climate change than upland grasslands in northern Britain [25]; however, they could not draw the conclusion on topographic effects because of the different geographic locations.

Canadian mixed grass prairie are experiencing increased frequency of extreme weather events [26], such as drought and floods, and the precipitation pattern may be subjected to change in the future based on climate models [27]. Under such circumstances, investigation on vegetation response to climate change is essential for coming up with suitable conservation plans. Our previous research in Grasslands National Park (GNP), portion of Canadian mixed grass prairie, indicated that both temperature and precipitation have significant and positive effects on vegetation growth [22]. Despite significance, temperature and precipitation can only account for 30% variations in vegetation biomass [22], which indicates that vegetation growth is also controlled by other factors, such as nutrition, and soil types and soil moisture. In natural grasslands, the accumulation of soil nutrition and the generation of soil moisture are closely related with topography which affects temperature, precipitation, and soil types and properties [28]. In this regard, topography may also play an essential role in vegetation growth. In addition, research has found that topographic effects make the response of vegetation to climate change pronounced [29]. Therefore, the objective of this study is to investigate topographic effects on vegetation under climatic variation. Our hypothesis is that topography may cause different response of vegetation to climate change even in relatively flat Canadian prairie region.

To achieve the objective of studying topographic effects on vegetation biomass under climate change, this paper first investigated the applicability of the chosen NDVI data reflecting vegetation biomass in the study area, and then compared range, standard deviation (SD), and trend of vegetation biomass using NDVI data as a proxy in both high and low elevation areas. In this study, aspect and slope as topographic properties were not considered due to the low spatial resolution NDVI and Digital Elevation Model (DEM) data used and introduced in section 2.2.

2. MATERIALS AND METHODS

2.1 Study site

The study site is the west block of GNP (49.10ºN, 106.89ºW) in southern Saskatchewan, Canada (Fig. 1). GNP was chosen because considerable climate change and ecology research has been conducted since it was established in 1984 [1,30]. The particular research interests in GNP are attributed to the fact that it is the northern edge of continental C_4 vegetation and a gene pool of native and endangered species, and had not been influenced by domestic animal grazing until 2006. In 2006, seventy-one bison including 60 calves were introduced to a large area (181km^2) in the west block of GNP for conservation purposes, and in 2007 cattle grazing started. However, such light to moderate grazing had not significantly affected vegetation productivity as climate change had done in both GNP and its surrounding area where light to moderate cattle grazing history extends for at least 100 years [31]. Our study period is 1985-2007. During that period, grazing only occurred in 2006 and 2007 and the grazing effects would not be significant based on the finding of [31]. In addition, natural fire was almost eliminated from the study area and no prescribed burning has occurred prior to 2007 since 1980s [32]. Therefore, the variation of vegetation productivity in the study area from 1985 to 2007 was mainly caused by climatic variation.

GNP is in a continental climate region of Köppen climate classification with hot summers and cold winters. Based on the climate record of 1971-2000 of Environment Canada, the mean annual temperature in GNP is 3.8ºC, the average daily July temperature is 28ºC, and the average low temperature in January is -22ºC. The average of the annual total precipitation is 347.7mm, while less than 100 mm in drought years. Rainfall during evening storms in May and June accounts for most of the precipitation. Consequently, the dominant climatic feature of GNP is low soil moisture availability [32]. Vegetation growth in this area is highly influenced by precipitation, although temperature also plays an important role [22].

Vegetation in GNP is generally classified as upland or valley vegetation based on the elevation ranging between 750 and 905 m (Fig.1). Upland makes up an approximate 70% of the total area. In the upland, the dominant vegetation species are Spear grass and Blue Grama grass (SB, *Stipacomata-Bouteloua gracilis*) and Western Wheatgrass and Sedge (AC*, Agropyron smithii-Carex sp.*). In the valley, the dominant vegetation species are Western Wheatgrass and Sagebrush (AAO, *Agropyron smithi-Artemesia sp.*), Rose and Buckbrush (RS, *Rose sp.-Symphoricarpos occidentalis*), Greasewood and Rillscale (SA, *Sarcobatus vermiculatus-Atriplex nuttallii*), Willow and Buckbrush (SaS, *Salix sp.-Symphoricarpos occidentalis*), and Thorny Buffaloberry and Buckbrush (ShS, *Shepherdia argentia - Symphoricarpos occidentalis*).

Field campaigns were conducted in the growing seasons of 2003 to 2005, and field data including aboveground biomass were collected over the sampling transects with crossing centers shown in Fig.1. The sampling transects were set up in both valley and upland grasslands (Fig. 1), and the number of transects was 12, 11, and 29 respectively in 2003, 2004, and 2005. Details on how the field data were sampled were introduced in section 2.2.

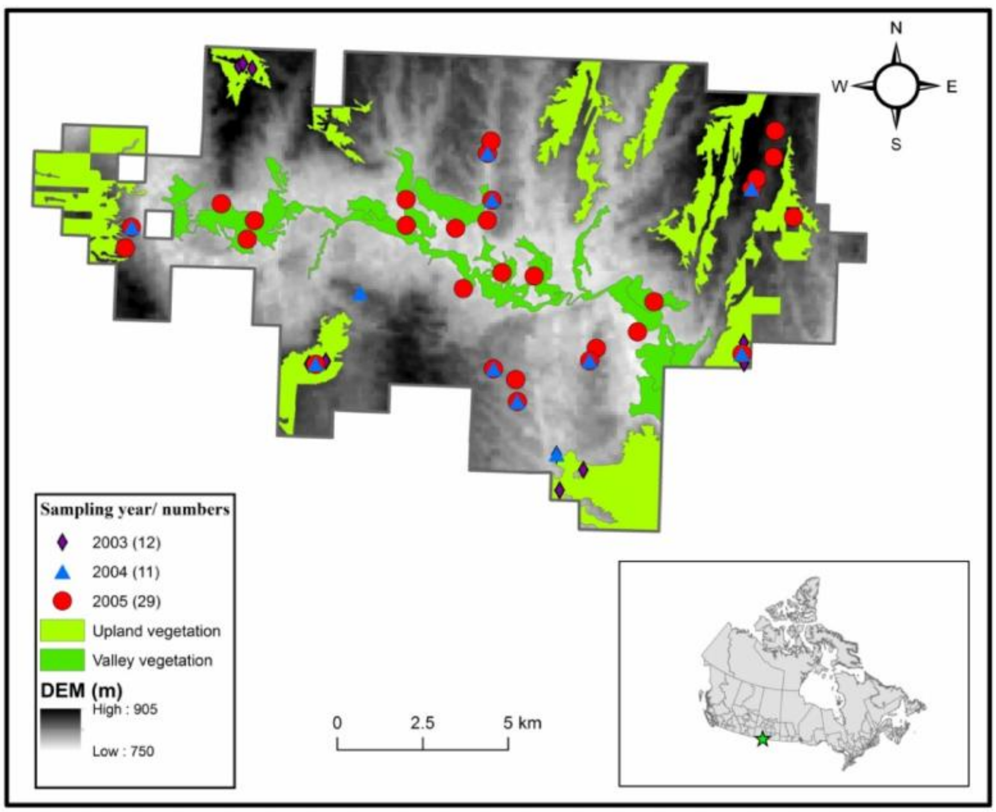

Fig. 1. The geographic location (shown in green star), current holding, Digital Elevation Model (DEM), and the distribution of the centers of biomass sampling transects in 2003 to 2005 of the west block of Grasslands National Park (GNP)

2.2 Data

Data used in this study are ground-level dry green biomass, space-level 10-day Advanced Very High Resolution Radiometer (AVHRR) NDVI 1km composites, and Global Digital Elevation Model derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER GDEM) 90m data. The dry green biomass data were obtained by drying fresh aboveground biomass harvested from the sampling sites shown in Fig. 1 for 48 h at 60ºC in an oven. At each sampling site, biomass was clipped within a 20×50 cm quadrat at 20m intervals over two 100m long transects crossing at right angles in 2003 to 2005. The sample number collected in mid June, late June, and early July of 2003 is 36, 48, and 72, in mid June and late June of 2004 is 132 and 36, and in mid June, late June, and mid July of 2005 is 168, 36, and 156 respectively.

The used NDVI composites were from April 1st to October 31st during the time period of 1985-2007, which were produced from the imagery of AVHRR onboard the National Oceanic and Atmospheric Administration (NOAA) 9, 11, 14, 16, 17, and 18 satellites. These image composites were processed via the New Geocoding and Compositing System (GEOCOMP-n) [33,34] by Manitoba Remote Sensing Centre, Canada. The GEOCOMP-n system can improve the quality of products through the improved geocoding, inter-sensor calibration, atmospheric correction, Bi-directional Reflectance Distribution Function (BRDF) correction, and identification and removal of cloud contamination [33]. ASTER GDEM data can be downloaded at no cost from http://gdem.ersdac.jspacesystems.or.jp/, which was used to classify the study area into valley and upland grassland together with the vegetation map provided by Parks Canada.

2.3 Methods

2.3.1 AVHRR/NDVI data as a proxy of vegetation biomass

Whether actual variations of vegetation cover in semiarid areas can be captured by variations of NDVI is arguable because variations of NDVI are influenced by many factors, such as seasonal variations in atmospheric water vapor [35] and atmospheric aerosol content [36], large percentage of bare soil [37,38] and orbital drift and sensor changes [39]. Although the application of AVHRR 1 km NDVI data as a proxy of vegetation vigor in GNP and the northern Great Plains [20,40] has demonstrated a promise, the representativeness of AVHRR 1 km NDVI data on vegetation biomass in Canadian semiarid mixed grass prairie is still worthy to be investigated. Therefore, testing the applicability of the NDVI data is the first step of this study. To test the applicability, first, NDVI data were extracted from the AVHRR NDVI composites and then negative NDVI values were removed as such values are certainly too low to reflect vegetation. Second, the biomass data collected from all the sampling sites were averaged for each 10 day period to match the compositing time period of AVHRR imagery. Finally, the representativeness of the NDVI data regarding biomass of the sampling sites was investigated by demonstrating those data in a graph.

2.3.2 Topographic effects on vegetation biomass

To investigate the topographic effects (elevation effects in this paper) on vegetation biomass, first, the variations of vegetation biomass in upland and valley during the study period of 1985 to 2007 were compared by range and standard deviation (SD). Second, the trend and the change rate of vegetation biomass in upland and valley during the study period under climatic variation were compared. The analysis was first conducted on each polygon (vegetation patch), and then on the entire upland and valley grassland respectively. To use AVHRR NDVI 1 km data effectively, only polygons with the legend of upland and valley vegetation in Fig. 1 that have an area larger than 1 km^2 were chosen.

2.3.2.1 Variations of vegetation biomass

To compare the elevation effects on the variations of vegetation biomass, annual mean NDVI (annual NDVI) was calculated, considering the greenup and senescence dates in each year determined in our previous research [22]. Next, annual NDVI of each vegetation patch having an area greater than 1km^2 was retrieved. Our previous study indicated that annual NDVI in 1999 was the maximum and in 2005 was the minimum during 1985-2007 [22]. Thus, the range of annual NDVI of each vegetation patch was calculated based on the NDVI data in 1999 and 2005. The SD values of annual NDVI of each patch during 1985-2007 were also computed. Finally, the ranges and SD values of annual NDVI in upland and valley were used to investigate the response of vegetation to elevation effects under climatic variation.

2.3.2.2 Trend and change rate of vegetation biomass

The variation trend of vegetation biomass in the study area was detected via the non-parametric Mann-Kendall (M-K) test [41,42] and the change rate was estimated based on the Sen's slope [43]. The M-K test has been widely used for detecting a trend of a normally or non-normally distributed time series in environmental sciences [44], such as changes of meteorological varaibles [e.g., 45,46], air pollutants [47], water quality parameters [48], river flow [49], and vegetation phenology and vegetation condition of grasslands [22].

Taking NDVI as an example, given the annual NDVI time series $NDVI_1$, $NDVI_2$ . . ., $NDVI_n$ are the sequential data values, n (23 in this study) is the data set record length, and the M-K test statistic S is given by the formula:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(NDVI_j - NDVI_k) \tag{1}$$

Where $NDVI_j$ and $NDVI_k$ are the annual values in years j and k, j > k, respectively, and

$$\mathrm{sgn}(NDVI_j - NDVI_k) = \begin{cases} 1 & NDVI_j - NDVI_k > 0 \\ 0 & NDVI_j - NDVI_k = 0 \\ -1 & NDVI_j - NDVI_k < 0 \end{cases} \tag{2}$$

The variance of S is computed as:

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The test statistic Z is calculated as below:

$$Z = \begin{cases} \frac{S+1}{\sqrt{VAR\,(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S-1}{\sqrt{VAR\,(S)}} & S < 0 \end{cases} \tag{4}$$

The statistical trend of mean NDVI is evaluated using the Z value. A negative Z value indicates a downward trend, a positive Z value shows an upward trend, and a zero Z value means that the time series data have no trend to change. The significance of the detected trend is tested based on a defined significance level, such as 0.05.

The slope of the existing trend (the change per year) was computed using the Sen's non-parametric method which is applicable when the trend can be assumed to be linear [43]. A time series data $f(t)$ with a continuous monotonic increasing or decreasing trend can be expressed as.

$$f(t) = Q_t + B \tag{5}$$

where Q is the slope and B is a constant. To estimate $\mathbf{Q}$,

$$Q_i = \frac{NDVI_j - NDVI_k}{j-k} \tag{6}$$

where j, k are the number of the year, and j > k. Sen's estimator of slope equals to the median slope (Q).

$$Q = \begin{cases} Q_{[(N+1/2)]} & \text{if N is odd} \\ \dfrac{Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]}}{2} & \text{if N is even} \end{cases} \tag{7}$$

Where $N = n(n-1)/2$ is the number of calculated slopes, and n is the data record lenth and equals 23 in this study.

3. RESULTS AND DISCUSSION

3.1 AVHRR/NDVI as a Proxy of Vegetation Biomass

The NDVI and dry green biomass during each sampling period are shown in Fig. 2. There is an inter-annual consistency between biomass and NDVI. The larger amount of dry biomass is reflected by the higher NDVI values in 2003 and 2004 and the smaller amount of biomass is captured by the lower NDVI in 2005. The intra-annual variations of biomass are also fairly well represented by the changes of NDVI. Using 2003 as an example, the largest amount of biomass in late June is captured by the highest NDVI and the smallest biomass in early July is reflected by the lowest NDVI. The intra- and inter-annual consistency of variations of NDVI and biomass allow the use of NDVI for studying vegetation response to climate change [50,51].

3.2 Elevation Effects on the Variations of Vegetation Biomass

The ranges and SD values of annual NDVI of each vegetation patch in the valley and upland are shown in Fig. 3. The NDVI range shows the variation of vegetation biomass under two different climate conditions in 1999 and 2005 (Fig. 3 (a)). In the valley, the ranges of annual NDVI of a few vegetation patches vary from 0.111-0.129, and the other values are between 0.130-0.153. In the upland, despite ranges of annual NDVI of some patches range from 0.130-0.153, the NDVI differences are greater than 0.154 in the other patches.

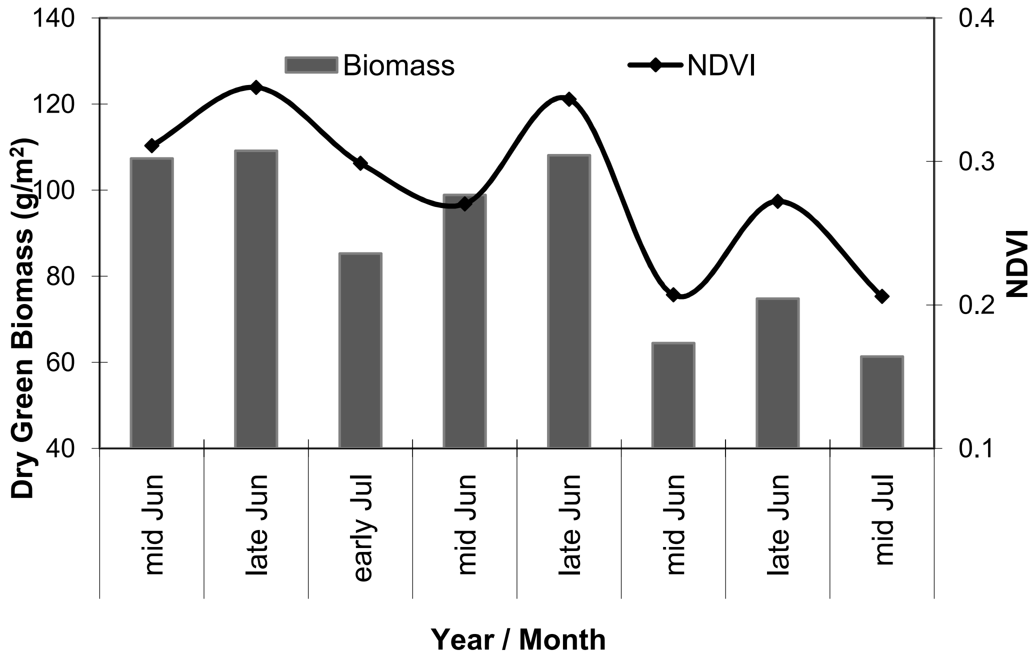

Fig. 2. Biomass versus NDVI averaged across the specific sampling sites in the west block of GNP from mid-June to mid-July in 2003 to 2005

The SD values of annual NDVI indicate the inter-annual variation of vegetation biomass under climatic variation. Shown in Fig. 3 (b), the majority of the SD values of NDVI in both valley and upland are between 0.037 and 0.043. However, there are a few patches in the valley having SD values smaller than 0.036 that is smaller than those of the majority of patches in the upland. In addition, the SD of NDVI of one vegetation patch in the upland is greater than 0.043, which is not observed in the valley vegetation patches. Overall, the SD values of NDVI in vegetation patches of valley are generally smaller than or close to the SD values of NDVI in the upland.

Our previous study [22] found that intra-annual and inter-annual variations of NDVI in the study area were significantly correlated with temperature and precipitation. Intra-annually, the variation in temperature was generally at the same pace with change of NDVI, although temperature within 20 days prior to NDVI measurements also significantly affected NDVI. Precipitation has more effects on NDVI than temperature and the effects of precipitation lasts much longer than those of temperature. Inter-annually, the co-effects of precipitation and temperature on NDVI are also statistically significant. In addition, as stated in Section 2.1, the study area had not been grazed or burned during the study period, and no other anthropological activities had been reported. Therefore, variations of NDVI during the study period were basically the consequences of climatic variations. Under such climatic variations, upland grassland was generally more affected than valley grassland.

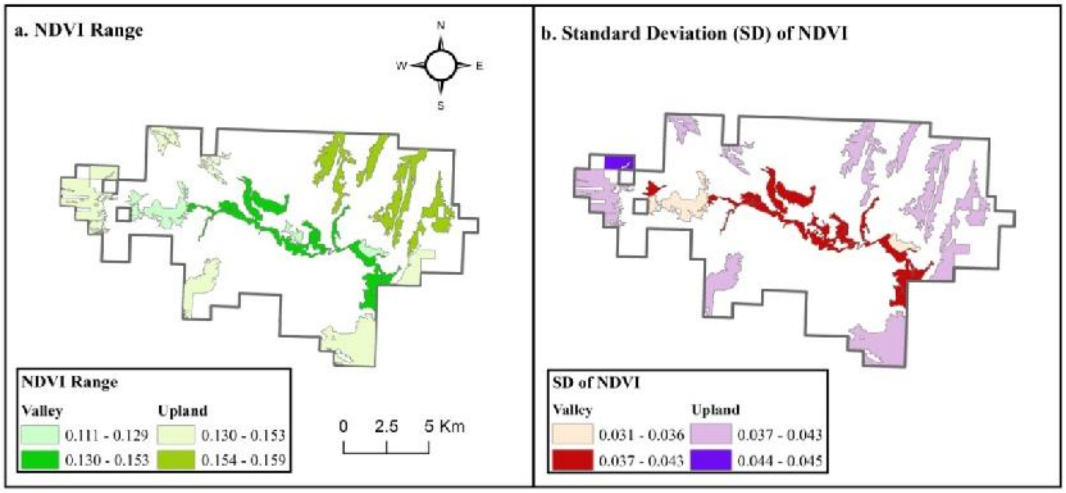

Fig. 3. (a). NDVI range and (b): Standard Deviation (SD) of NDVI in each vegetation patch of valley and upland grassland

3.3 Elevation Effects on Trend and Change Rate of Vegetation Biomass

The trends and changing rates of annual mean NDVI in the valley and upland vegetation patches are illustrated in Fig. 4. Sen's slope is larger than zero, which means the corresponding Z value is greater than zero and thus annual NDVI has an increase trend. Annual NDVI of the majority of vegetation patches in both valley and upland has an increase trend, but a few patches remain unchanged. In the valley, annual NDVI values of three patches have no trend change, while one patch has a trend to increase at a rate of 0.0011 and the majority valley patches have an increasing trend with moderate slopes ranging from 0.0001- 0.0005. The trend analyses of the majority patches are statistically significant at the 0.10 level. In the upland, although annual NDVI values of some patches have no trend to change or have a trend to increase at the moderate rates (0.0001-0.0005), three patches have annual NDVI change rates greater than 0.0006.

In addition to each individual vegetation patch, the M-K test and Sen's slope analyses were also applied to annual NDVI in the entire valley and upland. The results indicate that both valley and upland vegetation have increasing trends during the time period of 1985-2007, which is consistent with the conclusion on NDVI trend in the entire west block of GNP [22]. NDVI in the upland has an increase trend with a steeper slope (0.0005) than that in the valley (0.0002), although both are significant at the 0.10 level. Both temperature and precipitation in GNP shows an increasing trend during 1985-2007 [22] and other research found that precipitation in Canadian prairie has increased [52,53]. Considering the significant correlation between NDVI and temperature and precipitation, the increasing trend of annual NDVI can be accounted for by the increased precipitation and temperature [22]. In a specific area, a higher elevation zone experiences relatively higher wind speed than a lower elevation zone, which speed up evaporation and thus reduce soil moisture. Soil moisture as a limiting factor of vegetation growth in GNP is not only highly related to elevation, but also is controlled by precipitation and other soil properties. Since GNP is a conserved area without artificial fertilizer, as precipitation increases, the increased soil water facilitates vegetation growth in both upland and valley where temperature is favorable. Vegetation growth in the valley can be promoted by soil water supplied by the runoff from surrounding higher terrain [38]. Therefore, vegetation in the valley may be less affected by climatic variation, and vegetation biomass in upland generally increases at a greater rate. This conclusion is consistent with the assertion that mountainous ecosystems, such as Alpine grasslands, are more impacted by climate change [24].

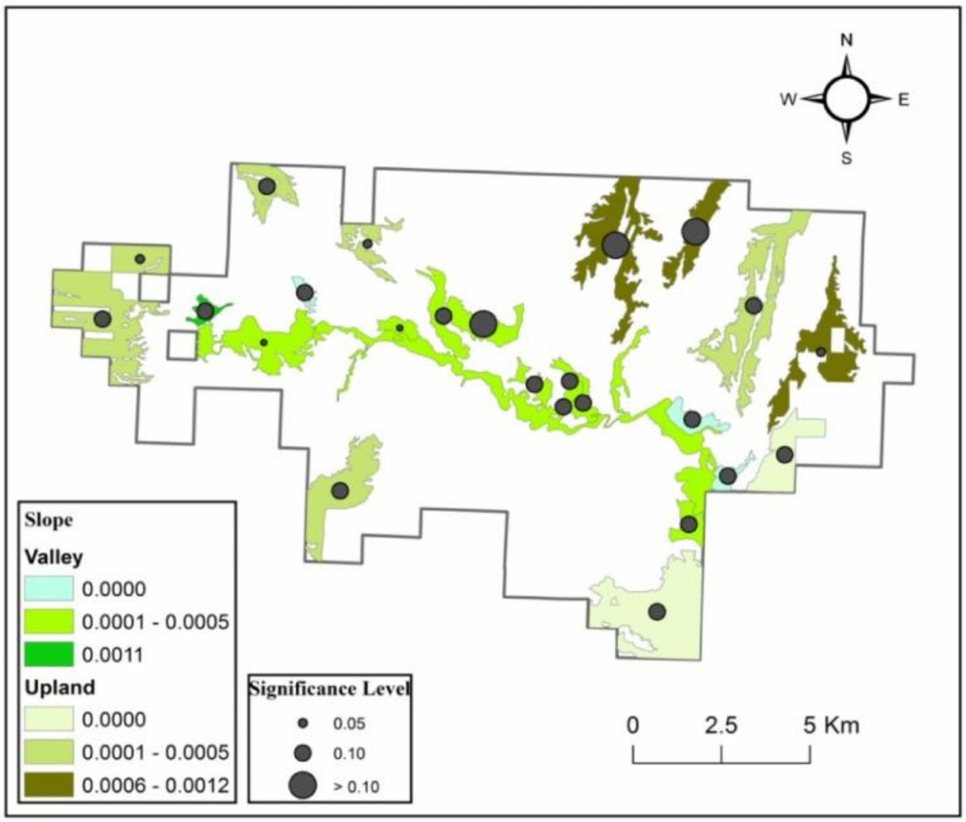

Fig. 4. The Sen's slopes of annual mean NDVI in the valley and upland with the significance levels

Elevation as one of the topographic variables demonstrated a strong relationship with vegetation biomass in mountainous environment [54]. However, topographic effects on vegetation under climatic variation in relatively flat regions have been ignored in previous studies. Our study has investigated the elevation effects on vegetation biomass in GNP and found that climatic impacts on vegetation in valley and upland are at different degrees although the largest elevation difference is only 155 m. Vegetation in the valley demonstrates less variation than that in the upland. In this paper, only elevation effects were taken into account, limited by the spatial resolution of AVHRR NDVI data and ASTER GDEM data. However, even if only elevation effects were considered, vegetation of valley has shown less sensitive to climate change than vegetation in upland. Therefore, our research hypothesis that topography may cause different responses of vegetation to climate change in relatively flat Canadian prairie region is acceptable. In reality, besides elevation, other topographic properties including terrain slope and aspect may exert more pronounced effects on vegetation growth because of their influence on microenvironment variables, such as wind, incident solar radiation, temperature, and soil moisture. Therefore, it is a good idea to take topographic effects into account while evaluating climate change impacts on vegetation and further on species habitats, especially in small spatial scales, even if the topography in the study area is not as complex as in mountainous regions.

4. CONCLUSION

The AVHRR 1 km NDVI data can be a proxy of vegetation condition in Grasslands National Park (GNP), portion of semiarid mixed grass prairie. Taking valley grassland as a whole and upland grassland as the other, the comparisons between the ranges and SD values of NDVI in upland and valley indicate that climatic variation has more effects on vegetation biomass in the upland than those in the valley. Under climatic variation from 1985 to 2007, vegetation biomass in both upland and valley has demonstrated an increasing trend, whereas the increase rate is larger in upland.

Although the largest elevation difference in the study area is only 155 m, the difference of vegetation biomass in valley and upland in response to climatic variation can be observed. This indicates that topographic effects are not negligible when studying climate impacts on vegetation in rolling topography of prairie. In addition, this study provides information for policy makers in GNP to make conservation plans for valley and upland respectively to adapt to climate change.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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