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Detecting Spatial and Temporal Patterns of Aboveground Production in a Tallgrass Prairie Using Remotely Sensed Data

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Abstract -- Spatial and temporal patterns of aboveground production in a tallgrass prairie ecosystem constitute one of the important spatial components associated with ecological processes and biophysical resources (e.g., water and nutrients). This study addresses the effects of disturbance, topography, and climate on the spatial and temporal patterns of North American tallgrass prairie at a landscape level by using high resolution satellite data. Spatial heterogeneity (SH) derived from the satellite data was related to the impacts of the disturbance of fire and grazing, topographical gradient, and amount of precipitation during the growing season. The result suggests that ecological processes and biophysical resources can be quantified with high resolution satellite data for tallgrass prairie management.

INTRODUCTION

Climatic change, disturbance (e.g., fire and grazing), and topography are three important factors influencing tallgrass prairie production and ecosystem function. Spatial variability in net primary production (NPP) is often associated with topographic gradients [1,2]. Topography is also related to soil moisture [3,4] and available soil nitrogen [5] gradients. The impacts of climate, disturbance, and topography on tallgrass production patterns and dynamics result in complete interactions among components with strong negative and positive feedbacks. Previous research on this issue focused on field-scale surveying and sampling, which make it difficult to extend the results to a spatially heterogeneous landscape if the number of field samples is limited. However, remote sensing techniques have provided the capability of detecting aboveground vegetation production for decades. As high resolution satellite images become available, detecting changes in vegetation patterns and dynamics within a watershed or landscape becomes possible.

Numerous studies have been reported on detecting and evaluating soil information [6], biophysical parameters [7], and primary production [8] in the tallgrass prairie ecosystem by using remotely sensed data. A few studies have addressed the spatial and temporal aspects of the landscape between the aboveground production patterns, derived from remotely sensed data, and the impacts of disturbance, topography, and environmental conditions. In an early study, Nellis and Briggs [9] suggested that Landsat TM and aerial photography are sufficient for conducting the landscape classification of burned

and unburned watersheds in the tallgrass prairie. Later, Briggs and Nellis [10] examined the intraseasonal variability of the spatial structure derived from SPOT satellite images. To link remote sensing data with ecological processes in the tallgrass prairie, Davis et al. [11] and Henebry [12] used spatial dependence measures to detect changes in the tallgrass prairie with Landsat TM data. In our study, we used a spatial heterogeneity (SH) measure, calculated from the normalized difference vegetation index (NDVI) images that were derived from Landsat TM images, as a texture measure, to determine the spatial and temporal patterns of the grassland production and its relation to topography, disturbance, and climate.

In this paper, we (1) evaluate relationships between tallgrass prairie production and topographic gradient from ground and satellite-based data and (2) link the changes in spatial and temporal patterns of the tallgrass prairie production with the effects of precipitation, disturbance (fire and grazing), and topography.

MATERIALS AND METHODS

Study Area

This study was conducted in the Konza Prairie Research Natural Area (KPRNA), a 3,786-ha native tallgrass prairie about 10 km south of Manhattan, Kansas, U.S.A. Vegetation in the study area was dominated by warm season grasses, *Andropogon gerardii* Vit., *Sorghastrum nutans* (Michx.) Nash, and *Panicum virgatum* L. Soils were developed from the Permian limestones and shales with alternating layers of strata. Occasional loess deposits are found on ridge tops at the KPRNA. Limestones in the study area contain cherty components, which prevent soils from being converted into cropland. Average annual precipitation is 835 mm/yr with a variable seasonal distribution resulting in many wet-dry cycles in soils during a typical growing season (April to September). Soil depth varies from uplands (< 0.4 m) to lowlands (< 1 m).

On the basis of fire (prescribed burning) frequency treatment and water catchment basins, KPRNA is divided into about 66 watersheds. In the fall of 1987, bison (*Bison bison*) were introduced into a fenced area with five contiguous watersheds (N1A, N2A, N2B, N4C, and N20A, where the number in the watershed code is years of burning intervals) with different burning frequencies on KPRNA. Bison can move freely within this area. The bison-grazing area was

expanded in 1992 to include an additional five watersheds (N1B, N2B, N4B, N4D, and N20B, where the number is burning interval years). A total of 145 animals were present in 1992.

Plant Sampling

Plant biomass data were collected at the time of maximum seasonal biomass (early August) at eleven sites along an annually burned (1D) and long-term unburned (20B) transect since 1989. Four 0.1 m² quadrants were harvested at each of the eleven sites within each ungrazed watershed. The sampled vegetation was sorted into live graminoids, forbs and woody plants, current year's dead, and previous year's dead vegetation. All data except previous year's dead were combined to provide an estimate of aboveground production or NPP. NPP data from 1989 to 1993, except for 1992, were included in this study.

Satellite Image Analysis

A series of nine Landsat TM images acquired during July through August from 1983 to 1991 were used to calculate the normalized difference vegetation index (NDVI) from red (TM band 3) and infrared (TM band 4) bands. All nine Landsat TM images of KPRNA were registered to Universal Transverse Mercator (UTM) coordinates with a 30-m pixel-resolution. A radiometric rectification procedure [13,14] was used to normalize all images onto the 1987 image (as a reference image) on the basis of pseudoinvariant features in real space. This procedure has the advantage of not requiring ancillary information or a complex atmospheric correction model. The suitability of using the 1987 image as the reference has been demonstrated elsewhere [14].

SH was calculated using the intrawindow range, a max-min texture measure [10], for all nine NDVI images. Median values of SH for each watershed and the whole area were also calculated to better represent the spatial structure and minimize the skewness effect. Window sizes, ranging from 3 × 3 to 11 × 11, were used to examine the possible effects of spatial scales. Watersheds (N1A, N20A, N1B, and N20B) were selected for individual spatial pattern comparison. N1A and N20A are both in the riparian area, including a small portion of forest cover; N1B and N20B are in the upper land areas.

Digital elevation model (DEM) data of the study area, with a 30-m resolution, were also available from the Konza geographical information system (GIS) database and were integrated with satellite images to extract elevation information in each transect and watershed on the KPRNA. The SH measure was also applied to the DEM data for the topographical effect analysis. Weather information (e.g., precipitation) from 1983 to 1991 was available for the analysis from the Konza Headquarters Weather station.

RESULTS

Table 1 shows the relationships between NPP and elevation for the annually burned (1D) and long-term unburned (20B) transect from 1989 to 1993 (1992 data were unavailable). A significant linear correlation ($p < 0.05$) was found between NPP and topographic position for the annually burned transect with r^2 from 0.42 to 0.72. No clear trends were evident for the long-term unburned transect, for which no statistical correlation was found in 1990 and 1993 data. Relationships between NDVI and elevation from 1987 to 1991, as shown in Table 2, also suggest that higher correlation occurs for the annually burned transect than for the long-term unburned transect, except for 1991, in which case the correlation is enhanced by a wildfire.

Table 3 shows the Spearman correlation coefficient for the relationships between SH for NDVI and SH for elevation. There was a statistically significant relationship for most of the nine NDVI images and elevation data, except for the images in 1983, 1986, and 1988. No clear trends were seen as window sizes increase from 3 × 3 to 11 × 11.

Table 1. Coefficient of determination between net primary production (NPP) and elevation for the annually burned (1D) and long-term unburned (20B) transect.

Year ¹	1D		20B	
	r^2 (n = 11)	<i>p</i>	r^2 (n = 11)	<i>p</i>
1989	0.42	0.03	0.00	0.98
1990	0.51	0.02	0.41	0.03
1991	0.42	0.03	0.33	0.06
1993	0.72	0.03	0.01	0.88

¹ 1992 NPP data were not available.

Table 2. Coefficient of determination between NDVI and elevation for the annually burned (1D) and long-term unburned (20B) transect from 1987 to 1991.

Year	1D		20B	
	r^2 (n = 10)	<i>p</i>	r^2 (n = 9)	<i>p</i>
1987	0.71	0.00	0.53	0.03
1988	0.65	0.00	0.66	0.01
1989	0.51	0.02	0.35	0.09
1990	0.63	0.01	0.46	0.04
1991	0.41	0.04	0.69	0.01

Fig. 1 shows a negative correlation between SH and total growing season (April through August) precipitation. SH increases as the precipitation decreases. Fig. 2 shows the fire and grazing effects of SH for watersheds N1A, N20A, N1B, and N20B. It appears that there is no clear trend of variation in SH between two adjacent watersheds (N1A -- burned annually; N20B -- long-term unburned) from 1983 to 1987. SH of the annually burned watershed (N1A) is higher than that of the long-term unburned watershed from 1988 to 1991. Watersheds N1B and N20B, which did not have bison grazing from 1983 to 1991, also show very little difference in SH with the different burning frequency treatments.

DISCUSSION

At a landscape level, topography plays an important role in soil moisture distribution [3,4], soil nutrient cycling and availability [5], plant and water relation [15], and microclimate [2]. All those factors influenced by topography finally contribute to spatial variability of primary production in the tallgrass prairie ecosystem. The correlation between NPP and elevation for the annually burned transect agreed with the findings of Barnes et al. [1] and Knapp [2]. However, this relationship may vary in a long-term unburned watershed because of increasing SH or patchiness with invasion of woody species [16] and variation in soil moisture and other biophysical resources [3]. The topographic effect interacted strongly with seasonal and intraseasonal climatic change (e.g., precipitation variation). For example, in the relative dry (1983 or 1988) and wet (1986) years, the variation of the NDVI patterns was not significantly related to the topography (Table 3).

Table 3. Spearman correlation coefficient for the relationships between SH for NDVI and SH for elevation for 49 selected watersheds from 1983 to 1991.

Year	Window Size (pixels)				
	3 × 3	5 × 5	7 × 7	9 × 9	11 × 11
1983	0.14	0.13	0.14	0.24	0.24
1984	0.37**	0.38**	0.37**	0.43**	0.41**
1985	0.55**	0.55**	0.57**	0.49**	0.38**
1986	0.24	0.19	0.12	0.16	0.19
1987	0.26	0.31*	0.29*	0.32*	0.37**
1988	0.20	0.20	0.06	0.13	0.33*
1989	0.41**	0.50**	0.52**	0.57**	0.56**
1990	0.53**	0.53**	0.52**	0.57**	0.50**
1991	0.54**	0.47**	0.46**	0.50**	0.47**

* Statistically significant at a level of 5%.

** Statistically significant at a level of 1%.

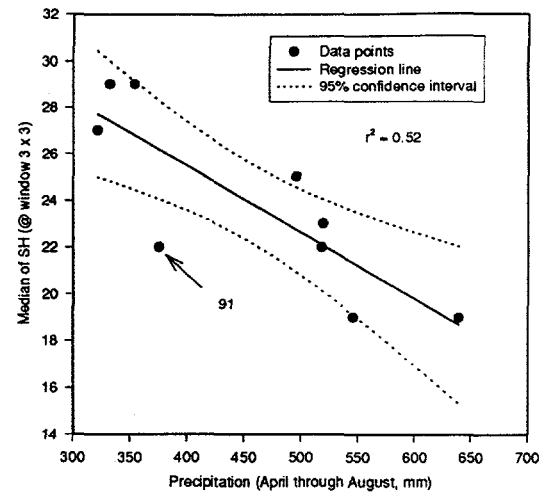


Fig. 1. Relationship between median of SH and total growing season precipitation for the nine Landsat TM images (1983-1991).

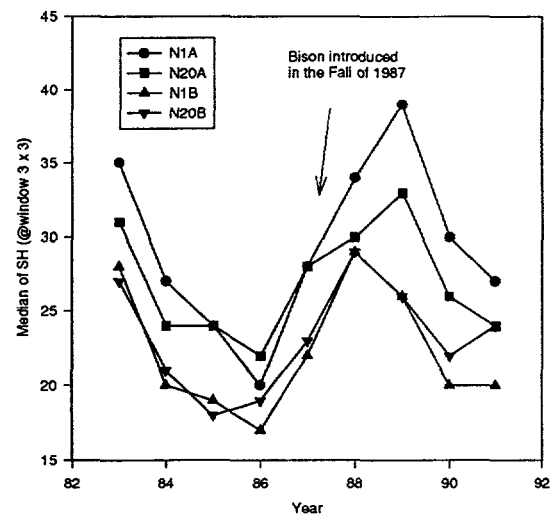


Fig. 2. Seasonal changes in SH values from 1983 to 1991 as affected by bison and fire. N1A is burned and grazed; N20A is unburned and grazed; N1B is burned and ungrazed; and N20B is unburned and ungrazed.

Total growing season precipitation, an important climatic variable, is a key parameter in vegetation production and is strongly correlated with the spatial structure of the NDVI patterns measured by the intrawindow range technique. Although Fig. 1 does not show the correlations for larger window sizes (> 3 × 3), the relation exhibits a similar trend.

Seasonal precipitation is responsible for increases or decreases in SH. However, the effect of precipitation could confound the topographic effect that causes the spatial variability in soil moisture [4], nutrients [5], and production [1]. It is not clear that the short-term drought from 1988 to 1989 caused plant species and community changes. Introduction of bison in the fall of 1987 may also have impacted the spatial structure.

Grazing not only removes vegetation but also increases compaction of soil by trampling and wallowing. Landscapes grazed by large herbivores can undergo changes in surface hydrology [17], plant community [18], and plant water relations [19], thereby creating SH (local patchiness) at the subpixel scale of the Landsat images. Grazing, coupled with the 1988-1989 drought, in the annually burned watershed (N1A) may be responsible for the increase of SH values after 1987. Selective grazing [19] on the annually burned watershed could be the major factor that results in higher SH values for the annually burned watershed compared to the long-term unburned watershed (N20A), even though the drought in 1988-1989 may have interacted with the grazing.

Nellis and Briggs [9] used a similar approach to assessing the effect of spatial scales on the impact of burning and grazing on the KPRNA. They suggested that finer scale remote sensing data, such as aerial photographs and Landsat TM, were sufficient for examining the SH of the burned and unburned areas (watersheds). However, on the basis of the results of our study, it is uncertain whether the burning effect can be assessed by the SH values derived from the Landsat TM images. Comparing the annually burned, ungrazed watershed (N1B) with the long-term unburned, ungrazed watershed (N20B), no clear trend suggested that the long-term unburned watershed exhibited higher SH. The interpretation by Nellis and Briggs [9] was based on a single Landsat TM image (1987) and different watersheds, which may not be comparable. We believe that the fire effect is scale dependent and may intermingle with other factors such as grazing, precipitation, and topography. However, further investigation is required to assess the spatial pattern and its relation to the ecological processes in the tallgrass prairie ecosystem.

CONCLUSIONS

Detecting spatial and temporal patterns in aboveground production is important for long-term monitoring of ecological and environmental conditions in the tallgrass prairie ecosystem. High resolution Landsat TM image data provide the capability of detecting landscape patterns in this ecosystem as affected by topography, disturbance (fire and grazing), and climatic change. We concluded that topographic effect in aboveground production was characterized by the SH measure derived from the Landsat TM images and intermingled with seasonal precipitation and possibly with fire and grazing. Landsat TM data are useful in detecting the spatial structure of the tallgrass prairie. However, the SH measure needs to be

further investigated as a metric to monitor and assess the changes in ecological and environmental conditions as affected by natural and/or human impacts.

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