Topography Affects Grassland Heterogeneity

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Abstract

Determining and monitoring ecosystem heterogeneity and biodiversity is important for grassland management and can be carried out through remote sensing such as satellite images. However, in rolling landscapes, biophysical properties of ecosystems, the indicators of heterogeneity and biodiversity are highly scale and location dependent and little research is reported on how topography affects biophysical properties of ecosystems quantitatively. The objective of this study is to examine how topography affects spatial biophysical variation using statistics and a wavelet approach in the mixed grassland ecosystem, Saskatchewan, Canada. Field leaf area index (LAI) was collected with an LAI-2000 instrument and topographical data were measured using a total station along five paralleled transects. Results showed that biophysical spatial variation is highly topography-controlled, and the wavelet approaches can be used to identify the spatial heterogeneity of a grassland ecosystem at different scales. This study suggests the potentials of using readily-available topography data to guide the ecosystems management and selection of the resolution of satellite images.

Introduction

Heterogeneity is one of the most important and widely applicable concepts in ecology (Armesto et al., 1991). The mixed grassland of North America is an important component of the global ecosystem as a pool of carbon dioxide and a gene pool of wild lives and vegetations (Hill et al. 2000). It has been described as inherently heterogeneous because composition, productivity, and diversity vary across multiple scales (Ludwig and Tongway, 1995). Policymaker and managers are also interested in the spatial variations of grassland biomass to put forward strategies to deal with unfavorable disturbances. Hence it is critical to assess the status of grassland ecosystem heterogeneity to know its current condition. Remote sensing provides a means for estimating mixed grassland variability in a spatially distributed and timely manner, vegetation conditions and productivity (Moran et al., 1995; Moulin et al., 1998).

Heterogeneity and biodiversity of grassland ecosystem are a function of the soil property, topographic and climatic factors that operate at relatively large spatial scales (Sims and Singh, 1978; Wardle and Grime, 2003). Topographic features are the dominant factors determining soil physical properties and fertility status as well as controlling water distribution after snowmelt and rainfall (Zeleke and Si, 2004). Consequentially, in rolling landscapes, biophysical properties of ecosystems, the indicators of heterogeneity and biodiversity are highly scale dependent. Hence, topography parameters can be regarded as composite parameters that reflect the combined influence of various yield-affecting factors and their interactions (Si and Farrell, 2004). In recent year, numerous studies have focused on mixed grassland variability under condition of soil distribution (Pennock, 2001), different soil water content (Nouvellon et. al., 2001) and diverse climate environments (Burke, 1991; Ojima, 1996; Mitchell and Csillag, 2001). However, little research is reported on how topography affects soil properties as well as soil micro-climate, and thus affects biophysical properties of mixed grassland ecosystems. The lack of this knowledge results in insufficient understanding of the appropriate scale of remote sensing products for different topography, thus leading to poor prediction of grassland biophysical variables (e.g., LAI) by spectral data of the remotely sensed sensors in topography of rolling landscapes. Therefore, it is desirable to examine the effect of topography on biophysical properties of ecosystems, and the research results may suggest the potentials of using readily-available topography data to guide the ecosystems management and selection of the scale of satellite images.

There are studies revealed a clear association between crop yield and topographical parameters (e.g., slope percentage, soil surface curvature, and elevation, wetness index) (Si and Farrell, 2004). Wavelet analysis has been demonstrated as a useful tool for examining the association between two variables because wavelet analysis can reveal both scale and localized information on yield and topographical parameters (Si and Farrell, 2004). This paper attempts to examine how topography affects spatial biophysical variation using a wavelet approach in the mixed grassland ecosystem, Saskatchewan, Canada. Specifically, this research focuses on: 1) how much of the variation in grassland community distribution was accounted for by topographic parameters (elevation, upslope length and the wetness index); and 2) how to determine the scales of the variability in LAI from that of elevation, upslope length, and wetness index of mixed grassland ecosystem.

Materials

The study was conducted in Grasslands National Park, Saskatchewan, Canada (GNP). The area is characterized as semi-arid mixed grass prairie ecosystem, with approximately 340 mm annual precipitation falling mainly in the growing season (May – September) and a mean annual temperature of 3.4^0C (Environment Canada 2003). The study plot was located on upland grass ecosystem in the West Block of Grasslands National Park and dominant soil type was brown chernozem soils.

Field data collection was performed in the summer of 2004 along five parallel transects (381 M in length) across the landscape with a lateral distance of 10-m between transects. The vegetation and topography samples were taken at quadrats with 3-m intervals along center transect (128 locations) and 6-m intervals along other four transects (64 locations per transect). In all, a total of 384 points of elevation were measured in an area of 1.905 ha (i.e., 381 by 50 m).

LAI, elevation, angle, and distance were recorded at each quadrat. LAI was measured using a LiCor-LAI-2000 Plant Canopy Analyzer. A laser theodolite was used to measure elevations, angles and distance. These topographic measurements allow for precise calculation of slope percentage, curvature, and upslope length at any point along transects.

Three topographical parameters—Elevation, Upslope Length, and Wetness index (WI)—were analyzed in this paper. Upslope length was calculated as the distance from the measurement point in the landscape to the highest elevation point along the local slope (Si and Farrell, 2004). The wetness of Beven and Kirkby (1979) was calculated as

$$WI = \ln(\frac{\gamma}{\tan\beta}) \qquad [1]$$

Where r is the upslope length and tan_ is the local terrain slope of the landscape elements.

The relationships between grassland LAI and elevation, between grassland LAI and upslope length, and between grassland LAI and wetness index also were analyzed using Pearson Correlation Analysis.

The Fourier transforms with Mexican hat wavelet approach was adopted to analyze the scale of the process and spatial variability of grassland vegetation. The continuous wavelet analysis was used to examine the spatial variability in wetness index, upslope length, elevation, and grassland LAI. To facilitate comparison between local wavelet spectra, grassland LAI, upslope length, and the wetness index were standardized by subtracting their mean from measurements and then dividing the difference by their standard deviation. Wavelet transform was implemented with the fast Fourier transform. Since Fourier transform operates on infinite data series and we have data series with limited data length, Fourier transform automatically connect the beginning of the data series with its end (Wrap-around). Effect of wrap-around embedded in Fourier transform can artificially alter wavelet coefficients at the end of the data series. At the same time, fast Fourier transform requires the length of the data series to be a power of two. There were 128 measurements for grassland LAI, elevation, upslope length, and wetness index along the transect. Therefore, we padded 128 zeros to the end of grassland LAI, elevation, upslope length, and wetness index, to eliminate the wrap-around effect and to make the length of data series to be 256 ($=2^8$). The detailed formulations of the continuous wavelet transform, wavelet power spectrum analysis can be found in Si and Farrell (2004).

Results

Statistical analyses of the relationships between LAI and topographic parameters

Figure 1 illustrates the measured elevation and grassland LAI, as well as the calculated upslope length, and wetness index along the transect. There are three main depressions (centered at 87, 210, 360m) and a small depression centered at 270m along the transect. The measured LAI, upslope length, and the wetness index show a similar trend: large values in the depressions and small values on the knoll. In addition, measured grassland LAI, upslope length, and wetness index increase sharply near the three large depressions. Clearly, spatial variations in grassland LAI, upslope length, wetness index are nonstationary, exhibiting localized features at the three large depressions.

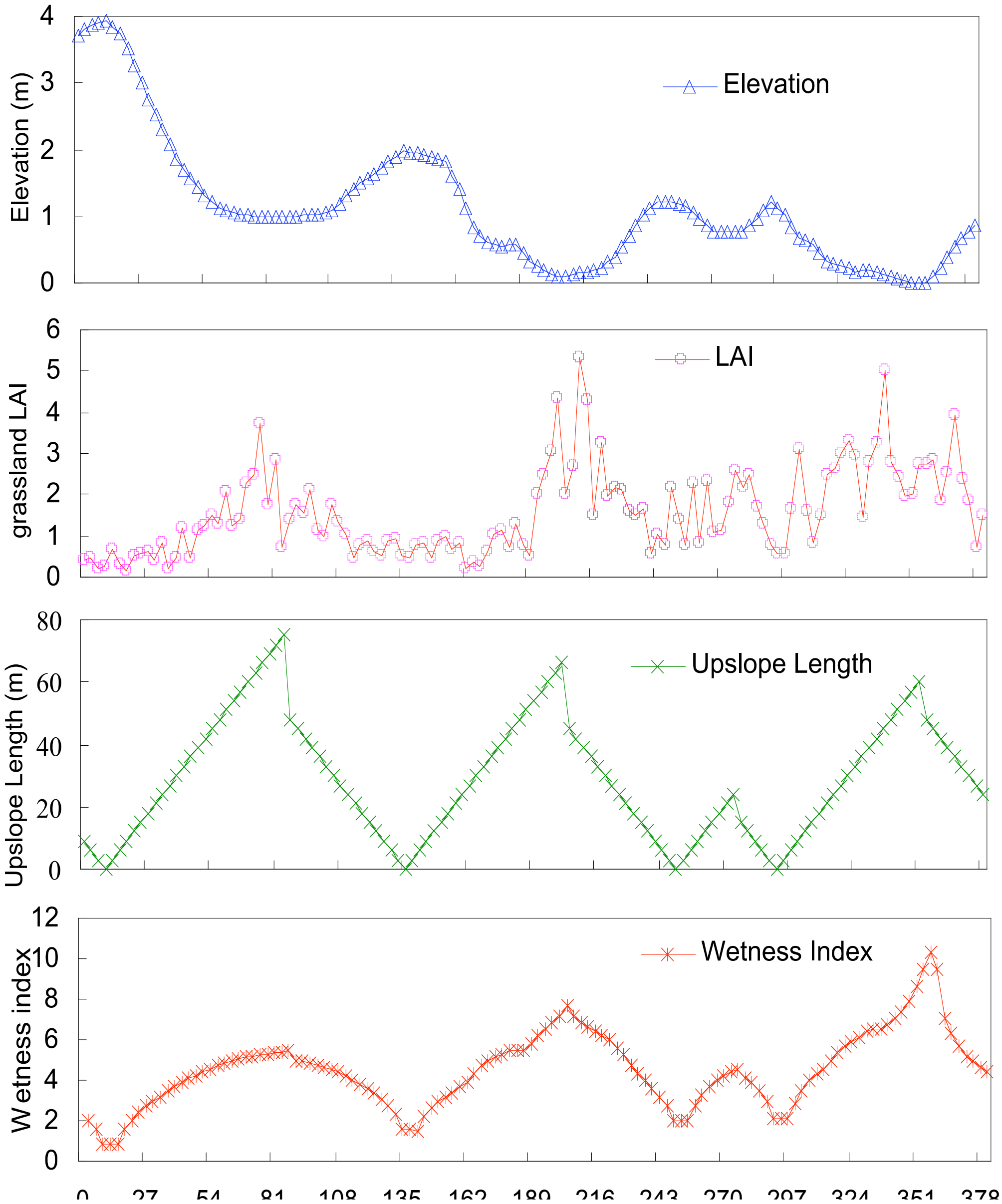

Fig. 1 Measured grassland elevation, LAI, upslope length, and the wetness index as a function of distance along the transect.

Statistics analysis indicates that there are strong correlations between grassland LAI and topography factors (i.e. elevation, upslope length, wetness index) (Table 1). This is not surprising, considering that soil water content (Hayashi et al., 2003), solar radiation (Seller, 1997) and soil organic community (Sebastiá, 2004) vary with rolling landscape. Water is the limiting factor for vegetation production in semiarid regions. Topography determines how soil moisture is distributed (Seller, 1997) when the soil is dry and thereby to a large extent determines an area's soil water content. Soil water storage before growing period becomes the most important water supply to grassland in GNP. Therefore the amount of snow accumulated, snow redistribution and snowmelt runoff largely determine soil water storage of GNP. Topographic variations have also an effect on the absorption and reflectance or emission of radiation by the surface (Seller, 1997), which directly effect photosynthesis of grassland. Soil organic community is the main environmental gradient structuring vegetation in grasslands at the landscape scale. Topography affects soil organic community distribution as well, although this effect can be mediated through soils. Landforms affect the amount of moisture and other materials available within landscapes, and contribute to developing and maintaining a patchwork ecosystem (Swanson et al., 1988). Slope, aspect and microtopography influence soil drought and plant evapotranspiration and also allow the accumulation or favor the export of nutrients and soil particles.

The coefficients of determinations between grassland LAI and upslope length (R^2= 0.22, p<0.001), between grassland LAI and elevation (R^2= 0.40, p<0.001), and between grassland LAI and wetness index (R^2= 0.42, p<0.001) are from low to high respectively. This indicates that the wetness index explained more of the total variation in grassland LAI than did elevation and upslope length. This reflects the fact that the wetness index is equal to the ratio of the upslope length to the local slope at a given point in the landscape (Eq. (1)) and, as such, reflects the steepness of the slope at that point. This result is different from Si and Farrel (2004) who showed stronger correlation between grain yield and upslope length than that between grain yield and wetness index. The different results might result from the difference between nature and man-made landscape. In nature grassland landscape, water and organic community accumulation is only effected by topography. While in cultivated land, the water and organic community accumulation are affected by cultivation in addition by topography. Therefore, in semi-arid regions, natural vegetation production at a point is more sensitive to both the steepness of the slope and the upslope length.

Table 1 Statistics of topographical parameters and grassland LAI obtained at 128 locations along the central sampling transect.

Variable	**Mean**	**SD–**	**Minimum**	**Maximum**	**R^2—**
LAI	1.57	1.06	0.14	5.35	_
Wetness index	4.48	1.84	0.83	10.27	0.42—–
Elevation	1.12	0.95	0	3.93	0.40—–
Upslope length	28.43	18.97	0	75	0.22—–

–– Significant at P<0.0001

– Standard Deviation

—Coefficient of determination between LAI and the column variable.

Wavelet analyses of the relationships between LAI and topographic parameters

Scales of variation in grassland LAI, elevation, upslope length, and the wetness index, were analyzed using the wavelet approach. As suggested by Si (2003), we first utilized exploratory analysis of the local wavelet spectrum to identify whether any patterns existed in the data and to determine whether these patterns were repeated across the transect (a global event) or were restricted to only one, or few, localized regions across the transect (localized events). The periodicity of the repeated pattern is referred to as the 'scale of variation'. If the pattern is global in scale, the global wavelet power spectrum is then analyzed to determine the significance of the variation.

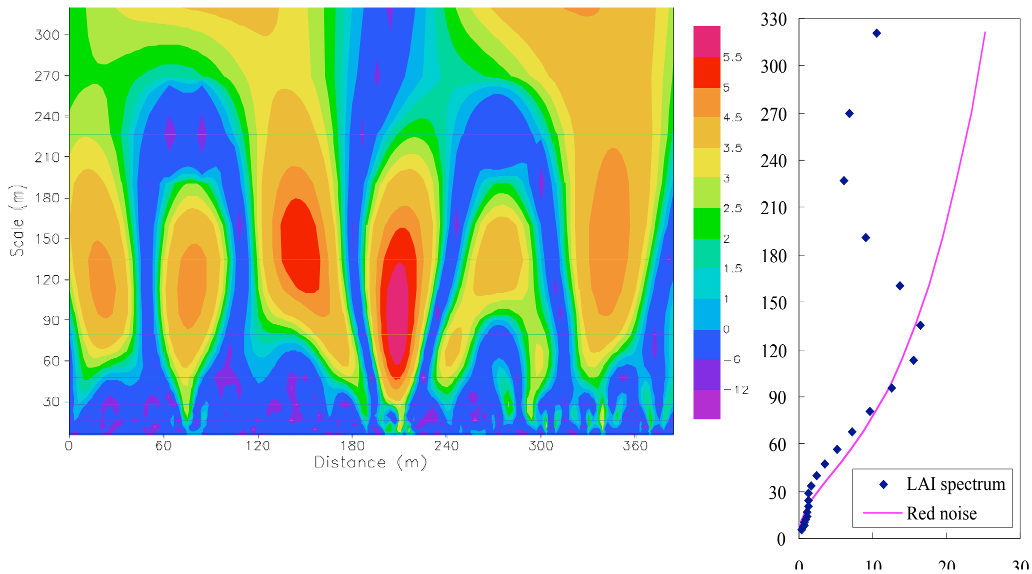

Fig. 2 Local (left) wavelet spectrum and global wavelet power spectrum of grassland LAI (right). The line in right figure is the power spectra of a red noise at a confidence level of 95%.

Visual inspection of the local wavelet spectrum for grassland LAI (Fig. 2 left) revealed three scales of variation across the transect 0-60 (majority of region with low variances, or light color) , and 60-180 (region interlaced with low and the highest variances), and over 180(another low variances). For the 0- and 60-m scale, the variances were relatively uniform and small, indicating small scale-variance in the grassland LAI was small. For the 60- and 180-m scale, regions of high variance were centered along the transect at 15, 80, 140, 210, 270, and 340m. The strongest variance was centered at 210 m. These regions correspond to the locations of knolls and depressions across the transect and indicate the presence of a global feature. To examine the distribution of variances in grassland LAI as a function of scale and perform statistical test of the global features for significance, the global wavelet power spectrum (Fig. 2 right) was obtained by integrating the local wavelet spectra across the transect. The contribution of variance from 0- to 15-m and from 80- to 140-m to total variance was significantly different from that of the red noise spectrum. The most contribution of variance to total variance was at the scale about 130 m. Conversely, variations at scales from 15- and 80-m and above 140m were not significantly different from that of the red noise spectrum. This indicates that the spatial variability associated with grassland LAI was controlled by knolls and depressions with a small scale from 0- to 15m and a large scale from 80- to 140-m. Variability from 15- to 80- m and above 140 m is localized features and global wavelet power spectrum cannot be used to test for statistical significance.

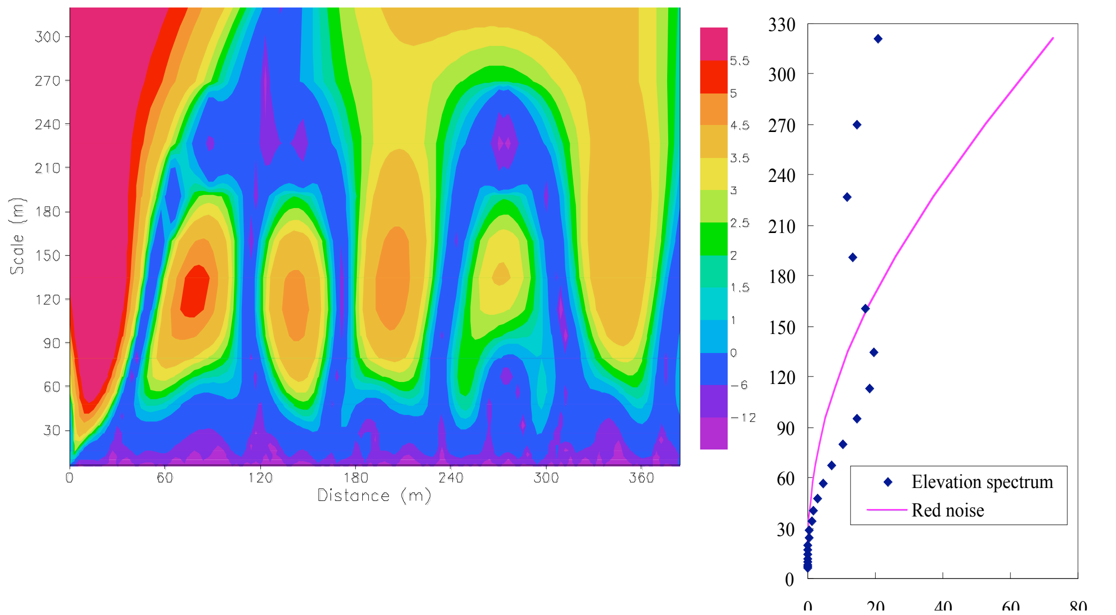

Fig. 3 Local (left) wavelet spectrum and global wavelet power spectrum of the elevation (right). The line in right figure is the power spectra of a red noise at a confidence level of 95%.

The local spectrum for elevation (Fig. 3 Left) revealed patterns similar to those observed for grassland LAI. That is, the local wavelet spectrum of elevation also exhibited three scales of variations at 0 to 60m, 60 to 180m, and >180m. For the 60- to 180-m scale, regions of high variance were centered at 10, 70, 140, 200, 270, and 340m across the transect. Again, these locations correspond to the knolls and depressions occurring along the transect. But the strongest variance centered at 10 m. The global wavelet power spectrum (Fig. 3 right) revealed that spatial variability associated with elevation had a similar trend from that observed for grassland LAI, the most contribution of variance to total variance was also at the scale of about 130 m. But the spatial variability of elevation was significantly different from that of the red noise spectrum for scales <150 m. This result indicates that there was a distinct spatial pattern at scales <150 m to elevation and most distinguishable spatial pattern of elevation is same as grassland LAI.

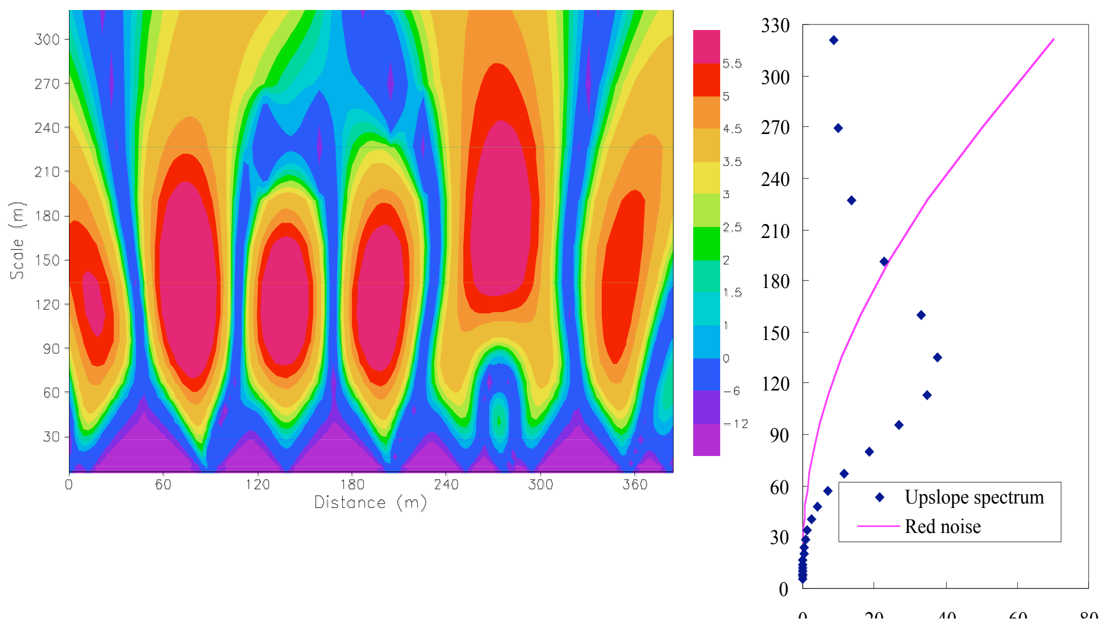

Fig. 4 Local (left) wavelet spectrum and global wavelet power spectrum of upslope length (right). The line in right figure is the power spectra of a red noise at a confidence level of 95%.

The local spectrum for upslope length (Fig. 4 Left) revealed patterns different from those observed for grassland LAI. The local wavelet spectrum of upslope length exhibited three scales of variations at 0 to 30m, 30 to 240m, and >240m. For the 30- to 240-m scale, regions of high variance were centered at 15, 80, 130, 200, 270, and 350 m across the transect. Again, these locations correspond to the knolls and depressions occurring along the transect. But the strong degree of high variance is mainly similar in these circles. The global wavelet power spectrum (Fig. 4 right) revealed that spatial variability associated with upslope length also had a similar trend to that observed for grassland LAI. However, the upslope length showed a significantly different spectrum from that of the red noise spectrum for a scale <190m, indicating that there was a distinct spatial pattern at these scales for the upslope length. The most contribution of variance to total variance was also at the scale about 130 m.

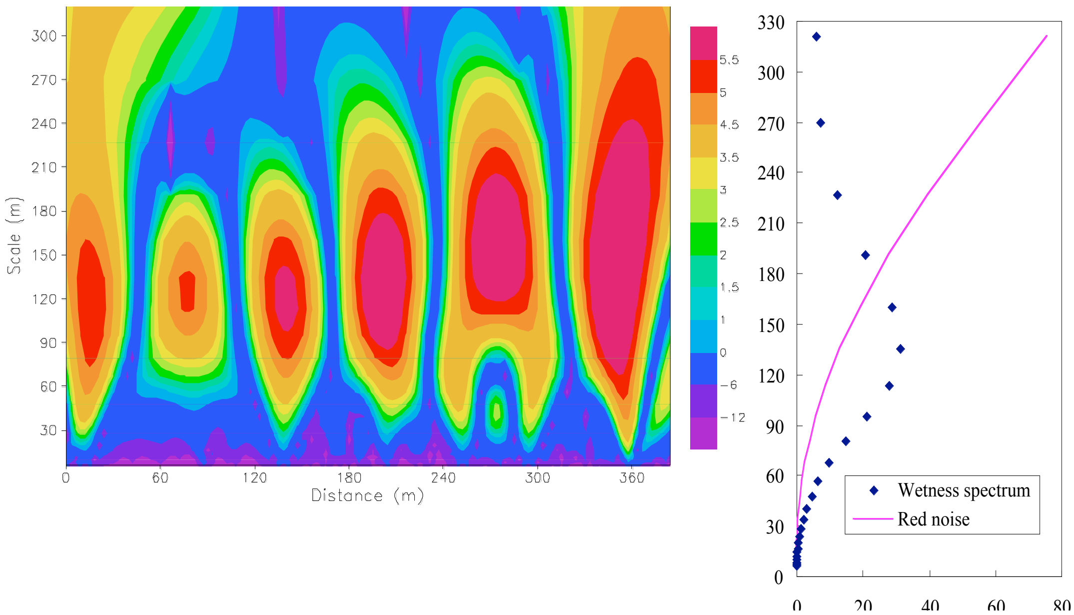

Fig. 5 Local (left) wavelet spectrum and global wavelet power spectrum of the wetness index (right). The line in right figure is the power spectra of a red noise at a confidence level of 95%.

The local spectrum for the wetness index (Fig. 5 Left) revealed patterns similar to those observed for grassland LAI. The local wavelet spectrum of upslope length exhibited three scales of variations at 0 to 60m, 60 to 180m, and >180m. For the 60- to 180-m scale, regions of high variance were centered at 15, 80, 130, 200, 270, and 360m across the transect. Again, these locations correspond to the knolls and depressions occurring along the transect. But the strong degree of high variance is mainly same in these circles. The global wavelet power spectrum (Fig. 5 right) revealed that spatial variability associated with wetness index also had a similar trend from that observed for grassland LAI, but was significantly different from that of the red noise spectrum for a scale <170m, indicating that there was a distinct spatial pattern at these scales to the wetness index. The most contribution of variance to total variance was also at the scale about 130 m.

Based on wavelet analysis, we can conclude that the local wavelet spectrum for LAI was quite similar to that of topography factors. Features within the scales of 60- and 180- m, are the dominant landscape features. While the global wavelet power spectrum was significantly different from that of a red noise at different scales for LAI and topography parameters. There are two scales from 0 to 15m and from 80 to 140m for grassland LAI, and only one scale from 0 to 150 m for elevation, from 0 to 190 m for upslope length, and from 0 to170m for the wetness index. But the most contribution of variance to total variance in both grassland LAI and topographic parameters was at the same scale about 130 m.

For the global wavelet power spectrum, grassland LAI was significantly different from that of a red noise at scales 0- and 15-m, 80- to 140-m. While all of topography parameters were significantly different from that of a red noise at only one scale, that is, the scale from 0- and 150- m for elevation, 0- and 190- m for upslope length, and 0- and 170- m for the wetness index. An important conclusion that can be draw from these global features is that topography parameters contribute to large scale (here say 80-140m) variation in grassland LAI. This indicates that topography greatly effects grassland LAI in landscape scale and thus topographic parameters can be used to analyze grassland productivity in landscape scale. For small scale (here say 0-15m), there is some other factors accounting for variability of grassland LAI. These factors could be disturbances, species competition, and micro-topography and so on. This result is consistent with study reported by Zhang et al. (submitted). Another conclusion drawn from the global wavelet power spectrum is that the most contribution of variance to total variance in both grassland LAI and topographic parameters was at the same scale about 130 m. This indicates that topographic parameters can be the best indicators to identify the scale of spatial variation in grassland biophysical parameters. Consequently, topographic parameters can be applied to select the appropriate resolution of remote sensing products for studying grassland ecosystem. It can avoid the error of estimating grassland biophysical properties in landscape level by replacing improper lower resolution of remote sensing products, as well as can be more cost-effective by replacing expensive higher resolution of remote sensing products or costly field surveys.

Conclusions and Discussion

This study investigated the relationships between grassland LAI and topographic parameters (i.e. elevation, upslope length, and the wetness index) at a site in the grassland national park of Saskatchewan, Canada. Whereas the correlations between LAI and all of three topographic factors were significant, more of the spatial variability associated with grassland LAI was explained by the wetness index than elevation and upslope length. This result is consistent with conclusion that topography influences hill slope hydrology or water redistribution (Huggett, 1975), microclimate (Rowe, 1984), soil type (Pennock et al., 1987), and differences in vegetation (Burke et al., 1989). It also demonstrated the importance of applying topography parameters to investigate grassland productivity.

Wavelet analysis was conducted to determine the scales of the variability in grassland LAI, elevation, upslope length, and the wetness index. The local wavelet spectrum for LAI was quite similar to that of topography factors. Features within the scales of 60- and 180- m, are the dominant landscape features. The regions of high variance correspond to the knolls and depressions occurring along the transect. This result indicates that topography parameters have the similar scale of variations with grassland LAI. Therefore, we can use topographic parameters to identify the scale of spatial variability of biophysical parameters and to help select the resolution of remote sensing images.

Differentiation between localized and global features has the potential to provide guidance in designing grassland management and the scale of satellite images. The implications of these results are that: (1) estimating grassland productivity should consider the effect of the witness index, upslope length, and elevation, not only at the local scale but also at global scale; (2) wavelet analyses are useful for revealing localized and as well as global landscape features that exert significant controls on grassland LAI; and (3) the resolution of remotely sensed data can be decided by topographic indicators. Therefore, accuracy and efficiency of estimating grassland productivity in large region will be improved.

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