The evaluation of broadband vegetation indices on monitoring northern mixed grassland

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Abstract: The northern mixed grassland is characterized by its high amount of non-photosynthetic materials and low to medium green vegetation cover, which has proven to be a challenge for the application of remotely sensed data in a vegetation study. This study was conducted to evaluate broadband based vegetation indices and determine the most effective spectral vegetation index to be used in this ecosystem. The study area was Grasslands National Park (GNP) and surrounding pastures. Fieldwork was conducted from late June to early July 2003. Biophysical variables, including canopy height, cover, biomass, and species composition, and a corresponding Landsat 5 image on August 10, 2003 were collected. Thirteen vegetation indices were calculated based on at-surface reflectance. Texture analysis was conducted on these vegetation indices to study biophysical parameter variation. Pearson correlation and regression analysis were used to study the relationships between vegetation indices and biophysical parameters. Results showed that brightness, Adjusted Transformed Soil Adjusted Vegetation Index (ATSAVI), Transformed Soil Adjusted Vegetation Index (TSAVI), wetness, and Global Environmental Monitoring Index (GEMI) have medium to high correlation with biophysical parameters. This shows the success of applying these broadband based vegetation indices to study biophysical measurements in the northern mixed grassland.

Introduction

Broad band based vegetation indices, based on sensors with broad wavelength region bands (e.g. Landsat and SPOT), are the most frequently used indicators for monitoring ecosystem dynamics. Many vegetation indices have been developed and applied in vegetation studies since the first vegetation index, Ratio Vegetation Index (RVI) (Jordan 1969). These vegetation indices can be categorized as four groups: ratio, orthogonal, hybrid, and nonlinear (Chen 1996; Broge and Leblanc 2000). RVI and the Normalized Difference Vegetation Index (NDVI) are ratio vegetation indices.

NDVI is the most commonly used vegetation index in grassland study, which has been widely used to evaluate cover (Dymond et al. 1992), above-ground biomass (Tucker 1985), chlorophyll content (Tucker 1985), leaf area (Asrar et al. 1986; Curran et al. 1992), phenology (Markon et al. 1995), absorbed photo-synthetically active radiation (Prince 1991), and NPP (Ruuning 1989).

However, NDVI is influenced by many environmental factors such as topography, bare soil (soil fraction, soil type and soil moisture), atmospheric condition (Pinty and Verstraiet 1992), vegetation association, rainfall (Schmidt and Karnieli 2002) nonphotosynthetic materials and others (Gamon et al. 1993). Therefore, adapted vegetation indices, like hybrid, orthogonal, and nonlinear indices, have been proposed to deal with the influences of background information. Huete (1988) developed a Soil Adjusted Vegetation Index (SAVI) using soil adjustment factor, which is decided by percentage of green cover, to adjust for the influence of soil in the spectral features. Unfortunately, the requirement of knowing percentage vegetation cover beforehand is not met in many cases. As a result, Qi et al. (1994) improved the performance of SAVI by proposing Modified Soil Adjusted Vegetation Index (MSAVI) and the second Modified Soil Adjusted Vegetation Index (MSAVI2) with an additional dynamic soil adjusting factor. Baret (1989) introduced the Transformed SAVI (TSAVI) and Adjusted TSAVI (ATSAVI) by taking into account the soil line slope and intercept of the soil line. Pinty and Verstraete (1992) developed a Global Environmental Monitoring Index (GEMI) to correct for the atmospheric contribution in AVHRR data specifically. Generally, hybrid vegetation indices are good for vegetation canopy of low cover (Ray 1994).

Orthogonal indices are different from ratio indices for the position of the greenness isolines (Broge and Leblanc 2000). The Perpendicular Vegetation Index (PVI) and the Weighted Difference Vegetation Index (WDVI) are typical orthogonal indices. They are not sensitive to soil background because they are parallel to the principle axis of soil spectral variation. Because the relationship between vegetation indices and biophysical parameters is not necessarily linear, nonlinear indices, the Nonlinear Index (NLI) and the Renormalized Difference Vegetation Index (RDVI), were developed to linearize their relationships with surface parameters (Chen 1996).

In addition, the Tasseled Cap Transformation (TCT) is a basic spectral enhancement method aimed primarily at analyzing vegetation cover making use of all bands (except the thermal band) of Landsat (Kauth and Thomas 1976). Greenness, brightness, and wetness, results of TCT when applied to TM or ETM+ data, are used to indicate vegetation canopy, bare soil, and moisture respectively.

Remote sensing application in the northern mixed grassland are challenging because of its high amount of non-photosynthetic materials and low to medium green vegetation cover even though remote sensing has been used on other grassland ecosystems (Guo et al. in press), e.g. studies in tallgrass prairie (e.g., Asrar et al. 1986; Asrar et al. 1989), shortgrass prairie (Lauver 1997), and other grasslands in semiarid and arid environment (e.g., Wilson 1989; Lewis 1994; Dilley et al. 2004). Few studies have been conducted in the mixed grassland (e.g.: Davidson and Csillag 2000). And performance of these vegetation indices in the mixed grass ecosystem has not been evaluated yet. Therefore, this study aims to investigate the effectiveness of the above vegetation indices in the northern mixed grassland. The objectives are to find the best vegetation indices at detecting biophysical parameters and to evaluate the texture analysis method on spatial variation analysis.

Study Area

The study area included Grasslands National Park (GNP) (49° N, 107° W) and surrounding pastures, located in southern Saskatchewan along the Canada - United States border. This area falls within the mixed grassland ecosystem. The park is approximately 906.5 km^2 in area but in two discontinuous blocks, west and east. The first land was acquired for the park in 1984; as a result, some areas of the park have been under protection from livestock grazing for almost 20 years. The park area consists of upland grasslands and lowland grasslands. The dominant plant community in the upland grasslands is Needle-and-thread—Blue grama (*Stipa-Bouteloua*), which covers nearly two thirds of the park's ground area. The dominant species in this community include needle-and-thread grass (*Stipa comata Trin. & Rupr*), blue grama grass (*Bouteloua gracilis (HBK*) *Lang. ex Steud*.), and western wheatgrass (*Agropyron smithii Rydb. Selaginella Beauv.*) (Fargey et al. 2000). Apart from the Needle-and-thread—Blue grama (*Stipa-Bouteloua*) community, lowland grasslands contain higher densities of shrubs and occasional trees. The entire area consists of northern mixed grassland (Davidson 2002). The GNP area has a mean annual temperature of 3.8^{0}C and a total annual precipitation of 325 mm (Environment Canada 2003); approximately half of the precipitation is received as rain during the growing season.

Methods

Field work and data processing:

Field work was conducted in June and July of 2003. Ten sites were randomly selected within the park and surrounding pastures. Three 100 x100 m plots were set up in each site, and each plot was composed of two 100 m transects placed perpendicularly to each other with a north-west orientation. Twenty-one quadrats (20 x 50 cm) were placed in each plot at 10 m intervals. Percent cover of grass, forb, shrub, standing dead, litter, moss, lichen, and bare ground as well as species composition was collected at each quadrat. Biomass was collected at 20 m intervals using the harvesting method. Clipped fresh biomass was sorted into four groups: grass, forb, shrub, and dead materials. They were then dried in an oven for 48 hours. LAI was measured using a LiCor-LAI-2000 Plant Canopy Analyzer. At each plot, LAI is the average of four automatically calculated LAI values; each was the result of one above canopy reading compared with ten below canopy readings. These measurements were completed within two minutes to avoid atmospheric variation. The ten below canopy readings were set at five meter intervals. The sensor was shaded when observations were being taken to reduce the glare effect from direct sunshine.

All biophysical parameters were averaged by sites, composing 36 quadrats for biomass and 63 quadrats other parameters. Standard deviation was used to measure the variation of biophysical parameters within sites. Shannon's index (Rosenzweig 1995) and Heterogeneity index of height (HIH) (Wiens, 1974) were also calculated to stand for species diversity and the variation of canopy height inside sites respectively (Table 1).

Table 1: *Calculated parameters based on biophysical parameters.*

Parameter	Equation	Note
Shannon's index	$-\sum p_i \ln(p_i)$	p_i is the proportion of the total number of individuals occurring in species i
Heterogeneity index of height (HIH)	$\frac{\sum (Max - Min)}{\sum \bar{x}}$	Max=maximum value of the canopy height within quadrats, Min=minimum value of the canopy height within quadrats, N=the total number of quadrats, $\bar{x}$ the mean value of canopy height in a quadrat

Satellite image and preprocessing:

A Landsat 5 Thematic Mapper (TM) image was acquired for this study. The image was taken on 10 August 2003, approximately four weeks after the field campaign. The image has a spatial resolution of 30 m except in the thermal band and contains seven bands. All bands except band six (thermal) were utilized in this study. Atmospheric and radiometric corrections were completed for the image, and digital numbers (DN) were converted to at surface reflectance. Because simple dark object subtraction can bring better results than more complex model (such as 6S model) (Song et al. 2001), an improved dark-object subtraction method (Chavez 1988) was applied during the atmospheric correction. The process of radiometric correction followed the procedure of Markham and Barker (1986). The image was registered to a Universal Transverse Mercator (UTM) projection and the nearest neighbour resampling method was used in geometric projection. Thirty GCPs were collected and the RMSE was less than 0.3 pixel (<10 m).

Vegetation indices and texture analysis:

In this study, we included indices evaluated by Chen (1996) and Peddle et al. (2001) plus TSAVI, ATSAVI, greenness, brightness, and wetness. Altogether thirteen vegetation indices were selected (Table 2). All vegetation indices were calculated based on at-surface reflectance with GEMI also calculated based on at-sensor reflectance. To investigate the

Table 2: *Methods of vegetation indices calculation in this study.*

Category	Vegetation index	Equation	References
Ratio Vegetation Index	Simple Ratio (SR) or Ratio Vegetation Index (RVI)	$\frac{TM4}{TM3}$	Jordan (1969)
	NDVI (Normalized Difference Vegetation Index)	$\frac{TM4-TM3}{TM4+TM3}$	Rouse et al. (1973)
Hybrid Vegetation Index	SAVI (Soil-adjusted vegetation index)	$\frac{TM4-TM3}{(TM4+TM3+L)(1+L)}$	Huete 1988
	TSAVI (Transformed Soil-adjusted Vegetation Index)	$\frac{a\times(TM4-a\times TM3-b)}{a\times TM4+TM3-a\times b}$	Baret,1989
	ATSAVI (Adjusted Transformed Soil-adjusted Vegetation Index)	$\frac{a\times(\mathrm{TM4}-a\times \mathrm{TM3}-b)}{a\times \mathrm{TM4}+\mathrm{TM3}-a\times b+0.08\times(1+a^2)}$	Baret and Guyot 1992
	MSAVI2 (Second Modified Soil Adjusted Vegetation Index)	$\frac{2\times \mathrm{TM4}+1-\sqrt{(2\mathrm{TM4}+1)^2-8\times(\mathrm{TM4}-\mathrm{TM3})}}{2}$	Qi et al. 1994
	Global Environmental Monitoring Index (GEMI)	$eta\times(1-0.25\times eta)-\frac{TM3-0.125}{1-TM3}$ where : $eta=\frac{2\times(\mathrm{TM4}^2-\mathrm{TM3}^2)+1.5\times \mathrm{TM4}+0.5\times \mathrm{TM3}}{TM4+TM3+0.5}$	Pinty and Verstraiet (1992)
Orthogonal Vegetation Index	WDVI (Weighted Difference Vegetation Index)	$\mathrm{TM4}-a\times \mathrm{TM3}$	Clevers (1989)
Nonlinear Vegetation Index	RDVI (Renormalized Difference Vegetation Index)	$\frac{TM4-TM3}{\sqrt{TM4+TM3}}$	Roujean and Breon (1995)
	NLI (Non-Linear Index)	$\frac{TM4^2-TM3}{TM4^2+TM3}$	Goel and Qin (1994)
Tassled Cap Transformation Indices	Brightness	0.2909 * TM1 + 0.2493 * TM2 + 0.4806 * TM3 + 0.5586 * TM4 + 0.4438 * TM5 + 0.1706 * TM7	Crist et al. (1986)
	Greenness	-0.2728 * TM1 - 0.2174 * TM2 - 0.5508 * TM3+ 0.7221 * TM4 + 0.0733 * TM5 - 0.1648 * TM7	
	Wetness	0.1446 * TM1+ 0.1761 * TM2 + 0.3322 * TM3 + 0.3396 * TM4 - 0.6210 * TM5 - 0.4186 * TM7	

spatial variation of the forb component in the grassland ecosystem, a texture analysis of a 3 x 3 window size was applied to these three indices. GLCM texture analysis is a commonly used method for describing localized variation of surface features in grey scale. During the process of texture analysis, a grey level co-occurrence matrix or grey level co-occurrence vector is computed to describe the stochastic properties of spatial distribution of grey levels (Hall-Beyer 2000; He and Wang 1990). Results of these textural algorithms can be used to describe the heterogeneity within a landscape (Woodcock and Strahler 1987; Briggs and Nellis 1991; Anys and He 1995). Three textural parameters, GLCM standard deviation, contrast, and entropy, are used as indicators of heterogeneity or local variance (Zhang et al. unpublished).

Data analysis:

Vegetation indices and textural parameters were averaged using a 3 x 3 window size (90 m x 90 m), which was centered at each plot on every site. Pearson's correlation analysis was conducted for all biophysical parameters and vegetation indices. A linear regression analysis was run to identify indices or textural parameters best suited to estimate the biophysical parameters. Prediction models were developed for biophysical parameters and the results were validated with jack-knife cross validation method, which withdraws one sample each iteration and runs the model for (n - 1) iterations.

Results

Biophysical parameters:

The mixed grassland is noted for its low vegetation cover, large amount of dead material, and biological crust. The grass cover and forb cover are around 30% and 15% respectively. A large amount of dead material, including standing dead grass and litter, have been accumulated in northern mixed grassland, especially in the park area due to the protection from grazing. Dead materials account for about 50% of total biomass (Guo et al. in press) and cover 80% of understory. Biological soil crust is an important component of the semiarid and arid grasslands including the breakdown of humus and the release of nutrients (Kauffman and Pyke 2001). Moss and lichen are important components of the understory biological crust in the northern mixed grassland with about 15% cover. As a result, the northern mixed grassland has a low percentage of bare ground due to low grazing density (about 2.5%), which is different from other grasslands in semiarid and arid environments.

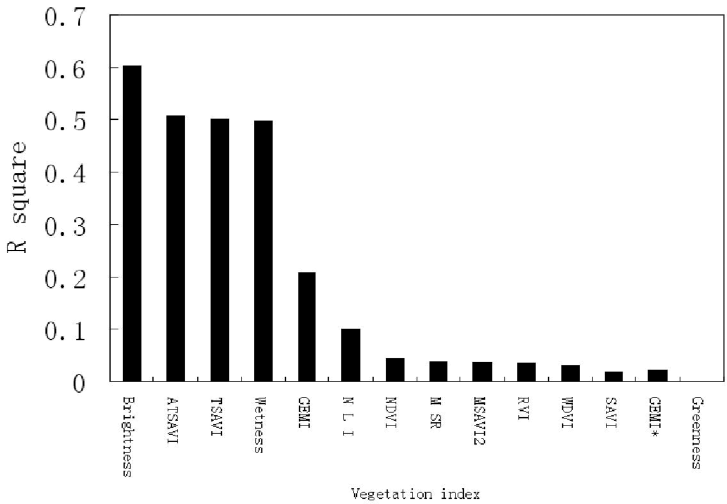

Figure 1: *Relationships between vegetation indices and LAI. While GEMI was calculated based on at surface.*

LAI and vegetation indices:

LAI is the total one-sided (or one half of the total all-sided) green leaf area, vertically projected, per unit ground surface area. It is an important vegetation structural parameter because it defines the area of leaf that interacts with solar radiation and provides the remote sensing signal. We have concluded that LAI is a good biophysical parameter in the mixed prairie region (Guo et al. unpublished). Therefore, the relationships between vegetation indices and LAI could be used to characterize the canopy directly. Results showed that LAI was moderately to highly correlated with brightness ($r = -0.77, p < 0.01$), ATSAVI, TSAVI ($r = -0.71, p < 0.05$), and wetness ($r = 0.71, p < 0.05$) (Figure 1, where r^2 values are shown). Brightness explains the variation of LAI better than ATSAVI, TSAVI, and wetness by nearly 10%. Brightness indicates non-photosynthesizing background information, such as dead materials, moss cover, lichen cover, and shadow. In northern mixed grasslands, the percentage of bare ground was very small and the amount of standing dead materials and litter (cover and biomass) was large (Guo et al. in press). Furthermore, spectral characteristics of dead materials are similar to that of bare soil (Baret and Guyot 1991). Decreasing LAI induced more background information in pixels, which resulted in negative relationships between LAI and brightness. Wetness, which indicates moisture, is positively correlated with LAI. Adequate moisture normally corresponds to higher primary productivity due to the critical role of soil moisture in vegetation growth and LAI is highly related to production. Therefore, high moisture level is corresponded to high wetness values. It is interesting that ATSAVI and TSAVI, which take into account soil background information, are negatively correlated to LAI. It indicated that the information about the green canopy did not dominate the remotely sensed data. Therefore, these four indices provide an indirect measure of green canopy by measuring background information. Relationships between VIs and LAI can be predicted using linear regression (Table 3). Sixty percent of LAI variation could be explained by brightness, while the number dropped to 55% when the cross validation was applied. For ATSAVI, TSAVI, and wetness, they could explain 50% of LAI variation (43% with cross validation). There were no significant relationships between other vegetation indices and LAI. reflectance, GEMI* was based on at sensor reflectance.

Table 3: *Linear regression models for vegetation indices and LAI.*

Equation	r^2	Adjusted r^2	SE
LAI = -10.854 × Brightness + 4.3409	0.60	0.55	0.16
LAI = -10.855 × ATSAVI + 14.725	0.51	0.45	0.17
LAI = -12.644 × TSAVI + 15.733	0.50	0.44	0.18
LAI = 27.06 × wetness + 5.22	0.50	0.44	0.18

Biomass and vegetation indices:

GEMI based on at surface reflectance correlated well with grass, forb, and total biomass by explaining about 45% of the variation (Table 4). The number dropped to around 40% when the cross validation was applied, but the negative relationships showed again that information contained in GEMI is not only green vegetation.

Table 4: *Linear regression results for GEMI and biomass (Biomass=s*GEMI+ i, where s means slope and i is intercept).*

Equation	r^2	Adjusted r^2	SE
Grass biomass = -980.203 × GEMI + 520.185	0.47	0.41	13.1
Dead biomass= -2494.259 × GEMI + 1166.412	0.46	0.40	32.9
Total biomass = -3050.133 × GEMI + 1561.287	0.44	0.37	43.6

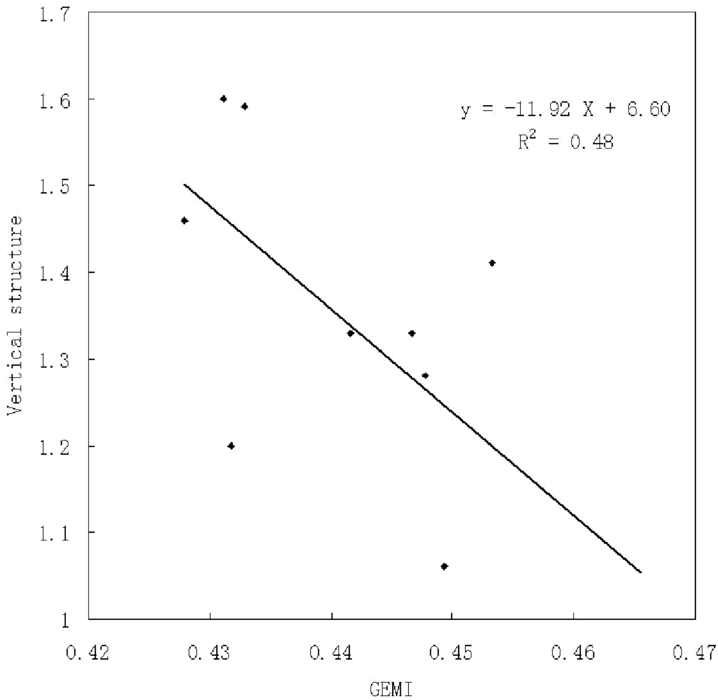

Figure 2: *The relationship between HIH and GEMI.*

Diversity and GEMI:

HIH is one of the indicators of within site variation. Results showed that only GEMI based on at-surface reflectance correlates well with HIH. GEMI based on at surface reflectance can explain about 48% of variation (Figure 2) and the value is 42% when validation was conducted. Shannon's index showed no significant relationships with GEMI calculated using at sensor reflectance ($r = 0.41$ and $p > 0.05$) and at surface reflectance ($r = -0.35, p > 0.05$).

Relationships between spatial heterogeneity and the spectral variation:

Variables of contrast, standard deviation, and entropy derived from texture analysis have proved to be an effective way to study grassland spatial variation (Zhang et al. unpublished). They are also correlated moderately well with standard deviation of LAI, percentage of bare ground, litter cover, and canopy height (Table 5). Approximately 50% of their

Table 5: *Coefficients of correlation between standard deviation of biophysical parameters and of textural parameters.*

		HIH	Average Height	LAI	Litter cover	% of Bare ground
	Contrast	-0.57	-0.52	-0.49	0.08	0.72*
ATSAVI	SD	0.74**	0.63*	0.55	0.16	0.65*
	Entropy	0.43	0.24	0.15	0.09	0.46
	Contrast	-0.72*	0.77**	-0.75**	-0.48	0.45
Brightness	SD	-0.67*	-0.69*	-0.72*	-0.47	0.41
	Entropy	-0.48	0.56	-0.73*	-0.33	0.42
	Contrast	0.41	0.30	0.27	0.45	0.10
Greenness	SD	0.52	0.39	0.19	0.46	0.02
	Entropy	0.69*	0.57	0.05	0.75**	0.03
	Contrast	-0.57	0.52	-0.50	0.08	0.72*
TSAVI	SD	-0.74**	0.63*	0.55	0.16	-0.65*
	Entropy	0.43	0.24	0.15	0.09	-0.46

Note: *significant at 0.05 level. ** significant at 0.01 level.

variation (r^2) could be explained by the three texture analysis variables from the greenness, brightness, TSAVI, and ATSAVI. The positive correlation between greenness and litter cover and the positive correlation between TSAVI and percentage of bare ground also indicate that remotely sensed data for northern mixed grasslands contains more information than just green canopy. It can be concluded that ATSAVI and TSAVI are good for HIH, brightness is good for average height and LAI, while greenness is good for litter cover and percentage of bare ground in a reverse relationship.

A factor that should be taken into account is the time of image acquisition. There is about one month's discrepancy between field work and satellite image acquisition. It contributes to the low correlation between vegetation indices and biophysical parameters, especially variables that change dramatically temporally, such as forb cover. In the northern mixed grassland, late June and early July are the full growing season, which is our field data collection duration, while the image was acquired slightly after the maximum growing condition.

Conclusion

For northern mixed grassland, standing dead material, litter, and moss constitute the gaps of the vegetation canopy and contribute as background information. Therefore, indices either measuring background information (brightness and wetness) or hybrid indices (ATSAVI, TSAVI, and GEMI) have relatively higher correlation with biophysical parameters. Brightness, ATSAVI, TSAVI, and wetness can be used to measure LAI, and GEMI can be used to extract biomass and diversity information. Other indices do not perform well in the northern mixed grassland, which imply the importance of background information. Vegetation indices can be also applied to study grassland heterogeneity. ATSAVI and TSAVI are good for HIH, brightness is good for average height and LAI. However, this study was based on one year's field data. Climate variation may have effects on the conclusions because 2003 was a dry year. Further field data will be collected to validate our results. Nevertheless, we believe that our sample scheme and sites selected are very representative in the mixed grassland ecosystem. Therefore, the results are reliable at least for the similar climate conditions.

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