Monitoring grassland health with remote sensing approaches

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Abstract: Grassland condition is not only important economically, as it reflects the number of grazers rangeland can support, but also crucial ecologically, as it indicates the integrity of wildlife habitats. Even though studies have demonstrated the effectiveness of remote sensing in grassland monitoring, it is still a challenge to use remotely sensed data in mixed grasslands because the large proportion of dead material complicates analysis for indices that were not developed for heterogeneous landscapes, especially in conservation areas. In this study, we investigated the relationship between remote sensing data and grassland biophysical measurement including aboveground biomass and plant moisture content in the native mixed prairie ecosystem, with its high litter component. Biophysical and spectral data were collected in the summer of 2003 at west block of Grasslands National Park of Canada and surrounding pastures. Field data collected at five ungrazed sites within the park and five grazed sites outside the park. The results from this study indicated that the Normalized Difference Vegetation Index (NDVI) is not suitable for biomass estimation although a moderate relationship was found between NDVI and plant moisture content. Compared to NDVI, leaf area index (LAI) provided promising results on both biomass and plant moisture content estimation.

Introduction

Grasslands, covering 24% of the Earth's vegetated area (Sims 1988), rank as the most human altered landscape worldwide. The long history of manipulation, together with ongoing conversion of native grassland to cultivation (and back) leaves us with little information on natural grassland ecological function and poses a problem for effective monitoring of the processes we do understand. The repeated monitoring of grassland condition is an essential tool both in developing our understanding of important ecological processes and for conservation. This, plus the strong agricultural and economic role of grasslands, makes monitoring grassland health of a broad interest among policy makers, ranchers and ecologists.

Remote sensing has played an important role in grassland ecosystem monitoring at landscape scales. With the improvement of remote sensing techniques and newly developed satellite sensors, remotely sensed data have been used in four major areas in grassland ecosystems study: plant composition including C3/C4 proportion and component of native species (Lauver and Whistler 1993; Goodin and Henebry 1997; Tieszen et al. 1997; Davidson and Csillag 2001; 2003), biophysical parameters, mainly component of biomass (Tucker 1978; 1980; Asrar et al. 1986; Weiser et al. 1986; Dyer 1991; Frank and Aase 1994; Csillag et al. 1996; Liang and Chen 1999; Guo et al. 2000; Nouvellon et al. 2001; Thoma et al. 2002; Wylie et al. 2002; Zha et al. 2003); climate change (Yang et al. 1998; Jobbagy et al. 2002; Ji and Peters 2003) and spatial pattern (Lobo et al. 1998; Rahman et al. 2003). Normalized Difference Vegetation Index (NDVI), the ratio of the difference of near infrared and red reflectance to the sum of these two variables, is the dominate spectral vegetation indicator of grassland biophysical measurements. NDVI tends to enhance the vegetation signal, reducing the atmospheric and edaphic influence, and standardizing the spectral data. This is particularly true when vegetation shows vigorous photosynthetic activity. Therefore, it has been used extensively in studies of vegetation production during the growing season.

However, NDVI has yet to prove its value in semi-arid and arid regions. This has been hypothesized to be due to lower biomass levels and strongly influenced by environmental factors such as temperature, precipitation, topography and soil condition (Huete and Jackson 1987). In addition, a mixture of living, senescent, and dead materials as well as exposed backgrounds makes arid rangeland remote sensing more complex. As Huete and Jackson (1987) indicated, “Remote sensing techniques have had little success in evaluating the quantity and quality of rangeland forage in arid ecosystems”. Tucker (1979) found that brown or dormant vegetation is not as highly correlated with spectral data as is green vegetation. Liang and Chen (1999) also found that the value of NDVI extracted from National Oceanic and Atmospheric Administration (NOAA) images increased as the grassland becomes greener or denser. In a study conducted by Guo (2002) for the Canadian prairie ecosystem, the lowest correlation between NDVI and climate variables was in the Mixed Grassland ecoregion compared to Moist Mixed grassland and Aspen Parkland ecoregions. A reverse correlation was found between NDVI and biomass in Grasslands National Park (McCanny et al. 1996). So while NDVI has remained the most popular spectral vegetation index in the mixed grassland ecosystem, it is unclear why NDVI fails to accurately reflect grassland biomass and production in some ecosystems.

The objective of our study was to determine how the components of native mixed grassland contribute to spectral reflectance in order to understand why NDVI performs as it does on these landscapes. NDVI is also compared to Leaf Area Index (LAI), which is a related, optical measure of grassland biomass.

Methods

Study Area:

Our study took place in Grasslands National Park, Saskatchewan, Canada (GNP) and surrounding pastures. Ten study sites were selected in upland native grasslands within the Park, and on federal, provincial, and privately managed rangelands surrounding the park. The area is a characteristic 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^{0}C (Environment Canada 2003). The dominant plant community in the upland of the mixed prairie ecosystem 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.*). Spikemoss (*Selaginella Beauv*.) and June grass (*Koeleria macrantha (Ledeb*) *J.A. Schultes f.*) are always present as well (Fargey et al. 2000). A comprehensive description of variety of site conditions was described by Scott (1995).

Field Data Collection:

Field data collection was conducted in the summer of 2003 (June-July) at the 10 sites with 3 plots in each site. Two 100 meter transects were set in each plot perpendicularly at north-south and west-east directions. A 20 x 50 cm quadrat was placed at each 10 meter intervals along each transect. LAI was measured using a LiCor-LAI-2000 Plant Canopy Analyzer at each quadrat. The spectral measurement was done with an ASD FR Pro spectroradiometer within 2 hours of solar noon on clear days at each quadrat. Vegetation was clipped to ground level at every second quadrat along each transect providing 12 biomass samples per plot, for a total of 36 per site. These are compared to 20 spectral and LAI readings for each plot (60 for each site). Biomass samples were weighed immediately after clipping to determine wet biomass. The samples were then sorted into green grass, forb, shrub and dead materials, and placed in a drying oven for 48 hours at 60^{0}C. The difference between wet biomass and the dry biomass was the plant moisture content.

Data Preprocessing and Analysis:

LAI, reflectance and oven-dry biomass (refer to biomass thereafter) data were averaged for each plot, then to each site. Simulated six optical Landsat Thematic Mapper TM bands were derived from the field spectral measurements; these are band 1 (Blue 0.4-0.5 um), 2 (Green 0.5-0.6 um), 3 (Red 0.6-0.7 um), 4 (Near Infrared (NIR) 0.7-0.9 um), 5 (Middle Infrared 1.55-1.75um (MIR1)) and 7 (Middle Infrared 2.08-2.35 um (MIR2)). NDVI was calculated based on the formula of (NIR-Red)/(NIR+Red). Correlation analysis was run between biophysical variables (total biomass, live grass biomass, forb biomass and plant moisture content) and NDVI as well as between biophysical variables and LAI. Further, regression analysis was performed for prediction of total biomass and plant moisture content using NDVI and LAI separately to determine the precise variation biophysical variables that can be explained by spectral data and LAI. Results were validated with Jackknife method. This approach was implemented by withholding the sample data for one site and building the regression model using the data from the remaining sites. The process of removing one site from the dataset was repeated until all sites had been withheld.

Results

Biophysical Measurements:

In the study area, dead material contributed nearly half (47%) of the total biomass, ranging from 38% to 61% among the 10 sites (Table 1), the

Table 1: *Field measured biophysical parameters, isolated components of biomass and plant moisture content. Numbers in parentheses are percentage in total biomass.*

Site	Total biomass (g/m^2)	Grass (g/m^2)	Forb (g/m^2)	Dead (g/m^2)	Shrub (g/m^2)	Moisture (g/m^2)
1	201.9	91.4 (45.3%)	20.2 (10.0%)	90.3 (44.7%)	0.0	115.2
2	151.3	77.5 (51.2%)	9.9 (6.6%)	63.9 (42.2%)	0.0	67.8
3	178.9	84.3 (47.1%)	26.2 (14.6%)	68.5 (38.3%)	0.0	158.2
4	173.2	56.0 (32.3%)	32.7 (18.9%)	74.3 (42.9%)	10.3 (5.9%)	131.8
5	183.8	86.4 (47.0%)	16.7 (9.1%)	80.8 (43.9%)	0.0	105.6
6	238.5	95.8 (40.1%)	26.9 (11.3%)	115.8 (48.6%)	0.0	157.6
7	331.1	107.4 (32.4%)	21.4 (6.5%)	201.3 (60.8%)	1.0 (0.3%)	210.8
8	274.5	113.9 (41.5%)	16.0 (5.8%)	144.6 (52.7%)	0.0	222.3
9	187.6	78.2 (41.7%)	19.5 (10.4%)	89.9 (47.9%)	0.0	142.0
10	186.8	71.1 (38.0%)	26.5 (14.2%)	89.3 (47.8%)	0.0	90.1
Mean	210.8	86.2 (41.7%)	21.6 (21.6%)	101.9 (47.0%)	1.1 (0.6%)	140.1

largest fraction among grass, forb, shrub and dead. The next highest fraction was green grass, averaging 41.7% and ranging from 32.3% to 51.2%. These two fractions composed nearly 89% of the total biomass.

Spectral Features:

NDVI values were in the range of 0.36 and 0.50 with an average of 0.44 in the study area. With a total possible range of -1 to +1 for NDVI, 0.44 indicated relatively high photosynthesis activity, contributed by the 41.7% green grass. The reflectance range was between 6.5% and 9.1% and the numbers were 17.7% and 21.1% for the NIR. LAI showed lower values, less than 1.28, with an average of 0.87 (Table 2).

Table 2: *Field measured LAI values and calculated reflectance of RED, NIR and NDVI based field level spectral measurements.*

SITE	LAI	RED (%)	NIR (%)	NDVI
1	0.77	7.35	19.38	0.45
2	0.56	9.11	19.36	0.36
3	0.84	7.58	21.05	0.47
4	0.68	7.50	19.96	0.45
5	0.72	8.65	19.22	0.38
6	1.05	6.95	17.77	0.44
7	1.09	6.98	17.69	0.43
8	1.28	6.48	19.32	0.50
9	1.06	6.73	19.53	0.49
10	0.66	8.09	18.09	0.38
Mean	0.87	7.54	19.14	0.44

Correlation between biophysical parameters and NDVI and between biophysical parameters and LAI:

The only significant correlation between NDVI and biophysical variables is for plant moisture content with r of 0.729 (Table 3). However, LAI showed a strong relationship with grass biomass (r = 0.761), dead material (r = 0.723), total biomass (r = 0.773) and plant moisture content (r = 0.903). Even though NDVI and LAI both are significantly related with plant moisture content, LAI showed a much stronger correlation (0.903 vs. 0.729). Subsequent regression analysis showed that LAI could explain 81.5% variation of plant moisture content and 59.8% variation of total biomass, while NDVI was not significantly related to biomass and could only explain 53.2% variation of plant moisture content (Figure 1). With Jackknife validation, the r^2 values dropped to 0.474 for NDVI and plant

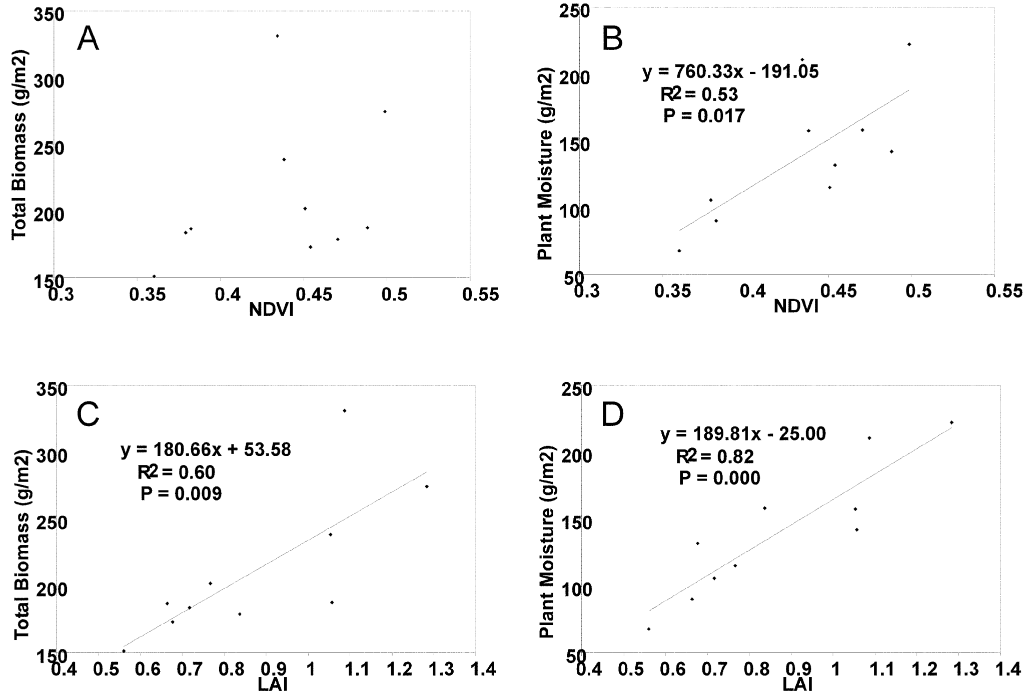

Figure 1: *Regression analysis results showing the relationship between (A) NDVI and total biomass (B) NDVI and plant moisture content (C) LAI and total biomass (D) LAI and plant moisture content. All measurements recorded in g/sqm.*

Table 3: *Correlation coefficient comparing biophysical parameters with NDVI and biophysical variables with LAI. Values in bold face indicate significant relationships.*

Variable		Grass	Forb	Dead	Total	Shrub	Moisture
NDVI	**r**	0.306	0.28	0.268	0.343	0.136	**0.729**
	Sig.	0.39	0.434	0.454	0.331	0.708	0.017*
LAI	**r**	**0.761**	-0.04	**0.723**	**0.773**	-0.259	**0.903**
	Sig.	0.011*	0.912	0.018*	0.009**	0.47	0.000**

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

moisture content, 0.547 for LAI and total biomass and 0.792 for LAI and plant moisture content.

Discussion

Higher dead component is an obstacle for the performance of NDVI in the mixed grassland ecosystem:

NDVI works better when vegetation shows "typical" spectral responses, higher near infrared reflectance and lower red reflectance. Figure 2 illustrates the difference in spectral signatures of tall grass prairie (Kansas), wheat crop (Saskatchewan) and mixed grassland (this study). Grasses in the tall grass prairie showed a typical vegetation spectral curve with higher near infrared reflectance and lower red reflectance (Lillesand and Kiefer 1994). The wheat field showed a weaker response in the NIR region compared to tallgrass prairie, but was stronger than the mixed grassland. This is because the wheat was in flowering stage when the spectral readings were taken, which is on the down side of the vegetation phenology curve (Reed et al. 1994). The mixed grassland showed a much higher reflectance in the red and middle infrared wavelength regions and lower near infrared wavelength region. This is mainly caused by the higher dead material component which significantly reduced the sensed photosynthesis rate. Therefore, NDVI is a good measure of biomass and production for grassland in tallgrass prairie (Guo et al. 2000) and agriculture (Scotford and Miller 2003), but it doesn't show promise for the mixed grass prairie. A significant relationship between NDVI and plant moisture content indicated that NDVI is more sensitive to water absorption than photosynthesis when dead material is present. The subpixel unmixing method may improve the performance of NDVI if different component information is considered. Figure 3 showed the spectral response of isolated vegetation components for the mixed grassland in a laboratory setting. It

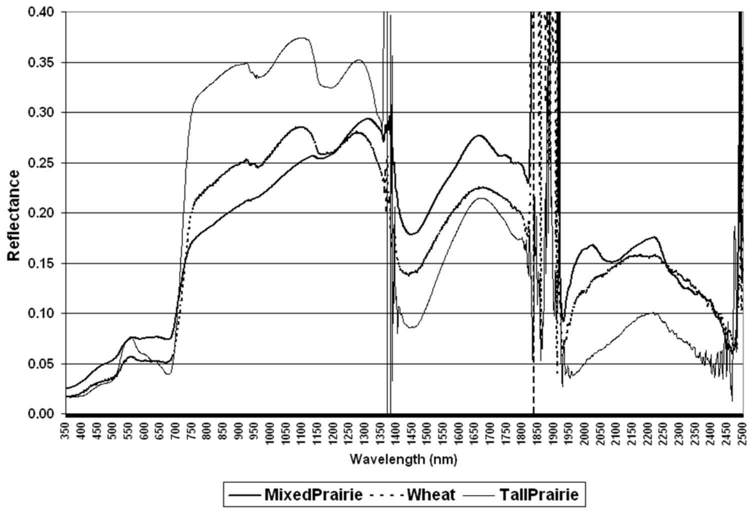

Figure 2: *Spectral response curves of grassland in tallgrass prairie, wheat field and mixed-grassland (mean of 30 samples). Spectral data for the tallgrass prairie were collected by Guo (unpublished data) at Douglas County, Kansas in June of 2000. Spectral data of wheat were collected by Guo (unpublished data) at the Agriculture and Agri-Food Canada Scott experiment field on July 18, 2003.*

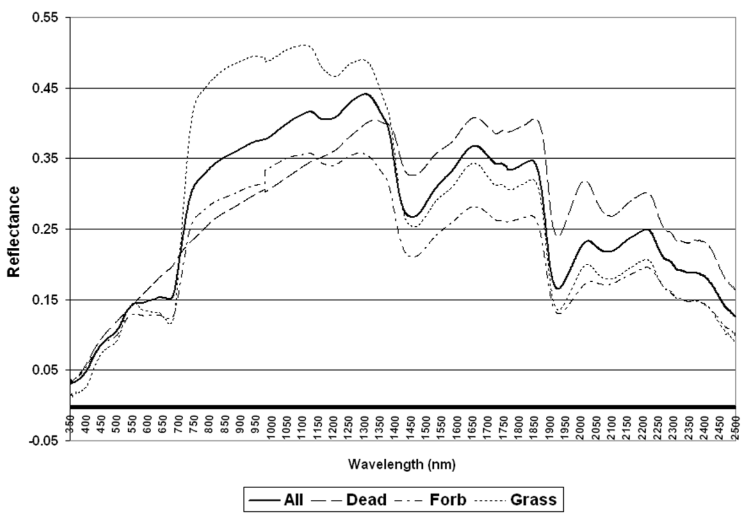

Figure 3: *Spectral response curves of different components of vegetation in the study area. Data were collected based on field collected samples after sorting in a laboratory setting with the same spectroradiometer as used in the field.*

is clear here that no single component of a complete mixed-grass sward dominates the total reflectance at all wavelengths. Indeed, the fact that the dead fraction has the highest reflectance in the visible range of red and the live fraction has the highest reflectance in the NIR range, suggests that the NDVI ratio is confounding the reflectance of two, distinct fractions.

LAI is an indirect method of estimating canopy structure in which the dead materials are counted:

LAI, defined as the total leaf area per ground area, is a direct canopy structure measure. Optical leaf area is measured indirectly via an instrument which detects gap fractions above and below the canopy. The LAI-2000 Plant Canopy Analyzer, used in this study, uses a fisheye light sensor that measures diffuse radiation simultaneously in five distinct angular bands about the zenith point. The sensor consists of five photodiodes whose active surfaces are arranged in concentric rings. The image of its hemispheric view is projected onto these rings, allowing each to measure the radiation in a band at the known zenith angle. In use, gap fractions at five zenith-angles can be measured by making a reference reading above the canopy and readings beneath the canopy both with sensor looking up. The below readings are divided by the above readings to obtain an estimate of the gap fraction at the five angles (Wells 1990). Since the measurement is based on the difference in diffuse radiation above and below a canopy, the measurement is not only for leaf area strictly, but a combination of whole canopy structure (e.g., stem and branches). Therefore, it incorporates a component of live and dead materials (standing dead). This explained why LAI was highly related with most biomass components and plant moisture content but forb biomass was not because a majority of forb component is at ground level.

Presence of moss and lichen enhanced the complexity of the mixed grass ecosystem:

Besides litter, moss and lichen cover the majority of ground which referred as soil crusts. The major species include Biological soil crusts serve a number of ecosystem functions that make them an important component of the biological diversity of many of the semiarid and environments of the world including breakdown humus and release nutrients (Kauffman and Pyke, 2001). These life form have significantly different spectral characteristics compared to bare ground since they are green (albeit, non-vascular) vegetation. Thus, while there is much exposed surface in an overhead image of mixed-grass prairie, little of this is exposed soil, but rather is a complex mix of materials that contribute independently to the spectral reflectance of the site.

Conclusion

NDVI, derived from remote sensing and applied to complete mixed-grass swards, is not suitable for mixed grassland ecosystem biomass estimations. It has marginal utility for plant moisture content prediction. Compared to NDVI, leaf area index (LAI) not only showed correlations with more biophysical variables, grass biomass, dead materials, total biomass and plant moisture content, but also could explain higher variability of total biomass and plant moisture content. An un-mixing model based on the components of grassland (grass, forb, and dead) should be further investigated.

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