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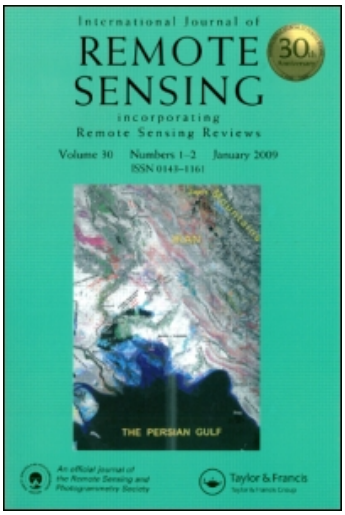

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Monitoring northern mixed prairie health using broadband satellite imagery

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Monitoring northern mixed prairie health using broadband satellite imagery

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The mixed prairie in Canada is characterized by its low to medium green vegetation cover, high amount of non-photosynthetic materials, and ground level biological crust. It has proven to be a challenge for the application of remotely sensed data in extracting biophysical variables for the purpose of monitoring grassland health. Therefore, this study was conducted to evaluate the efficiency of broadband-based reflectance and vegetation indices in extracting ground canopy information. The study area was Grasslands National Park (GNP) Canada and the surrounding pastures, which represent the northern mixed prairie. Fieldwork was conducted from late June to early July 2005. Biophysical variables—canopy height, cover, biomass, and species composition—were collected for 31 sites. Two satellite images, one SPOT 4 image on 22 June 2005, and one Landsat 5 TM image on 14 July 2005, were collected for the corresponding time period. Results show that the spectral curve of the grass canopy was similar to that of the bare soil with lower reflectance at each band. Consequently, commonly used vegetation indices were not necessarily better than reflectance when it comes to single wavelength regions at extracting biophysical information. Reflectance, NDVI, ATSAVI, and two new coined cover indices were good at extracting biophysical information.

1. Introduction

As a pool of carbon dioxide and a gene pool of wildlife and vegetation, the mixed prairie of North America is an important component of the global ecosystem (Coupland 1992). Most mixed prairies have been transformed to cultivated or ranch land for long time periods (Lauenroth *et al.* 1994). As a result, the original plant communities disturbed by bison and fire have different secondary succession, which largely changed the ecosystem condition. Therefore, it is important to evaluate and monitor grassland health to ensure a sustainable grassland ecosystem. Grassland health is 'the degree to which the integrity of the soil and the ecological processes of grassland ecosystem are sustained' (National Research Council 1994). Generally, contents of grassland health include soil stability, watershed function, and recovering mechanism (National Research Council 1994), with soil stability being one of the most important factors of grassland health (National Research Council 1994, Pyke *et al.* 2002). To monitor grassland health using satellite remote sensing,

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indicators are necessary to fulfil and simplify the process. Measurements can be made from two aspects: soil degradation and plant growth (National Research Council 1994). Specifically, information on percentage of bare ground, biomass, and vegetation cover should be first extracted as the first step towards grassland health evaluation.

Broadband vegetation indices, based on traditional optical sensors with broad wavelength region bands (e.g. Landsat and SPOT), are the most frequently used indicators for monitoring vegetation ecosystem dynamics due to their simplicity and efficiency. Many vegetation indices have been developed and applied in vegetation studies since the first vegetation index, Ratio Vegetation Index (RVI) (Jordan 1969, Broge and Leblanc 2000). There are various applications in different grassland ecosystems, such as tallgrass prairie (e.g. Asrar *et al.* 1986, 1989, Guo *et al.* 2003), short grass prairie (Lauver 1997), and other grassland types in semi-arid and arid environments (e.g. Wilson 1989, Lewis 1994, Dilley *et al.* 2004). However, only a few studies have been conducted in the mixed prairie using medium-resolution satellite imagery (Guo *et al.* 2005, Zhang *et al.* 2005). There has not been any comprehensive study designed to monitor the northern mixed prairie health using remote sensing techniques. Therefore, this study aims to investigate the spectral characteristics of the northern mixed prairie during the full growing season and to seek the possibility of extracting biophysical variables for the evaluation of grassland health.

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2. Study area

The study area includes the west block of Grasslands National Park (GNP) (49° N, 107° W) and surrounding pastures located in southern Saskatchewan along the Canada–United States border (figure 1). This area falls within the mixed prairie ecosystem (Coupland 1992). The park is approximately 906 km^2 in area, consisting of two discontinuous blocks, west and east. Land was first acquired for the park in 1984; hence, some areas of the park have been under protection from livestock grazing for over 20 years. The park area consists of upland, sloped, and valley grasslands. The dominant plant community in the uplands is *Stipa-Bouteloua*, which covers nearly two-thirds of the park's ground area. The dominant grass 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.). Comparatively, valley grasslands are dominated by western wheatgrass and northern wheatgrass (*Agropyron dasystachym*) along with higher densities of shrubs and occasional trees. The sloped grassland is a transitional area with species from both upland and valley grassland. The GNP area has a mean annual temperature of 3.8°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. Common soils in the Park areas are chernozemic soils and solonetzic soils (Fargey *et al.* 2000). Chernozemic soils are the most common in grassland communities, with a dark colour and high amount of organic content. Solonetzic soils, with their high salinity and lighter colour, are formed due to the drought and high evaporation. Under the sparse vegetation canopy in the Park area, a large part of the surface is covered by microphytic communities of small non-vascular plants. These microphytic communities include mainly mosses and lichens, which form biological crusts over soils and rocks. Biological soil crust is an important component of the semi-arid and arid grasslands. Its roles include the breakdown of humus, the release of nutrients, and the protection of soil from water erosion (Kauffman and Pyke 2001).

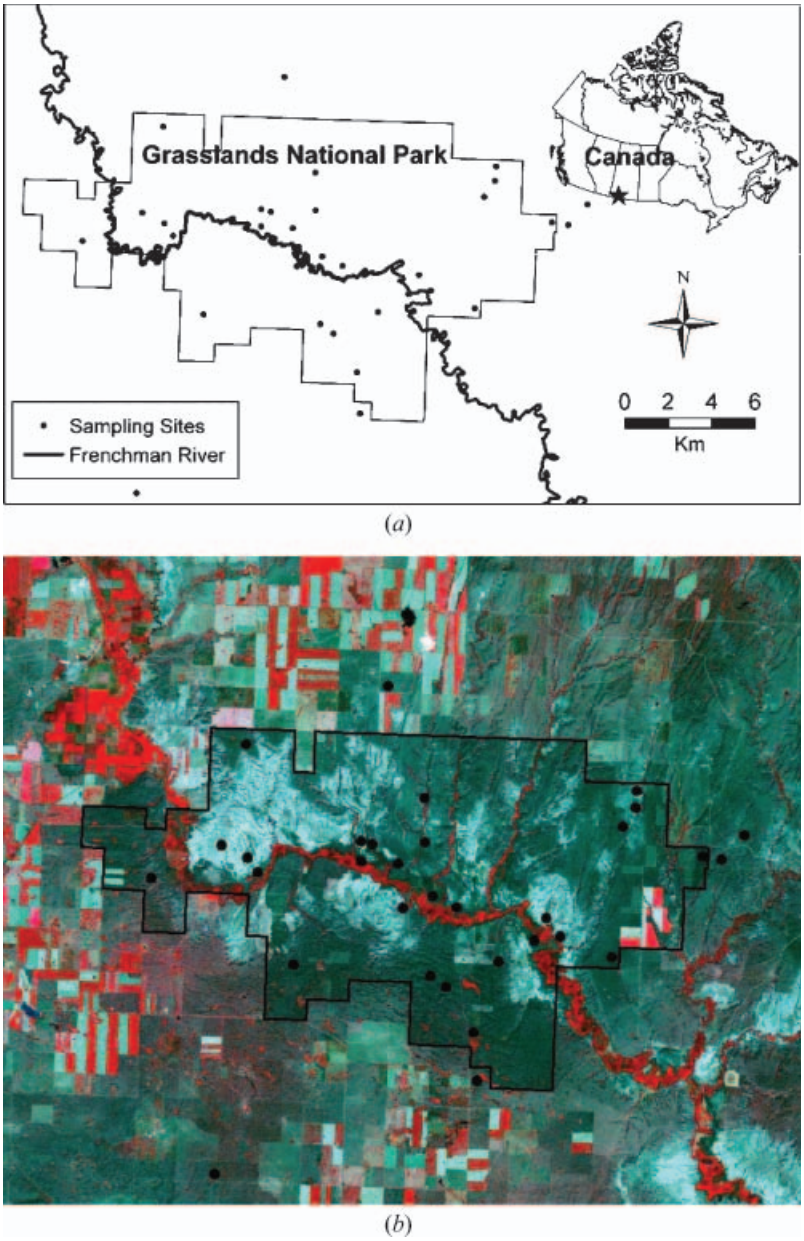

Figure 1. Study area, west block of Grasslands National Park (GNP) (*a*) and a false-colour composite of SPOT 4 image taken on 22 June 2005 (*b*). Field sampling locations are displayed as points.

3. Fieldwork and data preprocessing

Fieldwork was conducted in June and July of 2005, the maximum growing season of the northern mixed prairie. Thirty-one sites, selected based on a stratified random design and their accessibility, were distributed in the upland (10 sites), sloped land (seven sites), and valley grassland (14 sites). Two 100×100 m plots were set up in

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each site. Each plot was composed of two 100-m transects placed perpendicularly to each other so as to intersect in the centre to form a cross. Twenty-one quadrats (50×50 cm) were placed in each plot at 10-m intervals. The percentage cover of grass, forb, shrub, standing dead, litter, moss, lichen, and bare ground—as well as species composition—was collected at each quadrat, with litter, moss, lichen, and bareground counted as understorey. Due to the restriction of the Park, biomass was collected at 20-m intervals with a 20×50 cm quadrat using the harvesting method. Fresh biomass clipped with scissors was sorted into four groups; grass, forb, shrub, and dead materials. They were then dried in the oven for 48 h at 60°C. Plant Area Index (PAI, projected area of all vegetation parts normalized by the subtending ground area) was measured using a LiCor-PAI-2000 Plant Canopy Analyser. At each quadrat, PAI was the result of one above-canopy reading compared with nine below-canopy readings. The sensor was shaded when observations were being taken to reduce the glare effect from direct sunshine. To correlate with data from satellite imagery, all biophysical variables were averaged by sites.

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4. Methods

4.1 *Satellite image and preprocessing*

A SPOT 4 HRVIR image with 20-m resolution and a Landsat 5 Thematic Mapper (TM) image with 30-m resolution were collected for the field campaign on 22 June and 14 July 2005, respectively. Geometric, atmospheric, and radiometric corrections were applied on both images. The geometric correction was done with an accuracy of better than 0.3 pixel (RMSE <6 m) for SPOT and 0.5 pixel (<15 m) for the Landsat image. Both images were registered to a Universal Transverse Mercator (UTM) projection, and the nearest-neighbour resampling method was used in geometric projection. A cross-check of these two images showed that the shift between these two image is within half of a SPOT pixel (<10 m). Atmospheric corrections were conducted on the Landsat 5 imagery based on Chavez's improved dark object image subtraction approach (Chavez 1988) due to the lack of historical atmospheric data. Similarly, an algorithm ATCOR2 from PCI Geomatics™ was applied to the SPOT 4 imagery to remove any influences from the atmosphere. The process of radiometric correction followed the procedure of Markham and Barker (1986) with a set of different parameters applied to the SPOT image.

4.2 *Vegetation indices*

To study the canopy characteristics, spectral curves for typical mixed prairie, bare soil, and crested wheatgrass (*Agropyron cristatium*, which exemplifies green healthy vegetation) were extracted by visually identifying these features from both images. Crested wheatgrass indicates the cropland south of Val Marie mainly for bales, where crested wheatgrass was the main vegetation species.We then calculated Simple Ratio (SR), Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Transformed Soil-Adjusted Vegetation Index (TSAVI), Adjusted Transformed Soil-Adjusted Vegetation Index (ATSAVI), Second Modified Soil-Adjusted Vegetation Index (MSAVI2), Global Environmental Monitoring Index (GEMI), Weighted Difference Vegetation Index (WDVI), Renormalized Difference Vegetation Index (RDVI), and Nonlinear Index (NLI), which were evaluated by Chen (1996) and Peddle *et al.* (2001) (see their papers for an explicit description). The Normalized Difference Moisture Index (NDMI), and two

new indices, the Normalized Difference Cover Index (NDCI) and Ratio Cover Index (RCI), which combine reflectance from red and SWIR bands, were also calculated due to their ability to detect canopy moisture condition. Altogether, 13 vegetation indices were calculated (table 1).

Vegetation indices were averaged using a 5×5 (100×100 m) window for SPOT image and a 3×3 (90×90 m) window for the Landsat 5 TM image centred at each plot on every site, to correlate with field measured variables. The Shapiro–Wilk test was applied to check the normality of the dataset. Transformations were made to

Table 1. Vegetation indices used in this study.

Category	Vegetation index	Equation	References
Ratio Vegetation Index	Simple Ratio (SR) or Ratio Vegetation Index (RVI)	$\frac{NIR}{RED}$	Jordan (1969)
	NDVI (Normalized Difference Vegetation Index)	$\frac{NIR-RED}{NIR+RED}$	Rouse *et al.* (1973)
Hybrid Vegetation Index	SAVI (Soil-adjusted vegetation index)	$\frac{NIR-RED}{(NIR+RED+0.5)}(1+0.5)$	Huete (1988)
	TSAVI (Transformed Soil-adjusted Vegetation Index)	$\frac{1.219\times(NIR-1.219\times RED-0.029)}{1.219\times NIR+RED-1.219\times 0.029}$	Baret (1989)
	ATSAVI (Adjusted Transformed Soil-adjusted Vegetation Index)	$\frac{1.219\times(NIR-1.219\times RED-0.029)}{1.219\times NIR+RED-1.219\times 0.029+0.08\times\left(1+1.219^2\right)}$	Baret and Guyot (1992)
	MSAVI2 (Second Modified Soil Adjusted Vegetation Index)	$\frac{2\times NIR+1-\sqrt{(2\times NIR+1)^2-8\times(NIR-RED)}}{2}$	Qi *et al.* (1994)
	GEMI (Global Environmental Monitoring Index)	$eta\times(1-0.25\times eta)-\frac{RED-0.125}{1-RED}$ where $eta=\frac{2\times\left(NIR^2-RED^2\right)+1.5\times NIR+0.5\times RED}{NIR+RED+0.5}$	Pinty and Verstraiet (1992)
Orthogonal Vegetation Index	WDVI (Weighted Difference Vegetation Index) Clevers (1989)	$NIR - 1.219\times RED$	
Nonlinear Vegetation Index	RDVI (Renormalized Difference Vegetation Index)	$\frac{NIR-RED}{\sqrt{NIR+RED}}$	Roujean and Breon (1995)
	NLI (Nonlinear Index)	$\frac{NIR^2-RED}{NIR^2+RED}$	Goel and Qin (1994)
	NDMI (Normalized Difference Moisture Index)	$\frac{NIR-SWIR}{NIR+SWIR}$	Hardisky *et al.* (1983)
	Normalized Difference Cover Index (NDCI)	SWIR – Red/SWIR + Red	
	Ratio Cover Index (RCI)	SWIR/Red	

*NIR, RED, and SWIR indicate reflectance from the near-infrared, red, and middle-infrared wavelength region respectively.

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make the data close to a normal distribution. Pearson's correlation analysis was conducted for all biophysical variables and vegetation indices. Stepwise regression analyses were run to identify the relationships between biological variables and vegetation indices. Linear or nonlinear regression analyses were further applied to identify indices best suited to estimate the biophysical variables. Prediction models were developed for biophysical variables, and the results were validated with the Jack-knife cross validation method, which withdraws one sample in each iteration and runs the model for $n - 1$ iterations.

5. Results

5.1 *Species composition, dominant species, and vegetation canopy characteristics*

The name of the mixed prairie indicates that no single species dominates a plant community as in other grassland ecosystems. In our study area, *Stipa comata* Trin. & Rupr., *Bouteloua gracilis*, and *Agropyron smithii* Rydb. were dominant species (table 2), with *Stipa comata* Trin. & Rupr. having the highest percentage cover in all sites in the upland grassland.

Communities in upland and sloped grassland were mostly dominated by *Stipa comata* Trin. & Rupr., while communities in valley grassland (or in depressions in upland grassland) were dominated by *Agropyron smithii* Rydb. and *Agropyron dasystachyum*. Differences between these two groups mainly existed in soil moisture, topography, and soil characteristics. *Stipa comata* Trin. & Rupr dominated in dry upland soils and was rare in clay soils. *Agropyron smithii* Rydb. and *Agropyron dasystachyum* are rhizomatous and flourish on clay and clay loam soils in valley grasslands. The most dominant C4 grass species in the northern mixed prairie, *Bouteloua gracilis*, appeared in dry and clay loam soil. Silver sagebrush (*Artemisia cana*) is one of the most common shrub species in the valley grasslands. Forb species, such as narrow-leaved collomia (*Collomia linearis* Nutt.), and pasture sage (*Artemisia frigida*) were also commonly found in each site with slight changes of cover from site to site.

The mixed prairie is noted for its low vegetation cover, large amount of dead material, and biological crust. At the canopy level, the grass and forb covers were 16.8% and 5.4%, respectively, along with 11.1% for standing dead materials. The sparse canopy resulted in low biomass with an average above-ground biomass of 261.0 g m^{-2}. A large amount of dead materials, including standing dead materials

Table 2. Dominant species in the west block of Grasslands National Park and surrounding areas and their average cover.

Common name	Scientific name	Average cover (%)
Needle-and-thread grass	*Stipa comata* Trin. & Rupr.	17.5
Western wheat grass	*Agropyron smithii* Rydb.	8.3
Blue grama grass	*Bouteloua gracilis*	6.2
June grass	*Koeleria macrantha* (Ledeb.) J.A. Schultes f.	3.4
Threadleaf sedge	*Carex filifolia* Nutt.	5.3
Moss phlox	*Phlox hoodii*	2.2
Pasture sage	*Artemisia frigida*	3.1
American vetch	*Vicea Americana*	1.5
Silver sagebrush	*Artemisia cana*	1.2

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and litter, had been accumulated in the northern mixed prairie, especially in the park area. This is mainly due to the removal of grazing cattle. Dead materials accounted for about 50.0% of total biomass and covered 38.1% of the understorey. Moss and lichen were important components of understorey biological crust in the northern mixed prairie with 32.7% and 8.6% cover, respectively.

5.2 *Spectral characteristics of the northern mixed prairie*

The northern mixed prairie had a special spectral curve compared with typical green healthy vegetation (crested wheatgrass) (figure 2). Spectral differences between the prairie, bare soil, and crested wheatgrass are very clear. The crested wheatgrass had a typical spectral curve for green vegetation canopy, a red trough, an NIR peak, and low in SWIR. The reflectance of the grassland, however, even during the maximum growing season, was significantly different from the crested wheatgrass at each band ($P<0.01$). Compared with the green crested wheatgrass, the northern mixed prairie had a higher reflectance at red, green, and middle infrared wavelength regions and a lower reflectance at the near-infrared wavelength region. The northern mixed prairie was also specific at the SWIR band (SPOT) and SWIR1 and SWIR2 (Landsat 5 TM) with reflectance between bare soil and green healthy vegetation. This reflectance curve of the mixed prairie was more similar to that of the bare soil, with

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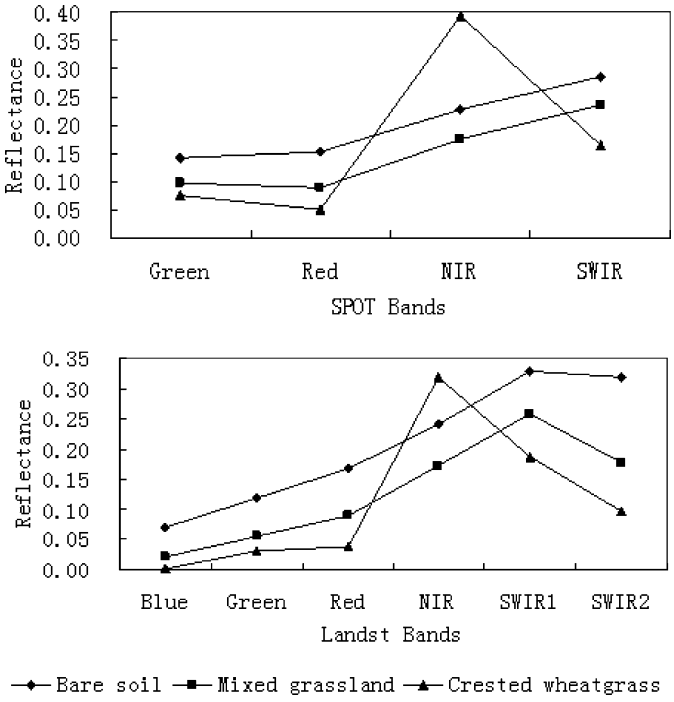

Figure 2. Reflectance of bare soil, crested wheatgrass, and the mixed prairie. Reflectance values were extracted from (*a*) SPOT 4 on 22 June 2005; (*b*) Landsat 5 TM on 14 July 2005. Crested wheatgrass indicates croplands close to Val Marie. These croplands are mainly used for bales, and the main grass species is crested wheatgrass (*Agropyron cristatium*). There is very sparse vegetation cover above the bare soil (<5%) mainly in the valley and sloped grassland. Therefore, the reflectance for mixed grassland at different bands is low compared with pure bare soil.

its value lower at each wavelength region. The main reasons could be ascribed to the existence of standing dead materials, litter, and biological crust in the sparse vegetation canopy. Differences between spectral curves from SPOT and Landsat 5 are due to the time of image acquisition. The Landsat 5 TM image was acquired at a later date than the SPOT image, corresponding to the late growing season for most native grass species while they were brown.

5.3 *Biophysical variables, spectral reflectance, and vegetation indices*

A Pearson correlation analysis was run to investigate the empirical relationships between spectral reflectance, vegetation indices, and biophysical variables. Correlation coefficients between reflectance, vegetation indices, and biophysical variables based on data extracted from the SPOT image are shown in table 3. Different wavelength regions and vegetation indices had different degrees of linear correlation with ground biophysical variables. Contrary to results for remote sensing of photosynthetically active vegetation (Lyon *et al.* 1998, Jenson 2000), the NIR band was not good for detecting biophysical variables in the northern mixed prairie. The correlations between NIR and biophysical variables were relatively low ($r<0.50$, $P<0.01$). This was primarily induced by the existence of the standing dead materials in the top canopy, under canopy litter, and bare soil which highly suppressed the reflectance in NIR. Other bands had a higher correlation with biophysical variables. Among them, reflectance of green (0.50–0.59 μm) and red (0.61–0.68 μm) had negative relationships with biophysical variables related to green vegetation growth (e.g. vegetation cover, biomass, and PAI). Reflectance at green and red had the highest correlations with green percentage cover (the sum of grass and forb), which is expected since the green cover influences the reflectance at green and red directly through absorption, reflection, and transmittance. Normally, high reflectance corresponds to low vegetation cover. Conversely, reflectance for green and red was positively related to the percentage of bare ground ($r=0.82$, $P<0.01$). The SWIR band also had negative relationships with PAI and total biomass ($r=-0.67$ and -0.65, respectively, $P<0.01$), which was mainly due to the variation of canopy cover and soil moisture content. Bare soil had a lower moisture content, while higher proportions of vegetation cover and dead materials have higher moisture contents.

Table 3. Correlation coefficients between reflectance, vegetation indices and biophysical variables based on SPOT image.

	Green	Red	NIR	SWIR	NDVI	ATSAVI	NDMI	NDCI	RCI
PAI	−0.54**	−0.56**	−0.28	**−0.67****	0.61**	0.60**	−0.49	0.37	0.36
Green cover*	**−0.78****	**−0.78****	−0.44	−0.45	**0.77****	**0.78****	0.00	**0.87****	**0.88****
Grass cover	**−0.75****	**−0.75****	−0.43	−0.44	0.73**	0.74**	0.00	**0.83****	**0.83****
Standing dead cover	**−0.61****	**−0.61****	−0.41	−0.42	0.56**	0.56**	0.00	0.47	0.47
Bare ground	**0.82****	**0.82****	0.54**	0.53**	**−0.74****	**−0.75****	−0.03	−0.02	−0.04
Grass biomass	**−0.62****	**−0.63****	−0.32	−0.61**	**0.67****	**0.67****	−0.35	0.40	0.40
Shrub biomass	0.01	−0.02	0.17	−0.37	0.18	0.16	**−0.69****	0.04	0.05
Dead biomass	−0.56**	−0.57**	−0.32	**−0.62****	0.60**	0.59**	−0.37	−0.24	−0.25
Total biomass	−0.45	−0.47	−0.17	**−0.65****	0.57**	0.55**	−0.60**	0.44	0.43

**Significant at the $P<0.01$ level.
*Green cover is the sum of grass cover and forb cover.

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Vegetation indices, such as ATSAVI and NDVI, did not have higher correlations with PAI and percentage cover than reflectance in green and red wavelength regions. This could be explained by the relatively low correlations between NIR and green canopy cover in the mixed prairie in Canada. ATSAVI was the best of all these vegetation indices because it takes into account soil background information, while dead materials, which have similar spectral characteristics to the bare soil, are important background in the mixed prairie. Similarly, the correlations between vegetation indices and biomass, especially grass biomass, were not as high as that of the reflectance from green and red bands. The main reason might be that the vegetation indices are more closely related to current year vegetation growth, while harvested biomass contains litter accumulated from previous years.

There were low correlations ($r<0.48$, $P>0.1$) between Landsat 5 TM based reflectance and vegetation indices and biophysical variables (data not shown), which might be explained by the senescence of the vegetation canopy when the image was taken.

Results of stepwise linear regression showed that information contained in NDCI, RCI, ATSAVI, and NDVI could be empirically explained by the variation of green cover, bare ground, and grass density (grass density is the division of grass cover and grass biomass, which is used to show the vertical structure of vegetation canopy) (table 4). This indicated the important contribution of green vegetation cover, bare ground (perhaps along with litter due to the spectral similarity of litter and bare ground), and grass density in remotely collected data. Beyond that, vegetation indices were also well correlated with single biophysical variables.

5.3.1 PAI and vegetation indices. Plant area index is an important vegetation structural parameter because it defines the area that interacts with solar radiation and provides the remote sensing signal. It is a good biophysical parameter for the application of satellite remote sensing in the prairie region (Baret *et al.* 1989, Goel and Qin 1994, Carlson and Ripley 1997). Plant area index is similar to LAI, except it includes information of standing dead materials and other parts of the plant, not just the leaves. The LiCor plant canopy analyser measures the difference in light intensity above and below the canopy. Large amounts of standing dead materials in the canopy contributed to the PAI values and therefore decreased its correlation with vegetation indices. There was a high correlation between PAI and canopy top cover (grass + forb + shrub + standing dead) ($r=0.73$, $P<0.01$). PAI was also

Table 4. Vegetation indices and biophysical variables.

	Equation	R^2	Adjusted R^2	Standard error
NDCI	$0.35+0.004\times$ Green cover – $0.001\times$ Bare ground percentage	0.84	0.83	0.016
RCI	$0.14+0.006\times$ Green cover + $0.001\times$ Bare ground percentage	0.83	0.82	0.096
ATSAVI	$-0.20+0.008\times$ Green cover – $0.011\times$ Grass density – $0.001\times$ Bare ground percentage	0.75	0.72	0.046
NDVI	$0.25+0.005\times$ Green cover – $0.006\times$ Grass density* – $0.001\times$ Bare ground percentage	0.74	0.71	0.025

*Grass density is the division of grass cover and grass biomass, which is calculated to indicate vertical structure of the grass canopy.

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highly correlated with SWIR ($r=-0.67$, $P<0.01$), ATSAVI ($r=0.60$, $P<0.01$), and NDVI ($r=0.60$, $P<0.01$) (table 3). In northern mixed prairie, there was a large amount of standing dead material and litter (cover and biomass) (Guo *et al.* 2005, Zhang *et al.* 2005). The plant area index was highly related to vegetation production, and so it can be an indicator of soil moisture in the northern mixed prairie due to the important influences of soil moisture on vegetation growth in this semi-arid environment (Si and Farrell 2004, Zhang *et al.* in press).

It is interesting that ATSAVI, which takes into account soil background information, did not perform better than NDVI. This phenomenon may indicate that in the northern mixed prairie, the influence of the dead materials is so significant that traditionally efficient vegetation indices for PAI measurement are not efficient enough compared with NDVI. Finally, the relationship between SWIR reflectance and PAI was strongest using an exponential model (figure 3). SWIR could explain about 42% of variation in PAI. The coefficient of determination (r^2) decreased to 0.41 after the validation. There were no significant correlations between cover indices and PAI, probably due to influences of standing dead materials.

5.3.2 Biomass and vegetation indices. Vegetation indices, specifically ATSAVI and NDVI, were significantly correlated with grass biomass. These two indices can explain approximately 45% of the variation in grass biomass (figure 4). The value decreases to 43% after the cross-validation. The SWIR band also had a negative correlation with total biomass ($r=-0.64$, $P<0.01$) (table 3), which could be explained by different moisture conditions in different canopies. Vegetation canopies with high biomass tend to have a high canopy moisture content (Jensen 2000) and large amount of dead material. Similarly, sites with a large amount of dead material had a high soil moisture content (Facelli 1991) owing to litter's role of keeping soil moisture. Consequently, the variation of biomass was indirectly captured by the SWIR band.

Figure 4 to be cross-referenced.

5.3.3 Green cover, reflectance, and vegetation indices. Green vegetation cover, the sum of grass and forb cover, is an important indicator of grassland health. Its variation may indicate over-grazing, soil erosion, and drought conditions. Green and red reflectance was negatively correlated with green cover ($r=-0.78$, $P<0.01$). Traditional vegetation indices, e.g. NDVI and ATSAVI, had positive correlations ($r=0.77$–0.78, $P<0.01$), with ATSAVI being the highest among the two vegetation indices (table 3). High green vegetation cover would absorb more incident and red light, and results in a low red reflectance. A lower vegetation canopy with bare

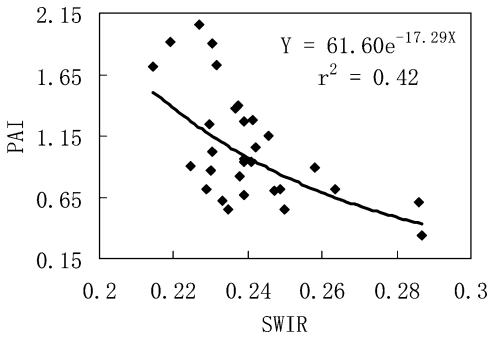

Figure 3. Relationships between reflectance in the shortwave infrared (SWIR) and plant area index (PAI) based on the SPOT image.

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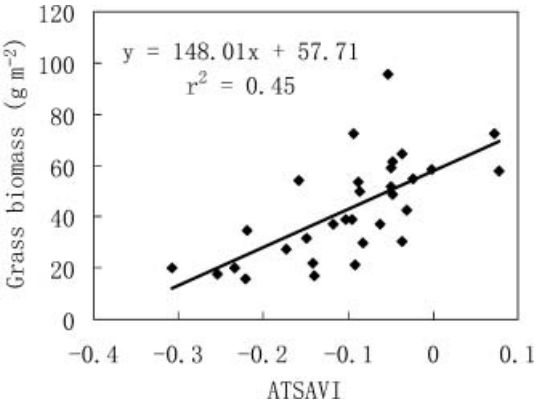

Figure 4. Grass biomass and ATSAVI based on the SPOT image. A linear regression can be used to model the relationship between them.

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ground would reflect more green and red light. Relationships between red reflectance and vegetation cover could be described using a power model (figure 5). Red and green (not shown) reflectance could explain 69% of the variation. The value decreased to 67% when validation was applied. Consistent with our expectation, RCI and NDCI were promising in detecting ground green canopy information. The ratio cover index had a linear relationship with green cover and could explain about 77.0% of the green canopy variation (figure 5). The ability of the SWIR band in detecting the change in moisture condition might make it stronger in extracting cover information than traditional vegetation indices and green and red reflectance.

6. Discussion

For the mixed prairie in Canada, standing dead materials, litter, and biological crust are interspersed in the vegetation canopy. There are various vegetation growth rates and litter accumulation rates for areas with different soil moisture. There was only a small amount of dead material in dry and sloped regions because the rate of accumulation was slow due to the sparse vegetation canopy. The accumulation rate was high where soil moisture was favourable for vegetation growth. In turn, the accumulation of dead material helped to retain soil moisture. Dead litter, along with bare ground, biological crust, and shadow, presents a serious problem to the interpretation of VIs (Van Leeuwen and Huete 1996). Influences from these specific backgrounds were so high that the spectral curve for the mixed prairie was similar to that of the bare soil, with lower reflectance values than that of bare soil at each band (figure 2). Consequently, NIR reflectance had low correlations with biophysical variables. Standing dead material in the green canopy and the background information tended to decrease the contrast between red and near-infrared bands (by lowering the reflectance in near-infrared and increasing the reflectance in the red band), thus decreasing the NDVI values. Therefore, traditionally efficient vegetation indices, e.g. NDVI, SAVI, and MSAVI2, might not be as efficient as they are for other vegetation ecosystems, to monitor ecosystem health. Among these vegetation indices, ATSAVI, which takes the bare soil factor into account, performed better than other vegetation indices listed in this study. However, there were no significant differences between ATSAVI and NDVI, which proves that the soil adjusted vegetation index is not very good for a litter-dominated ecosystem.

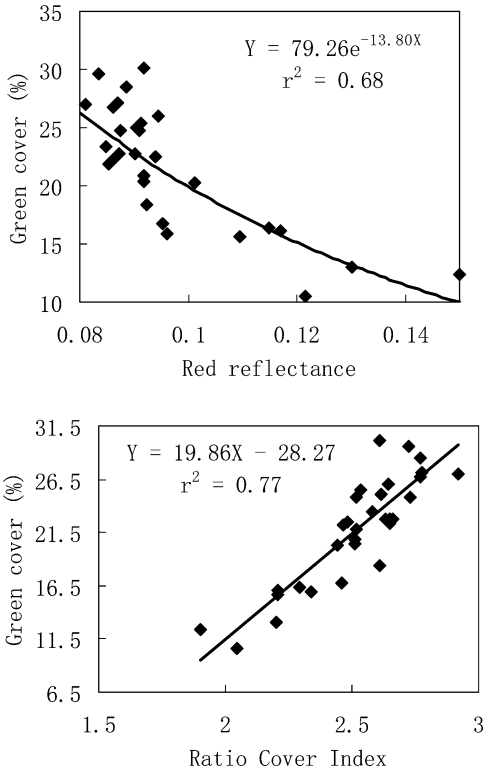

Figure 5. Relationships between green cover (grass plus forb cover), red reflectance, and Ratio Cover Index based on the SPOT image. Green cover is the sum of grass and forb cover. Ratio cover index is better at detecting green cover than red reflectance by increasing the r^2 value up to 13%.

However, other bands could provide a good estimation of the vegetation canopy. Reflectance from green and red can be used directly to monitor the changes in bare ground, vegetation cover, and biomass. Shortwave infrared bands were also highly correlated with biophysical variables due to its ability to detect canopy moisture and soil moisture. Consequently, it is promising that new indices combining these bands might be used to detect the sparse vegetation canopy. For the purpose of detecting biophysical variables, considering further the possible influences of haze and other atmospheric factors on the green band, emphasis should be placed on the red and SWIR bands. While reflectance at the red band indicates the amount of green cover and possibly the amount of standing dead material, reflectance at SWIR indicates canopy and soil moisture. Therefore, these two new cover indices, RCI and RDCI, had high correlations with green cover in the mixed prairie. The ratio cover index and NDCI increased the correlation coefficients with green cover from -0.78 to 0.88 and 0.87 ($P<0.01$), respectively, compared with the relationship between red reflectance and green cover. This means that the combination of these two bands probably removed noise for each band, which is also the hypothesis for NDVI. However, these new indices did not have high correlations with other biophysical variables. Further validation should be conducted for the next few years to test these new indices and possibly to make new indices to accommodate for the unique background for the northern mixed prairie. One important factor that should be

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considered is the discrepancy of the field campaign and date of image acquisition. The field campaign lasted for about one month, but the images were acquired at two separate time spots. This might have influenced the relationships we observed between biological variables and vegetation indices, since their associations are time- and area-specific (Jensen 2000). However, the grass canopy for the mixed prairie is quite stable during the full growing season for a normal year. The amount of above-ground biomass changed from 88.1 g m^{-2} (early June) to 128.3 g m^{-2} (early July), with most of the growth before the full growing season (Coupland 1999). Therefore, the relationships we obtained in the field should be reliable.

7. Conclusions

The sparse canopy in the northern mixed prairie is challenging for satellite remote sensing of grassland health because of the accumulation of dead materials in the canopy and the biological crust on the ground. The results of our study showed that the spectral curve of the vegetation canopy was midway between the spectral curve for bare soil and green healthy vegetation, which might be mainly explained by the dead materials and biological crust in and under the vegetation canopy. In spite of this, Pearson's correlation analyses indicated that it is still possible to extract information on biological parameters for the northern mixed prairie by using reflectance from green, red, and SWIR and vegetation indices. As a preliminary step towards monitoring grassland health, we found that different vegetation indices were good at detecting different biophysical variables, and some empirical relationships had been set up between reflectance, vegetation indices, and biophysical variables. While green and red were highly related to the percentage of bare ground and green cover, the SWIR band was highly correlated with PAI due to the influences of litter on soil moisture. Vegetation indices, e.g. ATASAVI and NDVI, could be applied to measure biomass. Furthermore, two new cover indices, RCI and NDCI, which combine SWIR and red bands, could be efficiently applied to detect green vegetation cover. These two indices could explain about 77% of the variation in green cover.

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