Leaf Area Index estimation using remotely sensed data for Grasslands National Park

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Abstract: Leaf Area Index (LAI), an important plant biophysical parameter, is widely used in ecological studies. There is a great deal of interest in estimating LAI and its variation in spatio-temporal dimensions using remote sensing based measurements. Currently, the major limitation of LAI mapping from satellite imagery is that these LAI maps have low accuracy because they are commonly produced from low spatial resolution satellite images (e.g., NOAA AVHRR (Advanced Very High Resolution Radiometer)). Also, NDVI (Normalized Difference Vegetation Index), the Vegetation Index (VI) commonly used to estimate LAI, is less accurate for semi-arid environments due to the spectral signal mixing errors arising from the low vegetation cover. To address these gaps and improve the accuracy of LAI maps, the research addressed the following objectives: (1) to develop an LAI prediction model based on a suitable spectral VI, (2) to produce an LAI map for the Grasslands National Park (GNP) area from a high resolution satellite image, and (3) to assess the mapping accuracy with ground-based measurements. This study utlized LAI measurements collected during the summer of 2005 and a SPOT-4 scene (20m spatial resolution) acquired for the same time frame. The results showed that in estimating a mixed grassland ecosystem's LAI, ATSAVI (Adjusted Transformed Soil-Adjusted Vegetation Index) could provide a high quality LAI map (66.7% accuracy). The methodology developed could be used to study other biophysical variables, for LAI mapping in similar ecosystems, for ecological studies, and for management practice guidance.

Introduction

Leaf Area Index (LAI, maximum projected leaf area per unit ground area), a vegetative structural parameter of terrestrial ecosystems (Fassnacht *et al.* 1997), is strongly correlated with many ecosystem processes and conditions, including evapotranspiration (McNaughton and Jarvis 1983), site water balance (Grier and Running 1977), canopy light interception

(Pierce and Running 1988; Fassnacht et al. 1994), above-ground net primary production (Gholz 1982), and total net primary production (Gower *et al.* 1992). Precise knowledge of LAI in large areas is necessary as input to models of carbon and nitrogen cycling, surface hydrology, net primary productivity, land use change, and land surface climate (Running *et al.* 1989). However, direct measures of canopy structure are extremely labor-intensive, and LAI estimation over large spatial extents is challenging. Remote sensing techniques, particularly with the use of satellite images, may offer a practical means to measure and understand the LAI variation at landscape or higher scales (Running *et al.* 1989).

The fact that reflectance measurements offer the opportunity for "scaling up" from the plot level to larger areas has produced sustained interest over the last three decades in investigations of the radiometric properties of canopies and their relationships to various plant parameters (Perry and Lautenschlager 1984; Friedl *et al.* 1994). Early spectroradiometer measurements of visible and infrared energy identified a strong correlation between the red and near-infrared (NIR) transmittance ratio and measured LAI (Jordan 1969). Chlorophyll absorbs red light energy, therefore, plant leaves have relatively low transmittance (and reflectance) of red energy. In contrast, plant cell walls scatter near-infrared energy, resulting in relatively high near-infrared transmittance and reflectance (Gates *et al.* 1965). These findings suggested that a scanning sensor may provide spectral measurements that are strongly related to the amount of leafy biomass or LAI (Tucker 1979). Subsequently, significant efforts have been made to estimate vegetation parameters in a spatially complete manner (Curran and Williamson 1986) from empirical algorithms relating LAI to spectral vegetation indices (VI) derived from red and NIR reflectance (Turner *et al.* 1999).

While numerous studies have shown a strong relationship between vegetation parameters and VI, these studies have also noted that observed relationships are highly site dependent (Friedl *et al.* 1994). For LAI estimation, the diversity of the suggested LAI–VI algorithms demonstrated a major limitation of the VI approach (Qi *et al.* 2000). These equations differ not only in mathematical form (e.g., linear, power, exponential), but also in their empirical coefficients, which primarily depend on the vegetation type of interest. Studies have been conducted on croplands (Wiegand et al. 1979; Asrar *et al.* 1984), grasslands (Friedl *et al.* 1994; Goetz 1997), shrublands (Law and Waring 1994), coniferous forests (Running *et al.* 1986; Spanner et al. 1994, Chen and Cihlar 1996), broadleaf forests (Badwar *et al.* 1986; Fassnacht *et al.* 1997), and mixed vegetation types (White *et al.* 1997). Red–NIR VI typically increases over an LAI range from 0 to about 3–5 before an asymptote is reached. Therefore, to use the VI approach, an LAI–VI equation must be established for each vegetation type, which requires substantial LAI measurements and corresponding remote sensing data.

Another limitation of VI is its sensitivity to the non-vegetation related factors such as soil background properties (e.g., Huete 1989; Qi et al. 1993), atmospheric conditions (e.g., Kaufman 1989; Vermote et al. 1990), topography (Holben and Justice 1980; Pinter et al. 1987), and the bidirectional nature of surfaces (Kimes et al. 1985; Deering 1989; Roujean et al. 1992; Burgess and Pairman 1997). Studies have shown that the effects from soil background variations and atmospheric conditions may be minimized by developing improved vegetation indices (Huete 1988; Clevers 1989).

Zhang (2005) investigated the relationships between LAI and satellite data in the mixed grasslands and found that several vegetation indices were highly correlated with LAI in the mixed grassland. Our study continues the investigation of the ability of satellite data to accurately estimate LAI in the mixed grassland ecosystem of Saskatchewan, Canada. The objectives are to develop algorithms for mapping LAI from high resolution satellite imagery and to provide a high quality LAI map with an assessment of its accuracy using ground measurements. The LAI map could, for example, be applied in the development of grassland ecological models and fire management strategies.

Materials and Methods

Study Area and Ground Data Collection:

This study was conducted at Grasslands National Park (GNP) in southern Saskatchewan. GNP is located within the mixed grass prairie biome, within the Great Plains. This biome is a transitional zone between tall grass and short grass prairie (Bragg 1995). The Park consists of two blocks, West and East, totaling approximately 906.5 sq. km. Approximately 340 mm of precipitation is received annually, the majority of which is received in the growing season (May – September). The 1971-2000 mean annual temperature was 3.4°C; the highest mean monthly temperature (18.5°C) is in July and the lowest mean monthly temperature (-13.6°C) is in January (data downloaded from Val Marie Southeast weather station, Environment Canada 2000). The soils in the study area are brown chernozemic clay loam soils (Saskatchewan Soil Survey 1992). The GNP consists of upland, slopeland, and valley grasslands, and the dominant native grasses are June grass (*Koeleria gracilis*), needle-and-thread grass

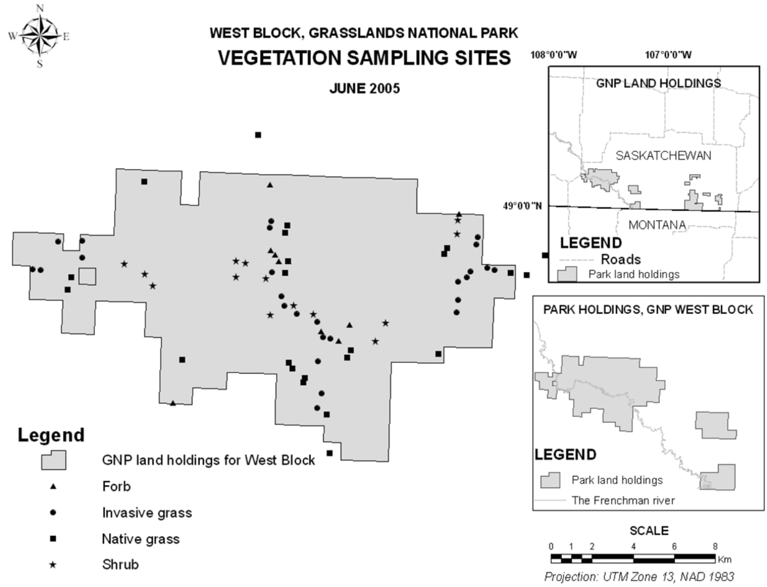

Figure 1: *The study area: Grasslands National Park and surrounding pastures, southern Saskatchewan, Canada, located at the international boundary of Canada and the United States. The Park is composed of two blocks: East and West. The 60 sites used in this study are located in the West block, and are marked with different symbols as shown in the legend.*

(*Stipa comata*), blue grama (*Bouteloua gracilis*), and western wheat grass (*Agropyron smithii*). In addition, invading weed grass species, forbs and shrubs are also widely distributed in the study area. The study sites in the West block of the GNP were in dense and sparse vegetation patches.

A total of 60 randomly selected sampling sites were visited during June of 2005 (Figure 1). These sites included native grass species (e.g., Grama, Needlegrass and Wheatgrass), invasive grass species (e.g., Smooth brome grass and Crested wheat grass), forb species (e.g., Sweet clover), and shrubs (e.g., Snowberry and Silver sage), distributed over the upland, slope land, and valley areas. Each sampling site was dominated by one type of vegetation community. At each of these sites, field sampling was conducted along two 100m transects, perpendicular to each other; one ran north-south and the other east-west. Along each of the 100 m transects, LAI measurements were collected using a LiCor-LAI-2000 Plant Canopy Analyzer (LiCor Inc., Lincoln, Nebraska) with a sampling resolution interval of 10m, for a total of 20 measurements per site. Each LAI measurement was comprised of one above-canopy reading followed by 9 below-canopy readings within two minutes to avoid atmospheric variation. These (20) measurements of LAI in a site were then averaged to provide an LAI value for the site. The LAI discussed in this paper is a canopy area index or plant area index. The geo-referenced coordinates for each of the site centres were determined with a 6m accuracy using a handheld Geographic Positioning System (GPS). The transect locations were permanently marked on the ground and these coordinates were later digitized into the Park's GIS data layers.

Remotely Sensed Data Acquisition and Processing:

A single SPOT 4 HRV image (Path 37, Row 26) for the study area was acquired for the date of June 22, 2005 (timed about half-way through the ground truth data collection). The satellite image was processed for geometric and radiometric corrections using PCI Geomatica V. 9.1. An accuracy of 0.3 RMS or better (representing approximately 6m or less error on the earth's surface) was ensured in the geometric correction process. Topography distortions were corrected using a Digital Elevation Model (DEM) obtained from the Park's GIS database. Atmospheric and radiometric corrections were conducted based on the improved dark object image subtraction method of Chavez et al. (1991). After correction, the digital number (DN) values were converted to reflectance values.

After preprocessing the image, RDVI (Renormalized Difference Vegetation Index; Roujean and Breon 1995) and ATSAVI (Adjusted Transformed Soil-Adjusted Vegetation Index; Baret et al. 1992) were derived from the NIR and Red bands to estimate LAI:

$$RDVI = \frac{\rho_{800} - \rho_{670}}{\sqrt{\rho_{800} + \rho_{670}}} \qquad (1)$$

$$ATSAVI = \frac{a(\rho_{NIR} - a\rho_{\mathrm{Re}d} - b)}{a\rho_{NIR} + \rho_{\mathrm{Re}d} - ab + X(1 + a^2)}, \text{X=0.08} \qquad (2)$$

RDVI is a hybrid index between DVI (Difference Vegetation Index) and NDVI (Normalized Difference Vegetation Index), and combines the advantages of DVI for low vegetation coverage and NDVI for high vegetation coverage (Haboudane et al. 2004). The ATSAVI index was developed to consider the actual gain (a) and intercept (b) values of the soil line and an adjustment factor X, which is set to minimize background effects (X = 0.08 in the original paper by Baret and Guyot 1991). Therefore, these two indices have strong theoretical bases to estimate LAI in locations with soil background variations. In addition, these two indices have been demonstrated to be good LAI indicators when using ground hyperspectral data in the same study region (He et al. 2006). Therefore this study tested ATSAVI and RDVI to estimate LAI. In order to match remote sensing data with LAI values for each site, we extracted and averaged the pixel data along the perpendicular transects within the sites, thus, the average LAI of a vegetation community was compared with the average VI derived from pixels representing that same vegetation community.

LAI Map Development and Evaluation:

Forty of the 60 sites were used to build the linear regression models between VI and LAI, and the remaining 20 sites were used to evaluate the models. The models have been validated by Jack-Knife cross validation. This Jack-Knife validation approach is implemented by withholding one sample and building the regression model using the data from the remaining samples. The process of removing one sample from the dataset was repeated until all samples had been withheld. Root mean squared error (RMSE) and map accuracy (MA) have been calculated to evaluate the models' accuracy for mapping LAI. The RMSE and MA can be computed as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \hat{x}_i)^2} \tag{3}$$

$$MA = \left(1 - \frac{RMSE}{\frac{1}{n}\sum_{i=1}^{n} x_i}\right) \times 100.00 \tag{4}$$

where n is 20 (sites), i is each site sequence, is measured LAI and $\hat{x}_i$ is LAI calculated from the regression model. The LAI map was developed using the regression model with the highest levels of accuracy.

Results and Discussions

LAI Data:

Table 1: *LAI descriptive statistics.*

Number of sites	Mean LAI	Range LAI	Min. LAI	Max. LAI	Std. Deviation
60	1.25	3.41	0.44	3.85	0.59

The standard deviation of 0.59 and the large range for LAI (0.44 - 3.85) demonstrates the spatial variation of the grassland land cover at the different sites. At the Park, the high LAI values (3.85) are generally seen in areas with invading grasses, forbs and shrubs, and lower LAI values (0.44) occur in the badlands or the salt valleys. The study shows that the LAI value averages to 1.25 for the mixed grassland, indicating the presence of low vegetation cover.

Relationships Between Vegetation Indices and LAI:

Forty sites were chosen to build regression models to assess the relationships between the two VIs (RDVI and ATSAVI) (Figure 2). Note that the two points which appear to be outliers are valid points representing high vegetation density in the invading grassland and shrub sites. Regression results demonstrated quite strong relationships between LAI and the two vegetation indices; the ATSAVI and RDVI model r^2 values were almost the same, with 0.64 and 0.63, respectively. The results are consistent with another study from the same area (Zhang 2005). In Zhang's study (2005), the ATSAVI is the second best LAI indicator, explaining 51% of LAI variation. The strong relationships between VIs (ATSAVI and RDVI) and LAI also demonstrate that the amounts of components such as litter

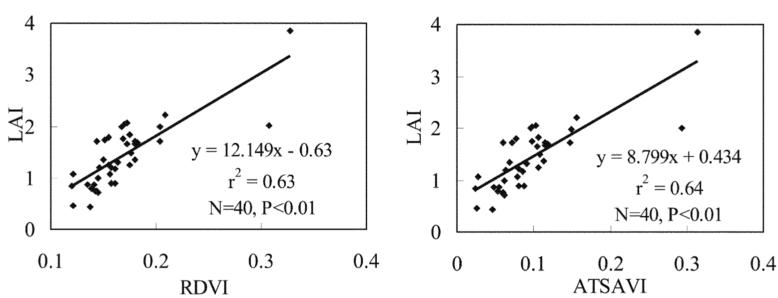

Figure 2: *Regressions between LAI and the vegetation indices (RDVI and ATSAVI).*

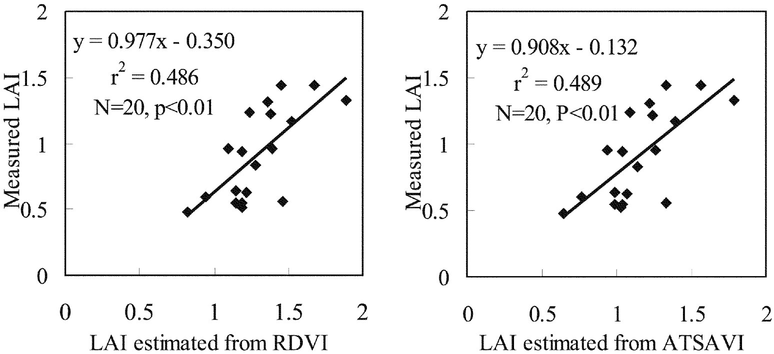

Figure 3: *The relationships between measured LAI and estimated LAI.*

and bare ground have little effect on the relationships when used with the selected indices. Since the 40 sites also include different terrains and plant communities (native grass, invading grass, forbs, and shrubs), the LAI estimation could be applied to the whole range of plant communities and the entire study area.

Model Assessment and Mapping LAI:

Remotely sensed data from the 20 sites not included in the regression analyses were used to assess the regression models. Figure 3 shows the relationships between measured and estimated LAI values. For both VI, the coefficient of X (0.997 for RDVI, 0.908 for ATSAVI) indicates that the regression models estimate LAI quite well, although LAI was slightly underestimated. The r^2 values for the ATSAVI and RDVI models are essentially the same, at 0.489 and 0.480, respectively. The ATSAVI model had a lower average error, a lower RMSE, and higher map accuracy than the RDVI model in estimating LAI for the 20 sites (Table 2). Overall, then, the results indicate that ATSAVI has a slight advantage over RDVI in estimating LAI.

Table 2: *Assessment of the regression models used to estimate LAI.*

	Average error	RMSE	Map accuracy
RDVI	0.858	0.411	53.9%
ATSAVI	0.771	0.297	66.7%

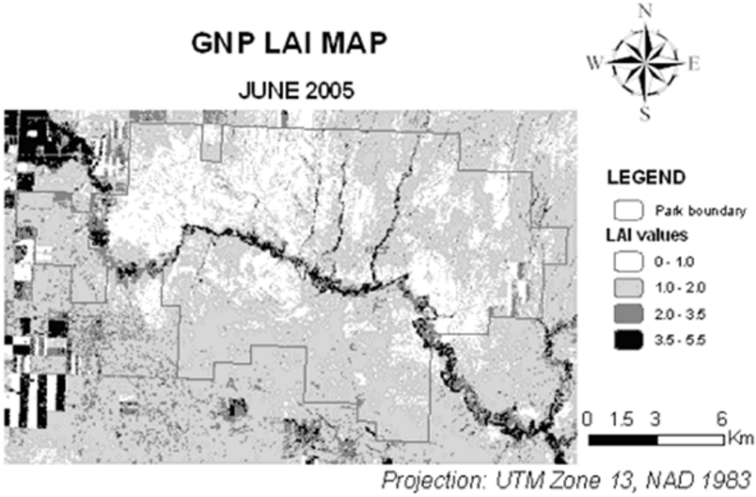

Figure 4: *LAI map produced from SPOT imagery using the ATSAVI-LAI regression model*

Thus, based on these results, we chose ATSAVI to develop the LAI map for the West Block of the GNP. In the final map product (Figure 4), the white color within the Park holdings represents low LAI values and lower vegetation. Light grey represents LAI values ranging from 1 to 2, which account for a majority of the Park area. Higher LAI values (2.0 - 3.5) are represented by dark grey and the highest LAI values associated with more vegetation cover are represented by the darkest tone. In general, areas with the highest LAI values are along the river banks and the lowest LAI values are towards the northwest part of the Park. The results are reasonable, given that the river banks have higher levels of moisture able to support more grass and that the sparsely vegetated badlands are located in the northwest

Conclusion

In this study we selected two vegetation indices, ATSAVI and RDVI, to estimate LAI and to prepare an LAI map for the West Block of the Grasslands National Park, Saskatchewan, Canada. The results of the linear regressions demonstrated strong relationships between LAI as measured by a Plant Canopy Analyzer and the selected vegetation indices. Further assessment of the accuracy of the regression models indicated that for a Northern mixed grassland ecosystem, ATSAVI was better at estimating and mapping LAI than RDVI. The accuracy of the LAI map derived from ATSAVI was calculated to be 66.7% and this map represented quite well the spatial distribution of the vegetation. It was seen that the higher LAI values were along the river banks where there are higher levels of soil moisture for plant growth, and lower LAI values were produced towards the northwest part of the Park where there is more sloped and sparsely-vegetated ground.

The study has demonstrated the feasibility of exploiting remote sensing data to provide park managers with landscape scale information on the spatial variation of a biophysical condition (*i.e.* LAI) of the grasslands. We believe that further applications of this study could benefit ecologists by helping to determine whether non-adaptive grazing management will ultimately result in overgrazing. Furthermore, wildfire management and prescribed burning programs could adopt LAI maps effectively, to update fuel load information for extensive rangelands. Conservation groups, government organizations, and managers in the Great Plains region could take advantage of LAI maps derived from imagery, to monitor important biophysical properties of the grasslands, for sustainable wildlife and critical habitat management.

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