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Estimation of Vegetative Characteristics by Remote Sensing

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Measurements of biomass, leaf area and carbon cycling rates are important components for understanding ecosystem processes. While other techniques are available to measure these components, remote sensing has the advantages of non-destructive sampling and sampling at large scales. An experiment was conducted from June through mid-October of 2006 to estimate gross canopy photosynthesis (GCP), leaf area index (LAI) and total aboveground biomass of an ungrazed tallgrass prairie with a hyperspectral radiometer and compare these estimates to flux chamber measurements. Four indices (Normalized Difference Vegetation Index (NDVI), Simple Ratio (SR), ($R_{nir}/R_{rededge}$)-1, and (R_{nir}/R_{green})-1 were used to predict LAI and total biomass. Six indices (NDVI, SR, [($R_{nir}/R_{rededge}$)-1]*photosynthetically active radiation (PAR),[(R_{nir}/R_{green})-1]*PAR, Photochemical Reflectance Index (PRI) and the Water Band Index (WBI)) were used to derive an estimate of GCP. All indices had poor correlations to LAI and total aboveground biomass. However, GCP was significantly correlated to all six indices utilized in this study. While GCP measured from June-October was significantly correlated to all indices, removal of the October scans greatly increased the accuracy of all models except the PRI. This study demonstrates the strong relationship between GCP and spectral reflectance in the tallgrass prairie. These relationships may be further utilized with other methods of measuring carbon exchange to gain greater understanding of larger scale ecosystem processes.

Keywords: Hyperspectral; LAI; total biomass; gross canopy photosynthesis.

INTRODUCTION

Remote sensing has the advantages of non-destructive sampling and sampling at large scales. Hyperspectral reflectance spectra are useful for estimating vegetation characteristics such as gross canopy photosynthesis (GCP), biomass, and leaf area index (LAI). Specific wavebands within the reflectance spectra are then utilized to calculate vegetation indices, which remove error caused by soil and atmospheric conditions as well as vegetation geometry (Blackburn and Stelle, 1999; Gao *et al.,* 2000). By using these indices, large data sets can be quickly collected to provide information on carbon cycling rates, fire fuel loads, ecosystem productivity, and parameters for modeling ecosystem function.

Some commonly used vegetation indices contrast spectral reflectance in the red and infrared wavelengths and are referred to as greenness indices. These vegetation indices contrast the high absorption of red spectra by chlorophyll to the high reflectance of near infrared spectra due to scattering (Myneni*et al.,* 1997). Two vegetation indices that utilize this relationship include the Normalized Difference Vegetation Index (NDVI) (Rouse *et al.,* 1973) and the Simple Ratio (SR) (Birth and McVey, 1968). However, the relationships between NDVI and certain vegetative characteristics (LAI and biomass) are curvilinear when LAI exceeds 2 under moderate to high biomass yields (Myneni*et al.,* 1997). This results from the high absorption of the red wavelengths by dense canopies (Gitelson, 2004).

Birth and McVey (1968) utilized the high absorption of red wavelengths and high reflectance of infrared wavelengths by green, actively growing leaves to determine the greenness of turf grass. Jordan (1969) later used the SR to estimate LAI of a broadleaf forest in Puerto Rico.

In an attempt to circumvent the problematic saturation of the red spectra at relatively low chlorophyll contents, Gitelson *et al.,* (2003) developed two new indices from relationships between the infrared and red-edge or green wavebands to estimate LAI and green leaf biomass. Absorption in these wavebands by chlorophyll does not saturate even at high chlorophyll content (Gitelson and Merzlyak, 1994; Gitelson et *al.,* 1996).

Gitelson and Merzlyak (2004) also demonstrated that these indices were linearly related to leaf chlorophyll content. Gitelson *et al.* (2006) determined the relationship between gross primary productivity and an index utilizing the estimated chlorophyll content multiplied by the photosynthetically active radiation (PAR) in uniform corn and soybean fields. While these algorithms successfully predicted GPP, LAI, and green biomass in uniform agronomic settings, the authors stressed the importance of further model validation with different crops and geographic sites (Gitelson*et al.,* 2006).

Other vegetation indices focus on measuring physiological functions that are related to plant productivity. Two of these vegetation indices include the Photochemical Reflectance Index (PRI) (Gamon *et al.,* 1992) and the Water Band Index (WBI) (Penuelas *et al.,* 1993). The PRI measures the conversion of violaxanthin to antheraxanthin and zeaxanthin by de-epoxidase reactions, which allow plants to dissipate excess light as heat (Demmig-Adams and Adams, 1996). The PRI is closely linked to photosystem II activity and has a high correlation with net carbon uptake from upper canopy leaves (Gamon *et al.,* 1997).

Penuelas*et al.* (1993) reported a significant correlation between the WBI, relative water content, stomatal conductance, and photosynthetic rates of *Gerbera jamesonii*, *Capsicum annuum*, and *Phaeolus vulgaris*. The importance of plant water status on leaf and canopy photosynthesis has also been demonstrated for the tallgrass prairie (Knapp, 1985; Suyker and Verma, 2001;Suyker*et al.,* 2003).

However, the relationships between vegetation indices and GCP, LAI, and biomass are influenced by plant species, leaf type, canopy architecture and geographic region and water status and some newer indices have only been tested on a few species (Billings and Morris, 1957; Clark and Lister, 1975; Reicosky and Hanover, 1978; Gitelson et *al.,* 2006).

The objective of this research was to use reflectance spectra to assess the relationships among various vegetative indices, LAI, biomass, and GCP of a tallgrass prairie throughout the growing season.

MATERIALS AND METHODS

STUDY AREA

The study was conducted from June through October during 2006. The site was an ungrazed pasture located in the Rannells Flint Hills Prairie Preserve, 5-km south of Manhattan, KS (39.11°N, 96.34°W, 324 m above sea level). The dominant vegetation consisted of the C4 species *Andropogon gerardii* Vitman and *Sorghastrumnutans* (L.) Nash while subdominants included *A. scoparius* Michx. and*Boutelouacurtipendula* (Michx.) Kunth. The remainder of the vegetation consisted of various sedges (C3), and C3 forbs including *Vernoniabaldwinii* (Small) Schub.,*Ambrosia psilostachya* DC., *Artemesialudoviciana* Nutt., and *Psoreleatenuiflora* var. *floribunda* (Nutt.) Rydb. The soil was a Dwightsilty clay (Fine, smectitic, mesicTypicNatrustolls) on a 1-3% slope. Average annual precipitation (1971-2000) is 884 mm with 542 mm (61%) occurring from May through September. Eighteen plots were established in mid-May of 2006 by pressing 0.85 m x 0.85 m soil collars into the soil. The soil collars were constructed of 5.1 cm x 7.6 cm x 0.5 cm angle iron into the soil until the top was 5 cm above the soil surface.

Measurement of CO_2fluxes

Net carbon exchange flux (NCE) and Ecosystem Respiration (R_E) were measured from 1 hour prior to 1 hour after solar noon with a non-steady-state closed system chamber (Murphy, 2007). The chamber footprint was 0.85m x 0.85m with a height of 0.25 m and total weight of 10.9 kg. Sides were constructed of 4.59-mm acrylic-FE (Acrylite, Cyro Industries, Clifton, NJ). The top was made from heat-stretched Propafilm-C (ICI Americas Inc., Wilmington, DE) with high thermal and visible transmittance (Hunt, 2003). A closed-cell foam gasket (Nomapack-WS, NomacoInc, Zebulon, NC) provided a tight seal between the bottom edges of the chamber sides and the soil collar. Two fans (700 L min-1, BD 12A3, Comair Rotron, San Diego, CA) circulated air through a perforated plenum attached to the inside wall near the bottom of the chamber. The rate change of CO_2 concentration within the chamber was measured with a closed path infrared gas analyzer (IRGA, LI-840, LiCor Industries, Lincoln, NE). Net carbon exchange was measured with the chamber exposed to ambient light. Chamber measurements were initiated by recording ambient conditions above the canopy for 20 seconds. Data acquisition was then paused for five seconds while the chamber was positioned over the canopy and placed onto the soil frame. Following the five-second pause, data acquisition resumed for a 40-second period with the chamber positioned over the canopy. Following each reading, the chamber was removed from the canopy and the CO_2 and water vapor concentrations and air temperature within the chamber were allowed to equilibrate with ambient conditions. Ecosystem respiration was then measured by excluding light with an opaque chamber positioned over the canopy. The sampling procedure was the same for NCE. Gross Canopy Photosynthesis (GCP) is the sum of net carbon exchange (NCE) and ecosystem respiration (R_E)

$$GCP = NCE + R_E$$

[eq. 1]

with all terms in µmol m^{-2} s^{-1}. The micrometeorological convention of labeling fluxes from the ecosystem to the atmosphere as positive (source of CO_2) was utilized in this study.

Reflectance measurements

Following the measurements of NCE and R_E, a dual-channel field spectrophotometer (Unispec-DC, PP Systems, Haverhill, MA) was utilized to record reflectance from the same plots used for the chamber measurements. The Unispec-DC consists of two spectrophotometers that measure reflectance between 310-1100 nm in 3.3 nm bandwidths, for a total of 256 data points collected per scan. One spectrophotometer, with a 12° field of view foreoptic, sampled upwelling radiation from the target while the second spectrophotometer had a hemispherical diffuser foreoptic that measured incoming irradiance. Both spectrophotometers were mounted on a tripod 1.5 m above the ground, which resulted in 0.07-m^2 view, 10% of the total plot area.

Prior to each scanning period, a two-step process calibrated the two spectrophotometers. First, a dark scan was conducted by completely blocking all radiation to the instrument. The dark scan removes sensor noise that is associated with the temperature of the spectrophotometers. The two spectrophotometers were then calibrated using a barium sulfate panel by comparing upwelling radiance measured from the panel to irradiance measured by the cosine diffuser.

A linear interpolation of the reflectance spectra was performed (Multspec 5.1, available from Specnet.info) that calculated values in 1 nm increments. These interpolated values were then used to calculate the vegetation indices.

Spectral indices

The two greenness indices, NDVI and SR, which are based on contrasting the absorption in the red and infrared regions of the spectrum were calculated as:

$$NDVI = \frac{(R_{800} - R_{680})}{(R_{800} + R_{680})}$$

[eq. 2]

$$SR = \frac{R_{800}}{R_{680}}$$

[eq. 3]

where R_{800} and R_{680} are reflectance values recorded in the infrared and red wavelengths, respectively.

The two indices developed by Gitelson *et al.* (2003) to predict LAI and green biomass using the relationships among wavebands that do not saturate at high biomass and LA were calculated as:

$$\frac{R_{840-870}}{R_{700-730}} - 1$$

[eq. 4]

$$\frac{R_{840-870}}{R_{545-565}} - 1$$

[eq. 5]

Where $R_{xxx\text{-}xxx}$ is the average reflectance value of the spectra within the denoted wavebands. The relationships between GCP was then estimated using:

$$\left[\frac{R_{840-870}}{R_{700-730}} - 1\right] * PAR$$

[eq. 6]

Table 1. Pearson's correlation coefficient for Gross Canopy Photosynthesis (GCP), Leaf Area Index (LAI), total biomass measured during either June 9 –October 12 (June-Oct), June 9 – August 16 (June-August) or June 9 – September 13 (June-Sept) and ($R_{nir}/R_{rededge}$)-1, NDVI, SR, WBI, (R_{nir}/R_{green})-1, and PRI vegetation indices and the number of hyperspectral scans (n).

	($R_{nir}/R_{rededge}$)-1	NDVI	SR	WBI	(R_{nir}/R_{green})-1	PRI	n
GCP *(June-Oct)*	-0.734***	-0.466***	-0.573***	-0.762***	-.0518***	-0.720***	99
GCP *(June-Sept)*	-0.905***	-0.872***	-0.868***	-0.865***	-0.845***	-0.676***	81
LAI *(June-Oct)*	0.469**	0.363*	0.498**	n/a	-0.144	n/a	36
LAI *(June-Aug)*	0.676**	0.654**	0.588*	n/a	0.680**	n/a	18
Biomass *(June-Oct)*	0.349*	0.192	0.305	n/a	-0.075	n/a	36
Biomass *(June-Aug)*	0.363	0.291	0.263	n/a	0.352	n/a	18

Correlations are significant at the 0.05 (*), 0.01 (**), and 0.0001 (***) levels. The n/a symbol indicates index was not utilized in comparison.

$$\left[\frac{R_{840-870}}{R_{545-565}} - 1\right] * PAR$$

[eq. 7]

where $\frac{R_{840-870}}{R_{700-730}} - 1$ and $\frac{R_{840-870}}{R_{545-565}} - 1$ are measures of the chlorophyll concentration as defined by Gitelson *et al.* (2005). Photosynthetically active radiation was measured with a quantum sensor (LI-190, LiCor Industries, Lincoln, NE).

The PRI, a reflection index that can be used to estimate xanthophyll concentration, was calculated as:

$$PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})}$$

[eq. 8]

where R_{531} is an estimate of xanthophyll concentration, while R_{570} is a reference band where absorption is not due to xanthophylls.

The WBI index value was calculated as:

$$WBI = \frac{R_{900}}{R_{970}}$$

[eq. 9]

where R_{970} is a wavelength absorbed by water and R_{900} is a reference wavelength outside the water absorption band.

Pearson's correlation analysis was performed to test the relationships between LAI, biomass, and equations 1-4, while equations 1, 2, 5, 6, 7, and 8 were tested against GCP (ProcCorr, SAS 9.1, SAS Institute, Cary, NC). Linear regression was then performed to determine the coefficients of determination and the equation describing the relationships (ProcReg, SAS 9.1).

Aboveground biomass and leaf area sampling

Following reflectance measurements, aboveground biomass and leaf area were determined at seven different times during the year by clipping to a height of 5 cm all of the vegetation within the plots used for both the chamber and hyperspectral measurements. The vegetation was then placed in an insulated container and transported to the laboratory where green and senesced vegetation was manually sorted. Green leaf area was measured for both graminoids and forbs with an area meter (Li-3100, LiCor, Lincoln, NE). Total aboveground biomass was determined gravimetrically after drying the vegetation at 55°C for 72 hrs. Total biomass was used in the calculation of the indices used for biomass estimation.

RESULTS

Gross canopy photosynthesis fluxes (GCP) and vegetation Indices

Ninety-nine hyperspectral scans were taken from June through October over plots with GCP ranging from –3.0 to –34.4 mmol m^{-2} s^{-1}. The Pearson's correlation analysis indicated that all indices were significantly correlated with GCP (Table 1). The WBI and PRI had the highest

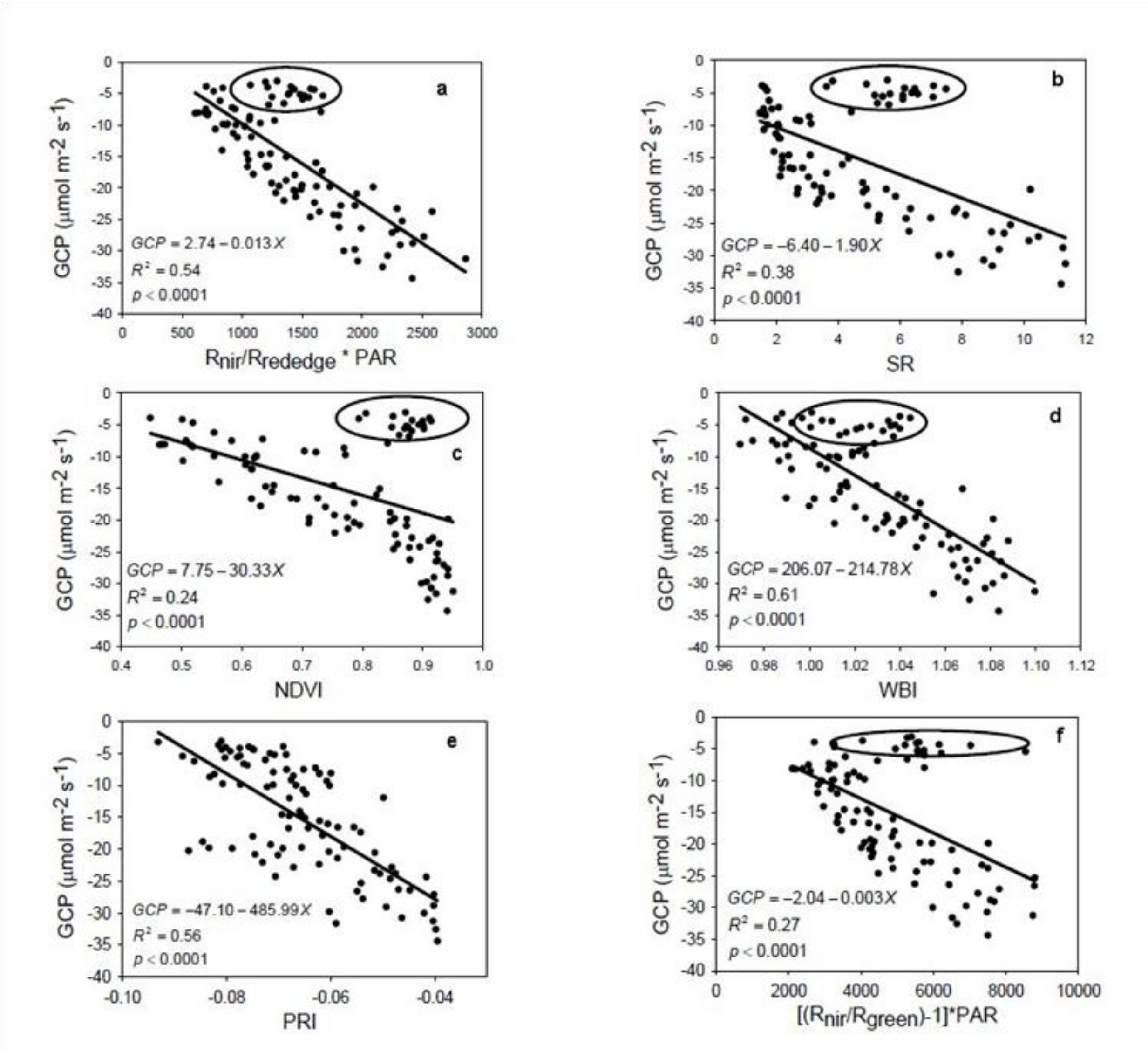

Figure 1. Relationships between $[(R_{nir}/R_{rededge})-1]$ * PAR (a), the Normalized Difference Vegetation Index (NDVI) (b),the PRI (c), the Simple Ratio (SR) (d), the Water Band Index (WBI) (e), $[(R_{nir}/R_{green})-1]$ * PAR (f), and Gross Canopy Photosynthesis (GCP) as determined by linear regression from June through October. The circled data points indicate the October 12^{th} scans (n=99).

correlation with GCP while $[(R_{nir}/R_{green})-1]$ * PAR and NDVI had the lowest correlation with GCP. The results of the linear regression analysis determined that only the WBI and PRI had coefficients of determination greater than 0.56 (Figures 1a,b,c,d,e,f). The $[(R_{nir}/R_{green})-1]$ * PAR index had the lowest coefficient of determination.

One interesting feature was the presence of 18 outlier scans for all indices except PRI (Figures 1a,b,c,d,e,f). The outliers represent a set of hyperspectral scans that were collected on October 12, when canopies had begun senescing. Removal of these scans increased the Pearson's correlation coefficients for all vegetation indices except the PRI. Following the removal of the outlier scans, the $[(R_{nir}/R_{rededge})-1]$ * PAR index had the highest correlation coefficient, while the PRI had the lowest correlation coefficient (Table 1). The coefficients of determination were greater than 0.56 for all comparisons except the PRI. Four indices had coefficients of

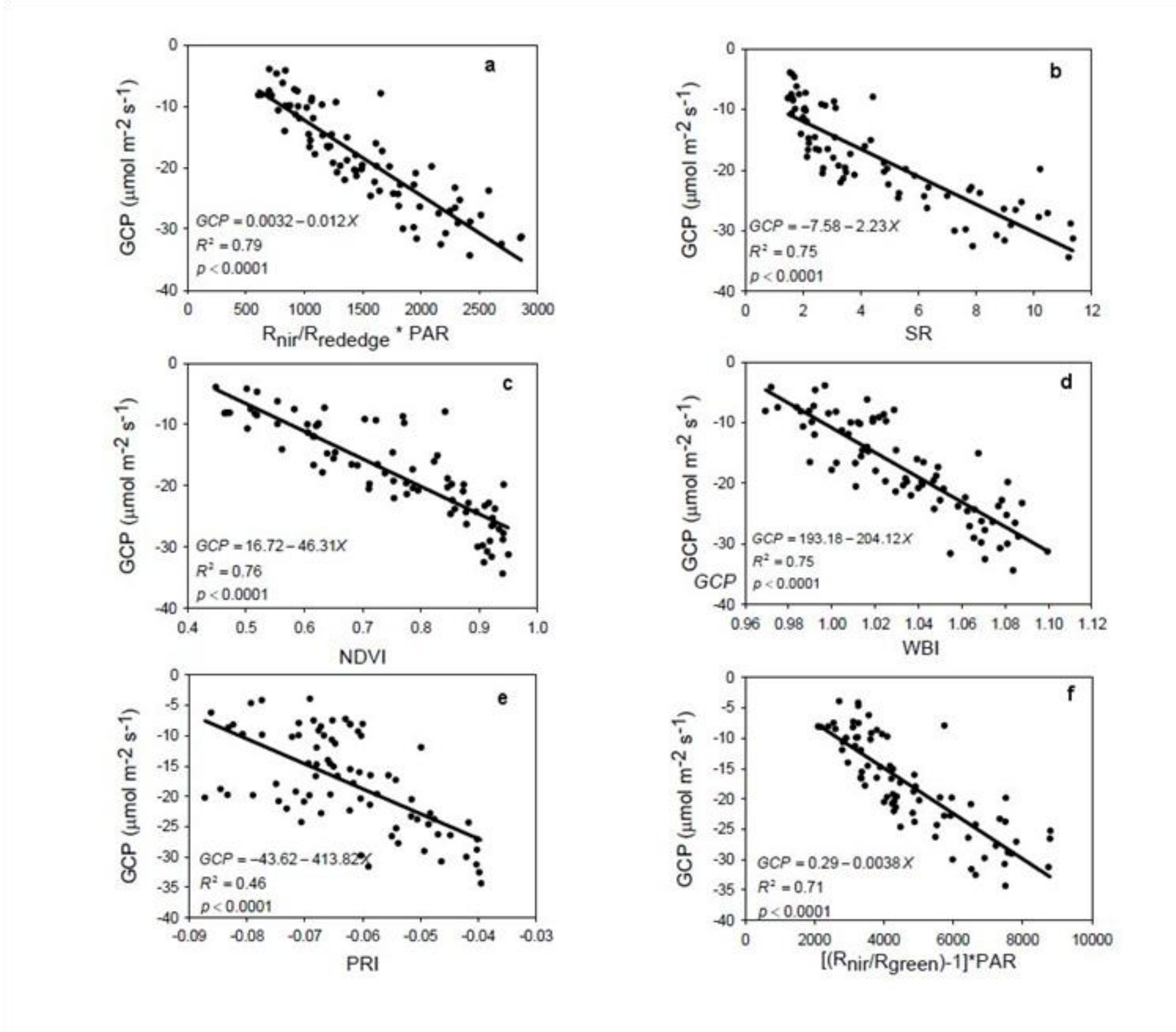

Figure 2. Relationships between [($R_{nir}/R_{rededge}$)-1] * PAR (a), Normalized Difference Vegetation Index (NDVI) (b), PRI (c), Simple Ratio (SR) (d), Water Band Index (WBI) (e), [(R_{nir}/R_{green})-1] * PAR (f), and Leaf Area Index (LAI) as determined by linear regression from June through September (n=81).

determination values ≥ 0.75 (Figure 2a, b, c, d, e, and f).

Leaf area index (LAI) and vegetation indices

Thirty-six hyperspectral scans were taken from June through October over plots with LAIs ranging from 0.28 to 2.12 m^2 m^{-2}. A Pearson's correlation analysis indicated that the SR, NDVI, and ($R_{nir}/R_{rededge}$)-1 were significantly correlated to LAI (Table 1). Regression analysis indicated that the SR index had the highest coefficient of determination (Figure3a,b,c,d) among the three indices. Similar to the GCP regression analysis, hyperspectral scans taken during October clustered together. Again, removal of the 18 October scans improved both the Pearson's correlation coefficients and coefficients of determination for all vegetation indices (Table 1).

The correlation analysis of the June to August data indicated all were significantly correlated to LAI (Table 1). The (R_{nir}/R_{green})-1 and ($R_{nir}/R_{rededge}$)-1 indices had the highest correlation coefficients, while SR had the lowest correlation coefficient. Linear regression analysis indicated that all models were significant, however, the coefficients of determination were considerably lower for

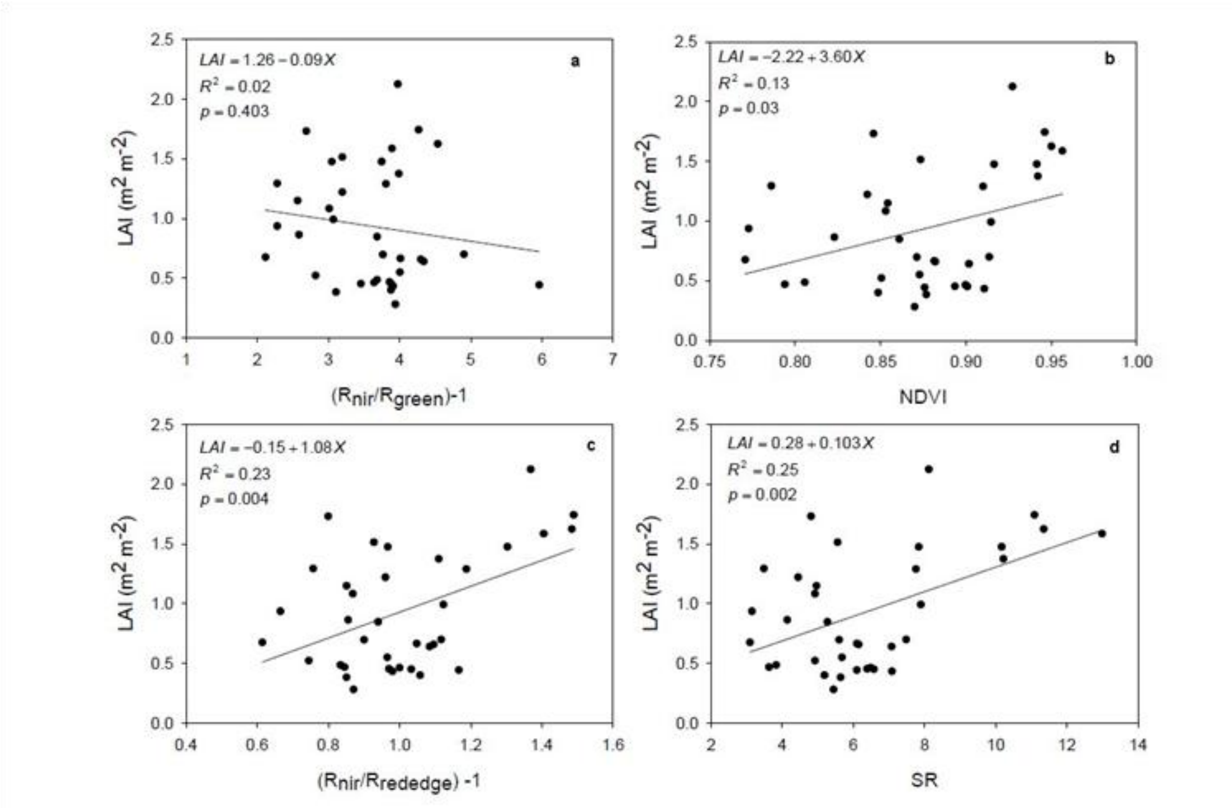

Figure 3. Relationships between (R_{nir}/R_{green})-1 (a), $(R_{nir}/R_{rededge})$-1 (b), Normalized Difference Vegetation Index (NDVI) (c), Simple Ratio (SR) (d) and Leaf Area Index (LAI) as determined by linear regression from June through October (n=36).

LAI than GCP (Figure 4a,b,c,d).

Total biomass and vegetation indices

Thirty-six hyperspectral scans were taken from June through October over plots with biomass ranging from 45.4 to 317.6 g m^{-2}. Of the indices utilized, only the $(R_{nir}/R_{rededge})$-1 index was determined to be significantly correlated to biomass by the Pearson's correlation analysis (Table 1). The results of the linear regression analysis showed that while significant ($p = 0.04$), the coefficient of determination was only 0.12.

Interestingly, following removal of the October spectral scans; none of the vegetation indices were significantly correlated to biomass (Table 1). The coefficients of variation ranged from minimum value of 0.069 for the SR index to a maximum value of only 0.132 for the $(R_{nir}/R_{rededge})$-1 index.

DISCUSSION

Surprisingly, all indices tested against LAI and biomass had poor correlations. Olson and Cochran (1989) and Villarreal *et al*. (2006), working in the tallgrass prairie, also reported weak relationships between NDVI and biomass. However, using the $(R_{nir}/R_{rededge})$-1 and (R_{nir}/R_{green})-1 indices, Gitelson *et al*. (2003) working with corn and soybeans reported R^2's of 0.98 and 0.96 for green leaf biomass and LAI, respectively. The considerably better correlations to biomass and LAI reported by Gitelson *et al.* (2003) are most likely reflect the more uniform field conditions, fertilization, measurement of an annual plant, and comparison to only green leaf biomass. The agronomic field setting resulted in a more uniform plant distribution. Unlike the fertilized, annual corn and soybean plants of Gitelson *et al.* (2003), that continue to partition nitrogen to the leaves, the Flint Hills is a nitrogen-limited environment (Owensby *et al*., 1970), and big bluestem and indiangrass, two dominant perennial grass species present in this study, conserve nitrogen by remobilizing the nitrogen from the leaves to the rhizomes during July (McKendrick *et al.,* 1975, Owensby *et al.,* 1977, Hayes, 1985). That nitrogen is utilized to initiate growth the following spring. As the nitrogen is translocated from the leaves, chlorophyll content declines, and hence indices that utilize

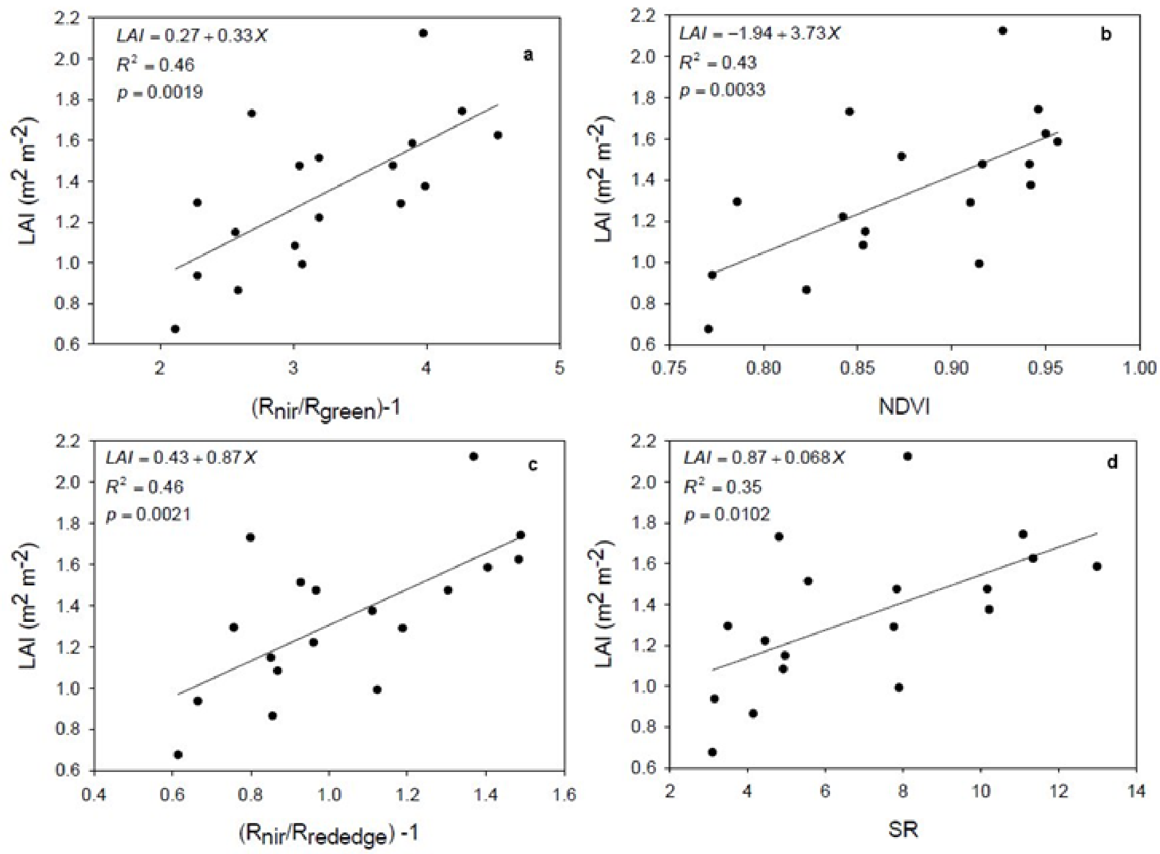

Figure 4. Relationships between (R_{nir}/R_{green})-1 (a), the ($R_{nir}/R_{rededge}$)-1 (b), Normalized Difference Vegetation Index (NDVI) (c), Simple Ratio (SR) (d), and Leaf Area Index (LAI) as determined by linear regression on data collect
from June through August (n=18)

chlorophyll content will poorly predict LAI and biomass. Gitelson *et al*., (2003) further improved accuracy of the biomass model by limiting the spectral indices to only green leaf biomass instead of total biomass as used in this study. Gamon et al. (1995) reported increased correlation coefficients when NDVI and SR were regressed against only green leaf biomass instead of total standing biomass.

All of the vegetation indices utilized during this study are related to GCP measured from June through October. However, for all but one index, the 18 scans taken during October decreased the strength of the GCP-index relationship and were clustered away from the remaining 81 scans representing June through September. Removal of the 18 October scans markedly improved the coefficients of determination for all indices except PRI. The increased correlation after removal of these scans most likely resulted from a large amount of senesced grass present in October. Because chlorophyll breaks down faster during senescence than xanthophyll (Gitelson and Merzlyak, 1994, Merzlyak*et al*., 1999) an index that measures xanthophyll appears to be better correlated to GCP than chlorophyll indices late in senescing canopies.

One surprising result of removing the October scans was the strong relationship between [($R_{nir}/R_{rededge}$)-1] $*$ PAR index and GCP. In monoculture stands of corn and soybean, Gitelson et al. (2004) reported a maximum R^2 = 0.85 for a net ecosystem exchange [($R_{nir}/R_{rededge}$)-1] $*$ PAR relationship, only slightly greater than that reported in this study in a heterogeneous ecosystem.

The high correlations between NDVI-GCP and SR-GCP were another unexpected finding since both indices were not related to biomass and only moderately related to LAI. The strength of the relationship is probably due to the allocation of nitrogen to the upper canopy leaves. Schimel *et al*., (1991), working in the tallgrass prairie, reported that nitrogen was preferentially allocated to the upper canopy leaves and that photosynthetic rates of those leaves was up to 3.2 times greater on the top canopy leaves than the lower leaves. If the majority of photosynthesis is occurring in the upper portion of the canopy, less self-shading of the most photosynthetically active leaves will occur and a better estimate of chlorophyll or greenness of the leaf is possible, which will increase the strength of the correlations to GCP.

The high R^2 of the WBI further confirms the importance of water on GCP. Knapp (1985), working with big bluestem, the dominant plant species in this study, reported leaf photosynthetic rates approaching zero under severe water stress. Hence, a measure of moisture stress should have good predictability of GCP.

CONCLUSIONS

The relationships between GCP and the vegetation indices utilized in this study demonstrate that that spectral reflectance measured by a hyperspectral radiometer can accurately estimate seasonal GCP from a tallgrass prairie. The results also indicate that indices developed in uniform, monoculture agronomic field settings can be successfully applied to much more heterogeneous environments. However, none of the indices utilized were able to satisfactorily estimate either LAI or biomass.

The strong relationship between GCP and spectral reflectance in the tallgrass prairie further stresses the importance of integrating remote sensing and flux measurements as proposed by Gamon *et al*. (2006). Further work is needed to test the applicability of using remote sensing at the scale of landscape fluxes. Also, further work is needed in developing vegetation indices that better estimate LAI and biomass, which are critical for a complete understanding of landscape scale processes.

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