Spatial and Temporal Variability of Surface Cover at BOREAS Using Reflectance from a Helicopter Platform

Sara E. Loechel +
Phone: 301/504-6823 ; Email: sloechel@geog.umd.edu
Charles L. Walthall *
Phone: 301/504-6074 ; Email: cwalthal@asrr.arsusda.gov
Eric Brown de Colstoun +
Phone: 301/405-3043 ; Email: ebrownde@geog.umd.edu
Jing M. Chen ☆
Phone: 613/947-1266 ; Email: Chen@ccrs.emr.ca
Brian L. Markham °
Phone: 301/286-5240; Email: markham@highwire.gsfc.nasa.gov

+ Laboratory for Global Remote Sensing Studies, University of Maryland, College Park, Maryland 20742
* Remote Sensing and Modeling Laboratory, Beltsville Agricultural Research Center, Beltsville, Maryland 20705
☆ Canadian Centre for Remote Sensing, Ottawa, Ontario K1A 1Y7
° Laboratory for Terrestrial Physics, Goddard Space Flight Center, Greenbelt, MD 20771

Abstract -- Helicopter-based radiometric measurements of forested sites acquired during the Boreal Ecosystem-Atmosphere Study (BOREAS) were used to examine the spatial, temporal, and spectral variability in surface reflectance and vegetation indices (VI), including the normalized difference vegetation index (NDVI) and the simple ratio (SR), and for comparison with surface cover and fluxes. In this analysis, the sensors, which were employed during all three intensive field campaigns (IFC) of 1994, consisted of an eight-channel modular multiband radiometer (MMR), ground-based sun photometer used for atmospheric correction, and LICOR LAI-2000, hemispherical photographs, and a ceptometer for retrieval of surface biophysical variables. Means and coefficients of variation were calculated and linear regression analysis performed on reflectances, VIs, and surface variables over the entire data set and as a function of season and cover type. Surface biophysical variables included leaf area index (LAI), effective LAI, and the fraction of absorbed photosynthetically-active radiation (green fAPAR). While each dominant species displayed recognizable reflectance spectra, variability in reflectance, which was high in every channel, was most likely strongly influenced by understory and ground reflectances, and by atmospheric effects. Of the eight MMR bands, those most responsive to surface variations were the third and second middle infrared (IR) (2.08-2.37 and 1.57-1.80 μm, respectively), the red (0.63-0.68 μm), and the blue (0.45-0.52 μm). Of the two VIs examined, our results showed that the NDVI offered more predictive information than the SR regarding temporal and spatial variations in surface characteristics. Linear regression analyses between the surface biophysical measurements and the helicopter reflectances and VIs resulted in low r^2 values (consistently < 0.5), which may be explained by the effects of incomplete canopy cover and background effects. Only among sites that were mainly vegetated by Aspen (*Populus tremuloides*) and observed during the summer IFC was a stronger relationship observed. Atmospheric contamination of the radiometric signal by clouds and smoke from forest fires may also have contributed to the unsatisfactory results. Improved estimates of aerosol optical depth, taken from a sun photometer mounted on the helicopter, will be available in the future.

INTRODUCTION

A central objective of the Boreal Ecosystem-Atmosphere Study (BOREAS) was to achieve an improved understanding of the behavior of the boreal biome for use in more accurately predicting the effects of global change [6]. Remote sensing techniques which estimate relevant biophysical and climatic variables are frequently used in models which predict global change. Therefore, the objective for remote sensing studies at BOREAS was to improve those techniques used for parameter retrieval. In particular, one objective of this research was to assess the utility of vegetation indices (VI), derived from helicopter-based modular multiband radiometer (MMR) reflectances, in estimating surface biophysical variables during all three intensive field campaigns (IFC) of 1994 at BOREAS [11]. This assessment should also assist in clarifying the methods used to estimate those same variables at global scales from satellite observations. A secondary objective of this preliminary analysis was to assess the quality of the helicopter and surface measurements at BOREAS to eliminate sources of error in evaluations of the predictive capabilities of VIs.

The current understanding of the use of satellite reflectance factors to categorize forest canopy characteristics is changing.

0-7803-3068-4/96$5.00

The relationships and models which are applied to forest canopies were developed over homogeneous agricultural crops or grassland canopies. Those relationships have not consistently applied to the forest environment with its natural variability, unique geometry, and layering characteristics. In agricultural crops and forests with full canopy cover, the relationship between LAI and reflectance factors in the red, near infra-red, and mid-infrared have been found to be negative, positive, and negative, respectively [2]. In incomplete canopies, however, a negative relationship was found between red reflectance and LAI, but no relationship between near infra-red reflectance and LAI [8]. In addition, analysis over Oregon forests (where LAI was correlated to canopy closure) showed a positive near IR-to-LAI relationship in deciduous and coniferous stands [7]. Thus, over the boreal forests where the relationship of canopy closure to LAI is unknown, this may be a factor when utilizing reflectance and VIs in modeling forest canopy processes.

METHODOLOGY

The analysis was performed in three stages. First, the helicopter MMR observations were converted to at surface reflectance factors through the processes of radiometric calibration and atmospheric correction. Second, an initial assessment in the form of measures of central tendency and variability in the MMR reflectance factors, MMR-derived VI products, and surface biophysical variables was made. This provided a broad understanding of the behavior of the variables and a glimpse at possible trends and patterns, as well as an assessment of data quality. Third, linear regression was used to assess the predictive capability of reflectances and VIs relative to the surface biophysical variables, which are commonly applied with satellite data, and as a function of dominant species and season. The dominant vegetation types which we focused on are Aspen (*Populus tremuloides*), Black Spruce (*Picea mariana*), and Jack Pine (*Pinus banksiana*) [6].

The helicopter and surface data used in this analysis were collected during all 3 IFCs of 1994 at numerous tower and auxiliary sites in both the northern and southern study areas at BOREAS. The dates of the IFCs were as follows: 24 May-16 June, 19 July-10 August, and 30 August-19 September, in sequence. The NASA Goddard Space Flight Center/Wallops Flight Facility (GSFC/WFF) helicopter was deployed and the data was acquired with a Barnes Modular Multispectral Radiometer (MMR) while the helicopter was hovering at an altitude of approximately 300 meters above ground level yielding an instantaneous field of view (IFOV) of ~ 23 m. The spectral bands of the MMR are as follows: 0.45-0.52 μm for MMR1 (blue), 0.51-0.52 μm for MMR2 (green), 0.63-0.68 μm for MMR3 (red), 0.75-0.88 μm for MMR4 (near infra-red (IR)), 1.17-1.33 μm for MMR5 (first middle IR), 1.57-1.80 μm for MMR6 (second middle IR), and 2.08-2.37 μm for MMR7 (farthest middle IR). The MMR voltages were processed to at-sensor radiances ($Wm^{-2}\mu m^{-1}sr^{-1}$) following procedures described in [4] and using calibration coefficients obtained during post-season calibrations performed at NASA/GSFC. The individual scans were examined and those with spurious values were removed. The mean helicopter MMR radiances and sun photometer data collected near-simultaneously on the ground were then input into Version 3.2 of the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) atmospheric correction program [9] to obtain surface reflectance factors. The sun photometer data set provided estimates of aerosol optical depths, which varied spatially and temporally especially during the summer due to the prevalence of forest fires. Descriptions of the methods used in deriving LAI and green fAPAR estimates are available in the literature [1,3,5]. The surface measurements used in the analysis were collected by BOREAS science teams (Chen, Cihlar and Penner; Gower; Plummer and Curran; Rich) and are defined as follows: (1) LAI -- one half the total leaf area per unit ground surface area (m^2m^{-2}); (2) effective LAI -- the product of LAI and a species-specific foliage clumping index; and (3) green fAPAR -- the fraction of photosynthetically active radiation absorbed by green plant matter (fAPAR). Time elasped between surface and helicopter observations was confined to less than three weeks for the conifer sites where seasonal variability was low, and to appoximately two weeks for the temporally-variable Aspen stands.

RESULTS AND DISCUSSION

Analysis of Central Tendency and Variability

BOREAS-Wide Analysis. The mean and coefficient of variation of surface reflectance, VIs, and surface biophysical variables in the data set are given inTable 1. Mean reflectance

Table 1: Mean and %CV for Collected MMR Spectral Reflectances, VIs, and Surface Biophysical Data Sets

	MMR1	MMR2	MMR3	MMR4	MMR5	MMR6	MMR7	SR	NDVI	LAI	EffLAI	fAPAR
N	214	214	214	214	214	214	214	214	214	96	80	85
Mean	0.019	0.032	0.03	0.191	0.203	0.125	0.054	7.475	0.717	2.929	2.088	0.694
%CV	39.3	31.2	40.6	35.7	32.2	35.7	44.1	55.2	15.5	41.3	40.8	20.8

clearly followed the spectral pattern expected for green vegetation. Low reflectance (and high absorption) was associated with the visible part of the spectrum, while high reflectance was found in the near infra-red (IR). In addition, the mean VIs (SR=MMR4/MMR3=7.5 and NDVI=(MMR4-MMR3)/ (MMR4+MMR3)=0.72) and surface parameters (LAI=2.93 and fAPAR=0.69) fell within expected values.

The variability of the SR (CV=55%) and of reflectance factors in the blue (MMR1 CV=39%), red (MMR3 CV=41%) and middle IR (MMR7 CV=44%) bands -- associated with leaf senescence, chlorophyll absorption, and tissue water content, respectively -- demonstrated markedly higher variability over the NDVI (CV=15%) and slightly higher variability relative to the other bands. The surface measurements showed similar ranges in variability (LAI CV=41%, Effective LAI CV=40%, and fAPAR CV=21%). At the First International Satellite Land Surface Climatology (ISLSCP) Field Experiment (FIFE), a similar experiment was carried out over the predominantly grass canopies of the Konza Prairie in Kansas [10]. A strong pattern of increased variability in those same variables was shown (with markedly lower variance in the other wavelengths) and was associated with a greater predictive capability. The weakness of this pattern at BOREAS suggests that the complexity and variability of forest ecosystems, variability in understory composition, and/or atmospheric effects may have introduced bias into the data set.

Figure 1 is a correlation matrix of MMR surface reflectances. High correlations (> approximately 0.8) were displayed between bands 1 through 3 and 7, while similarly high associations were seen in bands 4 and 5. This finding was consistent with the results found in Kansas [10]. However, a seasonal trend in correlations in our results indicated that the reflectances may have also been responding to other processes not associated with overstory vegetation. For example, the blue and the farthest IR (MMR1 and MMR7) showed decreasing correlations of 0.859, 0.756, and 0.689 for IFCs 1, 2, and 3, respectively. These two bands (which respond to leaf senescence and water content, respectively) should have exhibited consistently high associations, especially in the drier conditions that prevailed during the third IFC and that should have influenced both causal factors strongly. This absence of strong cross-seasonal correlations again implied the presence of complicating factors in the BOREAS data set.

Analysis of Variability Within Each Species and IFC. Mean vegetation indices and measured biophysical properties for the data set are presented in Table 2. Overall agreement in broad seasonal/cover type patterns were shown between VIs and surface biophysical variables in the helicopter data. For example, seasonal trends in SR and NDVI were observed in each species, and their relationship to cover type was observed at predominantly Aspen sites, which showed higher SR and NDVI than the Jack Pine or Black Spruce sites. Trends were less evident in the surface data, which was sampled with less frequency and regularity. For example, the same Aspen sites were not consistently sampled in every IFC. The density of the Aspen stands (relative to the conifer sites) was especially evident in the fAPAR estimates. Mild seasonal patterns were observed in the Pine and Spruce stands in both the surface and helicopter data. The sampling of LAI and effective LAI varied, especially in the second and third IFCs. Therefore, some trends were indistinguishable, as shown in Table 2 where N gives both the number of MMR and LAI samples in each dominant species type. The other surface parameters were sampled with slightly lower frequency than LAI. The inconsistent sampling regime of the surface measurements justified the further stratification of the data set.

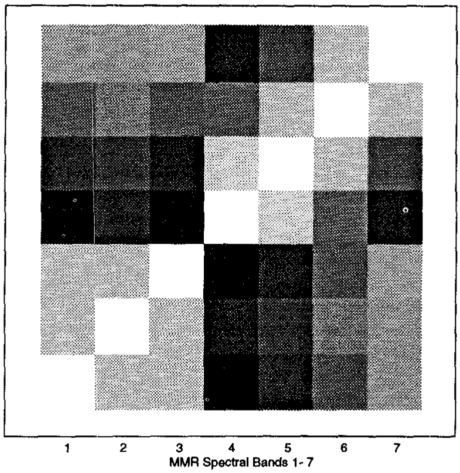

Figure 1: Correlation matrix between MMR surface reflectances. Grey scale indicates strengh of correlation ranging from 0 (black) to 1 (white); 20 greyscale steps.

Regression Analysis

BOREAS-Wide Analysis. The results of regression analyses (Table 3) showed poor relationships between surface variables and vegetation indices. Our results showed, however, implied the higher information content and predictive capability of the NDVI ($0.106 \le r^2 \le 0.276$) compared to the SR ($0.029 \le r^2 \le 0.162$). In each case, the addition of a quadratic term of LAI improved the results only slightly. The poor performance of the relationship between effective LAI and the VIs was clearly evident. Histograms of the data (which showed normal distributions in the surface variables and in the NDVI, while the SR did not) confirmed bias in the data set, though they offered little insight into causes or interactions.

Some improved relationships were found between reflectance factors in individual channels and the surface variables (Table 4). MMR bands 1-3 and 6-7 showed the strongest relationships to the surface vegetation. This confirmed the results of the analysis of mean and variability with suggested higher information content at those wavelengths. However,

Table 2: Mean Surface Variables and VIs by Species and IFC

IFC	N_{MMR} /N_{LAI}	SR	NDVI	LAI	EffLAI	fAPAR
			Aspen			
1	11/1	10.70	0.81	3.65	2.91	NA
2	28/7	14.42	0.85	2.90	1.82	0.80
3	6/1	6.63	0.70	2.66	2.21	0.84
			Pine			
1	21/12	4.16	0.59	2.17	1.62	0.60
2	37/25	5.96	0.68	2.46	1.92	0.64
3	12/6	5.62	0.68	2.84	1.64	0.79
			Spruce			
1	25/14	6.23	0.71	3.30	2.29	0.69
2	41/26	6.45	0.72	3.38	2.36	0.72
3	6/3	7.14	0.75	4.29	1.92	0.85

the slope of the regression lines were all negative, including that of near IR to LAI. The lack of a strong positive relationship between near IR reflectance and forest canopy LAI suggested, based on previous work [2,7,8], that canopy closure and LAI are not strongly correlated. Therefore, the reflectance factors were possibly influenced or biased by canopy closure, understory, and background cover.

Regression Analysis Within Species. To address the questions of the information content and predictive capability of the VIs for each species, the data set was confined to tower sites (those with intensive data collection from surface-based towers). Table 5 gives the results (r^2) of the species-by-species linear regression of the VIs and red and near IR reflectance against the three surface vegetation measurements at the tower sites. Although the quantity of sites was reduced by this restriction, as was shown in the number of observations in each analysis (N), some temporal consistency in sampling was attained. The most striking result, however, was the strong relationship (r^2>0.97) shown in the regressions of Aspen VI and individual band reflectances against surface variables. This confirms previous research [8,12], which implied that canopy closure and background effects are issues confined to coniferous tree species. The r^2 value of a regression of MMR4 and LAI in the full data set of Aspen sites was 0.61 with a positive slope, superior to the relationship for all Aspen stands in the full data set (r^2<0.03 in Table 4). This demonstrated the strength of the MMR4-LAI relationship over Aspen sites, and its weakness with coniferous species. However, SR- and NDVI-to-LAI regressions in the same data set resulted in r^2 values of only 0.32 and 0.27, respectively. Although this represented an increase relative to the significance for the entire data set (Table 3), the implication of this decrease in the significance of the relationship relative to the more restricted tower site data set was that atmospheric and aerosol contributions to the signal may have affected the visible bands. The Pine and Spruce tower site analysis showed much weaker relationships to each surface variable, which again suggested the interaction of canopy structure and background reflectance in the reflectance factors of these species. Again, effective LAI showed weak relationships in both conifer species.

Table 3: Regression Analyses for VIs (r^2)

	Predictor Variables		
Surface Variables	N	SR	NDVI
LAI	96	0.056	0.174
Eff LAI	80	0.029	0.106
fAPAR	85	0.162	0.276

The quality of performance of the NDVI in predicting surface biophysical quantities was demonstrated numerically in the slope and strength of their relationships with red and near IR reflectances. In the Aspen stands, high r^2 values and slopes conformed to expected values (red: negative; near IR: positive) which maximize the information content of the SR and NDVI [2]. The two conifer stands, however, had weak relationships, and the absence of the expected slope contributed to the weakness of the SR and NDVI relationships. A graphical depiction of this relationship is given in Figure 2. This plot of reflectance in the near IR (MMR4) as a function of LAI demonstrated the distinct behavior of the three tree species. In addition to distinct relationships as defined by the slope of the relationship (given in Table 5), the area occupied by each species in Cartesian space was mutually exclusive.

SUMMARY

The BOREAS field experiment allowed a critical assessment of the performance of vegetation indices in predicting surface conditions, a common satellite application, while use of the helicopter reflectances eliminated the issues of georegistration and scale which affect satellite observations. This preliminary analysis confirmed the utility of VIs in predicting surface conditions, and focused on an issue of concern in

Table 4: Regression Analyses for MMR Reflectance Factors and Surface Biophysical Variables (r^2)

	Predictor Variables							
Surface Variables	N	MMR1	MMR2	MMR3	MMR4	MMR5	MMR6	MMR7
LAI	96	0.268	0.271	0.332	0.027	0.183	0.403	0.450
Eff LAI	80	0.222	0.190	0.242	0.006	0.066	0.233	0.325
fAPAR	85	0.304	0.301	0.370	0.003	0.162	0.385	0.486

Table 5: Regression Analyses of VIs and Reflectances vs. Surface Variables for Each Species: Tower Sites Only

		Predictor Variables					
Surface Variables	N_{LAI}	SR (r^2)	NDVI (r^2)	MMR3 (r^2, slope)		MMR4 (r^2, slope)	
			Aspen				
LAI	3	0.998	0.999	0.99	neg	0.97	pos
Eff LAI	3	0.998	0.999				
fAPAR	3	0.998	0.999				
			Pine				
LAI	21	0.381	0.363	0.43	neg	0.00	no
Eff LAI	21	0.041	0.047				
fAPAR	21	0.086	0.198				
			Spruce				
LAI	10	0.274	0.265	0.24	no	0.02	no
Eff LAI	10	0.363	0.342				
fAPAR	10	0.362	0.309				

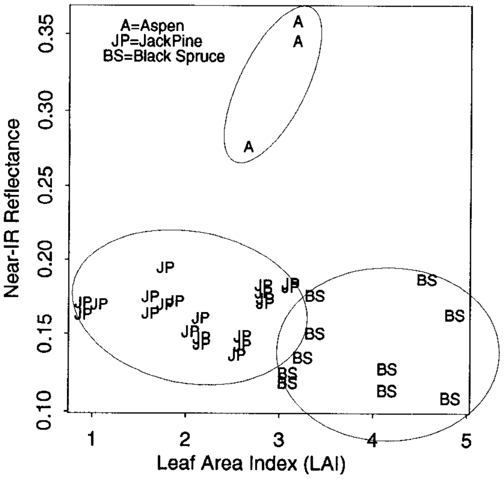

Figure 2: Near IR Reflectance as a function of LAI for the three tree species.

recent research: the behavior of the reflectance factor over coniferous forests and the interaction of leaf area index, canopy cover, understory and background composition in that behavior. However, the utility of VIs was reinforced over the Aspen sites. We observed a marked decrease in the predictive ability of the VIs over coniferous stands. In addition to an initial assessment of the application of remote sensing methods in the boreal forest, weaknesses or bias in the helicopter and surface variables were identified. Atmospheric correction using aerosol depths derived from a sun photometer mounted on the helicopter will strengthen the MMR observations. Options to improve the surface measurements include further restricting observations based on sampling consistency and methods and to account for understory and background reflectance factors when explaining the behavior of the VI-LAI relationships for conifers.

REFERENCES

[1] J.M. Chen and J. Cihlar, "Quantifying the effect of canopy architecture on optical measurements of leaf area index of plant canopies using two gap size analysis methods." IEEE Trans. Geosci. Remote Sens., vol. 33, pp. 777-787, 1995.

[2] F.M. Danson, "Developments in the Remote Sensing of Forest Canopy Structure," in Advances in Environmental Remote Sensing, F.M. Danson and S.E. Plummer, Eds. Chichester, England: John Wiley & Sons, 1995, pp. 53-69.

[3] S.T. Gower and J.M. Norman, 1991, "Rapid estimation of leaf area index in forests using the LI-COR LAI-2000," Ecology, vol. 72, pp. 1896-1900.

[4] B.L. Markham, F. M. Wood Jr., and S.P. Ahmad, Radiometric calibration of the reflective bands of NS001-thematic mapper simulator (TMS) and modular multispectral radiometers (MMR) in Recent Advances in Sensors, Radiometry, and Data Processing for Remote Sensing, Proc. SPIE, 24, pp. 96-108, 1988.

[5] P.M. Rich, "Characterizing plant canopies with hemispherical photographs," in Instrumentation for studying vegetation canopies for remote sensing in optical and thermal infrared regions, N.S. Goel and J.M. Norman, Eds., Remote Sensing Reviews, vol. 5, pp. 13-29, 1990.

[6] P.J. Sellers, F.G. Hall, M. Apps, D. Baldocchi, J. Cihlar, J. Den Hartog et al., BOREAS Experiment Plan (Version 3.0), NASA/GSFC, Greenbelt, Md. 20771, May 1994, pp 358 plus Appendices.

[7] M. Spanner, L. Johnson, J. Miller, R. McCreight, J. Freemantle, J. Runyon, and P. Gong, "Remote sensing of seasonal leaf area index across the Oregon transect," Ecological Applications, vol. 4, no. 2, pp. 258-271, 1994.

[8] M. Spanner, L. Pierce, D. Peterson, and S. Running, "Remote sensing of temperate coniferous forest leaf area index: The influence of canopy closure, understory vegetation, and background reflectance," Intl. J. Rem. Sen., vol. 11, pp. 95-111, January 1990.

[9] E. Vermote, D. Tanre, J. Deuz, M. Herman, and J. Morcrette, "Second simulation of the satellite signal in the solar spectrum: an overview," IEEE Trans. Geosci. Remote Sens., in press.

[10] C. Walthall and E. Middleton, "Assessing spatial and seasonal variations in grasslands with spectral reflectances from a helicopter platform," J. Geophys. Res., vol. 97, no. D17, pp. 18905-18912, November 1992.

[11] C. Walthall, D.L. Williams, B. Markham, J. Kalshoven, R. Nelson, "Development and present configuration of the NASA GSFC/WFF helicopter-based remote sensing system," this issue.

[12] D. Williams, "A comparison of spectral reflectance properties at the needle, branch, and canopy level for selected conifer species," Remote Sens. Environ., vol. 35, no. 2, pp. 79-93, February 1991.