EVALUATION OF VEGETATION INDICES AND A MODIFIED SIMPLE RATIO FOR BOREAL APPLICATIONS

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RÉSUMÉ

*Un ratio simple modifié (MSR) est proposé pour extraire les paramètres biophysiques des forêts boréales à l'aide de données de télédétection. Cet indice de végétation est formulé en fonction de l'évaluation de plusieurs indices de végétation dérivés de la combinaison de deux bandes spectrales, dont les suivants : indice de végétation par différence normalisée ou indice d'activité végétale (NDVI), ratio simple (SR), indice de végétation ajusté en fonction des sols (SAVI, SAVI1, SAVI2), indice de végétation par différence pondérée (WDVI), indice de végétation zonale (GEMI), indice de végétation non linéaire (NLI) et indice de végétation par différence renormalisée (RDVI). Le ratio simple modifié est une version améliorée des indices de végétation par différence renormalisée et sert à délimiter les relations de ces derniers avec les paramètres biophysiques. Tous les indices ont été obtenus à partir d'images acquises par le capteur thématique de Landsat-5 dans les bandes 3 (visible) et 4 (proche infrarouge) après correction des effets de l'atmosphère (à l'exception de l'indice de végétation zonale). De plus, ils ont été corrélés avec des données de terrain obtenues dans vingt peuplements de pins de Banks (**Pinus Banksiana**) et d'épinettes noires (**Picea mariana**) au cours de l'expérience BOREAS menée en 1994. Ces mesures comprennent l'indice de surface foliaire (LAI) et la fraction du rayonnement photosynthétiquement utilisable (FPAR) absorbée par le couvert forestier. Parmi ces indices de végétation, les indices SR, MSR et NDVI présentaient la meilleure corrélation avec les indices LAI et FPAR, tant au printemps qu'en été. Tous les autres indices ont donné de piètres résultats. Les indices NDVI et MSR peuvent être exprimés comme une fonction de SR.*

Des erreurs de mesure se produisent souvent avec les données de télédétection en raison des variations de l'angle zénithal du soleil, des effets de recouvrement partiel des pixels par des nuages, des caractéristiques de surface dissemblables, des variations de la topographie, ainsi que d'autres facteurs environnementaux. Ces erreurs entraînent généralement un accroissement ou une diminution simultanées des réflectances dans le rouge et le proche infrarouge; leurs effets peuvent être largement atténués en effectuant des rapports de bandes. Pour tous les autres indices impliquant des opérations mathématiques autres que des rapports de bandes, les erreurs peuvent être maintenues ou même amplifiées.

Le principal problème que pose l'utilisation des indices de végétation obtenus à partir de données acquises dans les bandes rouges et infrarouges réside dans leur faible sensibilité aux conditions de végétation de l'étage dominant. Bien qu'un bon nombre des indices de végétation, tels que les indices SAVI, SAVI1 et SAVI2, soient développés afin de réduire au minimum les effets de l'arrière-plan sur l'extraction de l'information relative à la végétation, la sensibilité de ces indices aux changements de conditions de l'étage dominant est également réduite.

SUMMARY

A Modified Simple Ratio (MSR) Is proposed for retrieving biophysical parameters of boreal forests using remote sensing data. This vegetation index is formulated based on an evaluation of several two-band vegetation indices, including the Normalized Difference Vegetation Index (NDVI), Simple Ratio (SR), Soil Adjusted Vegetation Indices (SAVI, SAVI1, SAVI2), Weighted Difference Vegetation Index (WDVI), Global Environment Monitoring Index (GEMI), Non-Linear Index (NLI), and Renormalized Difference Vegetation Index (RDVI). MSR is an improved version of RDVI for the purpose of

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*linearizing their relationships with biophysical parameters. All indices were obtained from Landsat-5 TM band 3 (visible) and band 4 (near infrared) images after atmospheric corrections (except for GEMI) and were correlated with ground-based measurements made in 20 Jack Pine **(Pinus banksiana)** and Black Spruce (**Picea mariana**) stands during the BOREAS field experiment in 1994. The measurements include Leaf Area Index (LAI) and the Fraction of Photosynthetically Active Radiation (FPAR) absorbed by the forest canopies. Among these vegetation indices, SR, MSR, and NDVI were found to be best correlated with LAI and FPAR in both spring and summer. All other indices performed poorly. Both NDVI and MSR can be expressed as a function of SR.*

Measurement errors in remote sensing data often occur due to changes in solar zenith angle, subpixel contamination of clouds, or dissimilar surface features and the variation in the local topography and other environmental factors. These errors generally cause simultaneous increases or decreases in the red and near infrared reflectances, and their effects can be greatly reduced by taking the ratio. All other indices involving mathematical operations other than ratioing could retain the errors or even amplify them.

The major problem in using the vegetation indices obtained from red and near infrared bands is the small sensitivity to the overstorey vegetation conditions. Although many of the vegetation indices such as SAVI, SAVI1, and SAVI2 are developed to minimize the effect of the background on retrieving the vegetation information, they also reduce their sensitivity to the changes in the overstorey conditions.

Key words: vegetation index, LAI, FPAR, boreal forests

INTRODUCTION

Driven by the need in ecological, climate, and many other studies to quantitatively assess vegetation conditions from remote sensing measurements, numerous vegetation indices have been developed using the measurements in red (or visible) and near infrared (NIR) bands. All two-band indices are based on simple physics: plants reflect less visible light but more NIR radiation compared with non-vegetated surfaces. However, different indices have different advantages in retrieving vegetation information. The major two-band indices (their definition and sources) included in this investigation, where ρ_n is NIR reflectance and ρ_r is red reflectance, are shown in **Table 1**. The Simple Ratio (SR) is the simplest way to combine red and NIR data for retrieving surface biophysical parameters, but in some rare cases its value increases with no bounds when ρ_r is small and approaches zero. The Normalized Difference Vegetation Index (NDVI) avoids this problem by normalizing the difference between ρ_n and ρ_r with the sum of them. However, NDVI and SR are fundamentally the same: one can be readily calculated from the other without additional information; in other words, NDVI=(SR-1)/(SR+1) or SR=(NDVI+1)/(NDVI-1). While NDVI has the advantage of the fixed range from 0 to 1, SR is sometimes preferred for its better sensitivity and more linearity with biophysical parameters (Chen and Cihlar, 1996; Chen, 1996b). Both indices are most widely used (Sellers *et al.*, 1994; Hall *et al.*, 1995; Running *et al.*, 1994), but the following underlying assumption in their formulation is often not met: for a given vegetated surface, ρ_n and ρ_r increase or decrease simultaneously in the same proportion.

Table 1.
Definition and sources of vegetation indices used in this study.

Name	Formula	Reference
NDVI	$\frac{(\rho_n - \rho_r)}{(\rho_n + \rho_r)}$	Rouse *et al.*, 1974
SR	$\frac{\rho_n}{\rho_r}$	Jordan, 1969
MSR	$\frac{\frac{\rho_n}{\rho_r} - 1}{\sqrt{\frac{\rho_n}{\rho_r}} + 1}$	this paper
RDVI	$\frac{\rho_n - \rho_r}{\sqrt{\rho_n + \rho_r}}$	Roujean and Breon, 1995
WDVI	$\rho_n - a \cdot \rho_r, a = \frac{\rho_{n,\,soil}}{\rho_{r,\,soil}}$	Clevers, 1989
SAVI	$\frac{(\rho_n - \rho_r)\,(1+L)}{(\rho_n + \rho_r + L)}, L = 0.5$	Huete, 1988
SAVI1	$\frac{(\rho_n - \rho_r)\,(1+L)}{(\rho_n + \rho_r + L)}$, $L = 1 - 2.12 \cdot NDVI \cdot WDVI$	Qu *et al.*, 1994
SAVI2	$\rho_n + 0.5 - \sqrt{(\rho_n + 0.5)^2 - 2(\rho_n - \rho_r)}$	
GEMI	$\frac{\eta(1 - 0.25 \cdot \eta) - (\rho_r - 0.125)}{(1 - \rho_r)}$, $\eta = \frac{2(\rho_n^2 - \rho_r^2) + 1.5\rho_n + 0.5\rho_r}{\rho_n + \rho_r + 0.5}$	Pinty and Verstraete, 1992
NLI	$\frac{(\rho_n^2 - \rho_r)}{(\rho_n^2 + \rho_r)}$	Goel and Qin, 1994

Under this assumption, the lines with fixed SR or NDVI values plotted on the ρ_n and ρ_r coordinates converge to the origin. Experimental evidence has shown that the converging point often does not occur at the origin but at some negative point on both ρ_n and ρ_r coordinates (Huete, 1988) because of the soil background effect. The Soil Adjusted Vegetation Index (SAVI) was developed to remove this effect by introducing a parameter L into the calculation of NDVI. This parameter is determined by the position of the convergence point. In SAVI, it is taken as a constant of 0.5, while in SAVI1, an improvement is made by allowing L to vary with the condition of the surface quantified using other indices because the convergence point is, in fact, not fixed (Qi *et al.*, 1994). The Global Environment Monitoring Index (GEMI) was derived to reduce the atmospheric effect at the global scale. The functional form of GEMI is not linear with ρ_n and ρ_r because the atmospheric effects on ρ_n and ρ_r are considerably different. The relationships between many vegetation indices and surface biophysical parameters are often non-linear, causing inconvenience in algorithm development. Therefore, some indices, such as the Non-Linear Index (NLI) and the Renormalized Difference Vegetation Index (RDVI), have been developed to linearize their relationships with surface parameters. The above-mentioned indices are all based on the slope of constant-index lines in the ρ_n versus ρ_r plot. There are also indices based on the distance between the lines, assuming the lines are parallel to each other. Examples of indices of this kind are the Weighted Difference Vegetation Index (WDVI) and the Perpendicular Vegetation Index (PVI) (Richardson and Weigand, 1977).

The performance of many of these indices has been simulated using radiative transfer models or tested using data from hand-held radiometers for agricultural crops. A key factor that has not been seriously considered in formulating these indices is the noise in remote sensing measurements. Remote sensing data, especially those from satellites, contain unwanted environmental noise due to many factors, including solar and view geometry, uneven atmospheric conditions, dissimilar subpixel surface features, topography variation, and other environmental inhomogeneities. The noise from one source often causes simultaneous increases or decreases in red and NIR reflectances. One example, where a subpixel cloud causes red and NIR reflectances to increase in one pixel and to decrease in another, is provided in **Figure 1**. Any localized distributions of fog, dust, smoke, and aerosols can have a similar effect. In many cases, the increases or decreases in ρ_n and ρ_r have approximately the same proportion relative to their unaffected values. Noise of this kind, therefore, can be eliminated or greatly reduced when data of these two bands are appropriately combined but can be amplified when some unfavourable mathematical operations are performed on ρ_n and ρ_r.

The objectives of this paper are to:

- evaluate the above-mentioned vegetation indices against experimental data sets for their performance in terms of the ability to minimize the error induced by noise in remote sensing data; and
- propose a non-linear index that has the advantage of both low noise effect and good linearity with biophysical parameters.

This paper only examines the effect of measurement noise on the various indices, not the fundamental assumptions made about these indices.

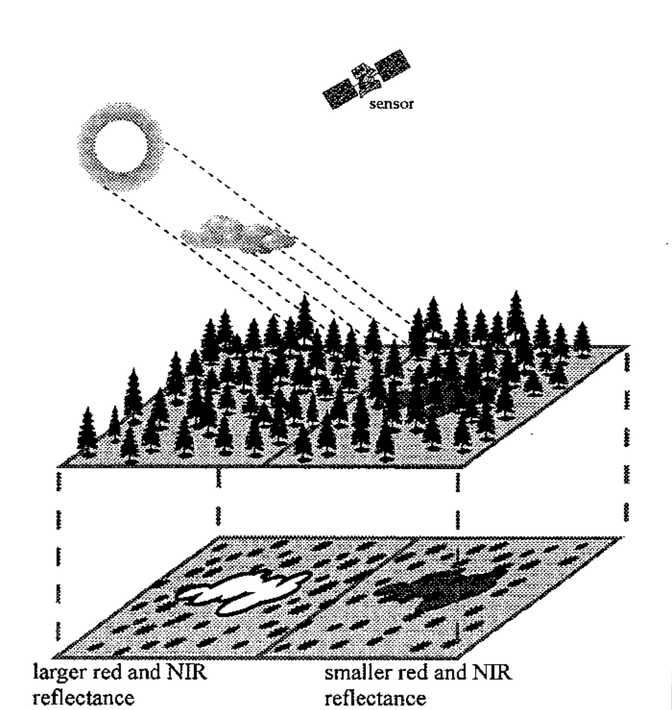


Figure 1.
The effect of a subpixel cloud: simultaneous increase in red and NIR reflectance in one pixel and decrease in another.

THEORETICAL CONSIDERATIONS

The criteria used in this paper for evaluating vegetation indices are twofold: low noise effect judged according to the level of significance in the correlation between the indices and ground-truth data; and the linearity of their relationship with biophysical parameters. The first criterion may be subject to the accuracy of ground-truth data, but in the comparison of the significance of correlation, the accuracy may only have secondary importance. The second criterion is also important because linear relationships help to simplify remote sensing algorithms and improve the accuracy in retrieving surface parameters (Roujean and Breon, 1995; Goel and Qin, 1995).

Since noise from many sources often causes increases or decreases in red and NIR reflectances in roughly the same proportion, it can be greatly reduced when the simple ratio between these two reflectances is taken. Shown in **Figure 2a** is the difference in the effects of noise on SR and SAVI, where, by definition, constant SR lines converge at the origin, while constant SAVI lines converge at a point at ($-l_1$ $-l_2$). The double-ended arrows indicate the direction and magnitude of the variation caused by noise. Since the variations are parallel with the SR lines, they make no difference in the calculated SR values, but they induce biases in SAVI because the arrows move across the SAVI lines. The direction of the arrows is by no means always parallel to the SR lines. Subpixel water bodies and shadows of clouds, for example, would reduce a larger proportion of the NIR reflectance than the red reflectance, resulting in a smaller SR

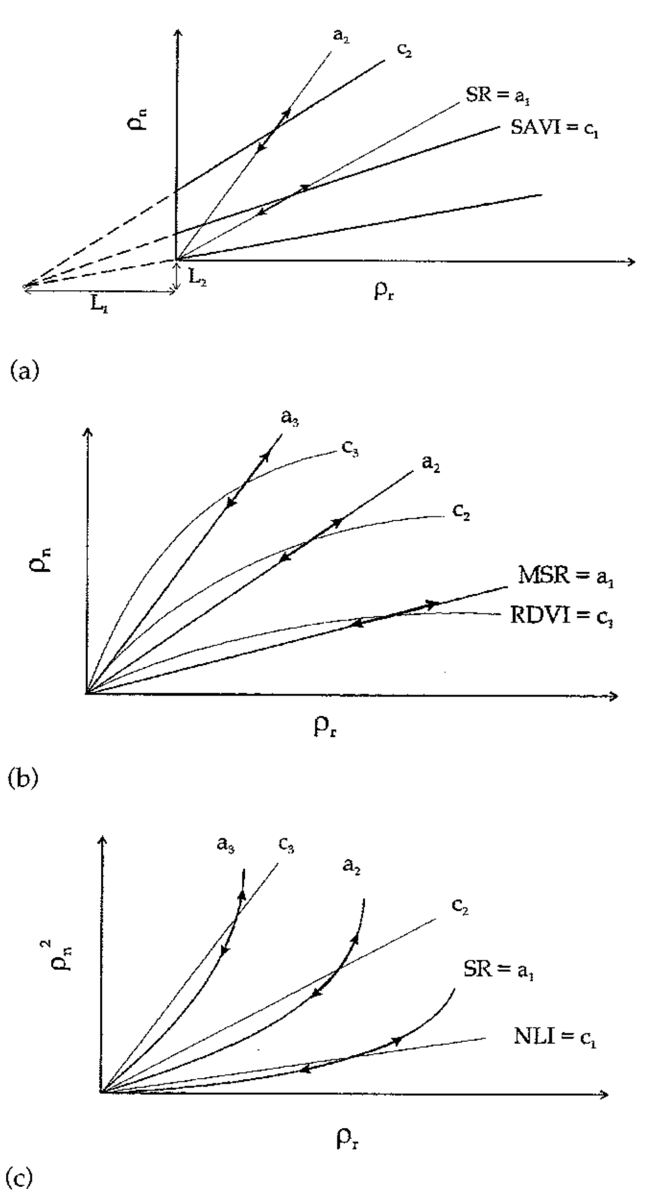


Figure 2.
Schematic illustration on the effects of environmental noise on vegetation indices. (a) SR versus SAVI, (b) MSR versus RDVI, and (c) SR versus NLI.

as expected. In such cases, the arrows would be more vertical than those shown in **Figure 2a**. As well, the angles between the arrows and the SAVI lines would become larger. Similarly, patches of deciduous trees mixed in a predominantly conifer forest having relatively low SR values would increase a larger proportion of the NIR reflectance than the red reflectance, making the arrows more vertical. Inaccurate atmospheric corrections can cause the direction of the arrows to change in both ways from the SR lines. On the other hand, subpixel clouds and other reflective atmospheric constituents can make the arrows more horizontal (more parallel with the SAVI). The arrows shown in **Figures 2a–2c** only represent the general case.

The different noise effects on SR and NLI are shown in **Figure 2b**. By definition, constant NLI lines are linear in the coordinate system with ρ^2_n and ρ_r, while the SR lines are curved. Again the noise arrows along the SR curves intercept the NLI lines, indicating that noise in data can cause large errors in NLI. Similar problems exist in using GEMI and SAVI2.

Based on the SAIL model, Roujean and Breon (1995) investigated the weaknesses of NDVI when used for deriving FPAR. They showed large scatter of simulated data points in plots of NDVI against FPAR for plant canopies with different foliage angle distributions and optical scattering coefficients. The scatter was largely reduced when NDVI was replaced with RDVI. As a non-linear index, RDVI is not only less sensitive to variations in the unknown foliage geometrical and optical properties but also less affected by the solar and view geometry. If remote sensing data contain no environmental noise as those calculated using the model, RDVI would be an improvement over NDVI. However, the drawback is that RDVI is more prone to measurement noise than NDVI because much noise is reduced in NDVI as a function of SR.

A new index, the Modified Simple Ratio (MSR) proposed in this paper, is developed based on RDVI. By the definitions of MSR and RDVI, presented in **Table 1**, it can be shown that:

$$MSR = RDVI / \sqrt{\rho_r} \, . \qquad (1)$$

Since MSR is a function of SR, the constant MSR lines appear to be linear in **Figure 2c**, but RDVI lines are curved because as ρ_r increases, RDVI becomes small relative to MSR, which remains the same for the same SR. The noise arrows are parallel to MSR lines but intercept RDVI lines, changing the values of RDVI depending on the strength of the noise. MSR is therefore an improvement over RDVI in terms of its sensitivity to useful information. MSR is also a non-linear index because it uses a non-linear combination of ρ_n and ρ_r. Since

$$MSR = (SR - 1) / \sqrt{SR + 1} \qquad (2)$$

and

$$SR = (1 + NDVI) / (1 - NDVI) \, , \qquad (3)$$

it can be shown that

$$SMR = \sqrt{2}\, NDVI / \sqrt{1 - NDVI} \, . \qquad (4)$$

From Equations 3 to 4, it can be seen that both SR and MSR are non-linear functions of NDVI, approaching infinity when NDVI = 1. Both are similar, but SR increases faster than MSR with NDVI. Since the relationships between NDVI and biophysical parameters are not linear — that is, NDVI increases slower than biophysical parameters — it is expected that SR and MSR are more linearly related to the parameters than NDVI. The linearity of SR is different from that of MSR, suggesting that they have different degrees of usefulness.

GROUND-BASED MEASUREMENTS

Site Description

Ground-based measurements of LAI and FPAR were made in 20 different conifer stands, which consisted of either Jack Pine (*Pinus banksiana*) or Black Spruce (*Picea mariana*). These sites were selected for the BOReal Ecosystem-Atmosphere Study (BOREAS) and were located in the Northern Study Area (NSA) near Thompson, Manitoba, and the Southern Study Area (SSA) near Candle Lake, Saskatchewan. This paper includes results from six intensive sites (BOREAS tower sites) and 14 auxiliary sites. Each intensive site can be characterized as being homogeneous at a scale of 1 km while the auxiliary sites are homogeneous at smaller scales. Understorey was very different and distinct between these two species. The undergrowth in Jack Pine stands consisted mainly of lichen (*Cladina spp*), blueberry (*Vaccinium myrtilloides*), and cranberry (*Vaccinium vitis-idaea*). In addition to vegetation, Jack Pine stands, especially younger stands, contained significant amounts of dead wood and some exposed sandy soil. In contrast, soil in Black Spruce stands was wetter and was almost completely covered by sphagnum moss (*Sphagnum sp*), feather moss (*Pleurozium schreben*), Labrador tea (*Ledum groenlandicum*), and bog cranberry (*Vaccinium vitis-idaea*).

LAI and FPAR Measurements

Ground-based optical measurements of LAI and FPAR were made during three BOREAS field campaigns. This paper includes results from IFC-1 and IFC-2 that correspond to late spring and mid-summer growing seasons. Measurements were made along transects located at each intensive and auxiliary site. The transect lengths ranged from 150–300 m for intensive sites to 50 m for auxiliary sites. Leaf Area Index was measured using the PCA (LI-COR LAI 2000). Three units of PCA were used, with one recording above-stand reference readings either at the top of the flux tower or in a large nearby opening and the other two taking in-stand measurements along the transect at a 10-m interval (Chen, 1996a). These PAC measurements are considered as the effective LAI which includes the effects of non-random leaf spatial distribution and the woody material. The TRAC (Tracing Radiation and Architecture of Canopies) instrument was used for measuring canopy architectural parameters as a correction to remove the effect of foliage clumping at scales larger than the shoots (the basic collection of needles) on the PCA measurements (Chen and Cihlar, 1995a, 1995b). About 27 to 45 shoot samples were taken in each IFC from each of the intensive sites for laboratory analysis to estimate the effect of foliage clumping within the shoots. The ratio of woody area to plant (green leaf and woody) area was also obtained for three intensive sites by cutting entire trees and measuring the total woody and green leaf area. Allometric relationships relating the tree-trunk diameter at breast height to plant and woody areas were established to obtain the average ratio for a stand. This optically-based method supplemented by allometric measurements presents important improvements over previous methods for measuring LAI over large areas in conifer canopies with distinct architecture.

The TRAC instrument also provided measurements of the transmitted and reflected PAR near the forest floor at a 10-mm interval along the transects. This measurement technique is critical for estimating the average FPAR for a stand. Measured instantaneous FPAR values from the intensive sites by the same definition as that given in Goward and Huemmerich (1992) were used to validate a model of daily green FPAR based on the effective LAI obtained from the PCA. The model was then used to calculate daily green FPAR of the auxiliary sites (Chen, 1996b). All FPAR values used in this paper are daily green FPAR.

LANDSAT IMAGE PROCESSING

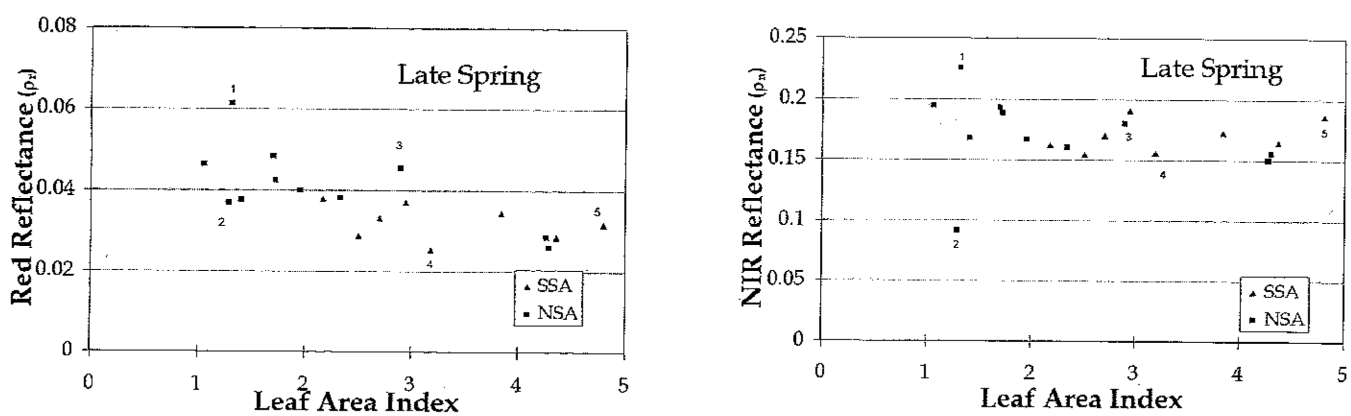
The indices included in this paper were calculated using reflectance data from bands 3 and 4 from Landsat-5 TM images. Using PCI 5.2 image processing software, a total of four images was processed: one summer scene and one late-spring scene for both the SSA and NSA. These images were considered to have the best atmospheric conditions (cloud-free, etc.) among all images available for this study. Images for the SSA were from June 6, 1991 and August 11, 1986, while those for the NSA were taken on June 9, 1994 and August 19, 1985. The images were first geometrically corrected by registering over 20 ground control points to their corresponding position on each image. After pixel registration and resampling, each image was atmospherically corrected using the '5S' model (Tanre *et al.*, 1986; Teillet and Santer, 1991). Finally, indices for all intensive sites were calculated using a mean reflectance value from each band taken as the average of eight pixels corresponding to a distance of approximately 300 m along the main transect. Values for the auxiliary sites were calculated as an average of nine pixels (3 x 3 square) corresponding to the area where ground measurements were made. Background and understorey reflectance (values) were also measured for several stands (White *et al.*, 1995) and were used in the calculation of WDVI and SAVI1.

RESULTS AND DISCUSSION

The characteristics of the stands and their respective indices in IFC-1 and IFC-2 are summarized in **Tables 2** and **3**, respectively, along with the regression results. The LAI values in these tables are 15% larger than those in Chen and Cihlar (1996) because a 15% correction is suggested by Chen (1996b) for the measurements of LAI-2000 to remove the effect of blue light scattering within the canopies on the measurements. Two curve-fitting techniques were used for each Vegetation Index (VI): $VI = A + B^{*}LAI$ or $VI = A + B^{*}FPAR$; and $VI = A^{*}LAI^{B}$ or $VI = A^{*}FPAR^{B}$. SR and its associates (NDVI and MSR) are most significantly correlated to LAI and FPAR in both IFC-1 and IFC-2. All other indices performed poorly (close to zero R^2). All indices except for GEMI (TOA) were calculated based on reflectance at the surface level after atmospheric corrections.

Table 2.
Summary of stand attributes and VI for late spring (IFC-1).

Stand	ρ_r	ρ_n	LAI	FPAR	NDVI	RDVI	MSR	SR	SAVI
NOJP	0.040	0.167	1.96	0.631	0.61	0.28	1.40	4.18	0.27
NOBS	0.029	0.150	4.27	0.78	0.68	0.29	1.70	5.26	0.27
NYJP	0.042	0.189	1.73	0.54	0.63	0.30	1.48	4.44	0.30
SOJP	0.038	0.162	2.17	0.692	0.62	0.28	1.43	4.29	0.27
SOBS	0.034	0.173	3.84	0.72	0.67	0.30	1.93	5.03	0.29
SYJP	0.037	0.190	2.94	0.59	0.68	0.32	1.67	5.15	0.32
T6R5S	0.026	0.156	4.28	0.84	0.71	0.30	1.88	5.96	0.29
T7R9S	—	—	1.06	0.45	0.62	0.30	1.40	4.20	0.30
T8Q9P	0.038	0.168	1.40	0.55	0.63	0.29	1.48	4.47	0.08
F7R9S	0.025	0.155	3.18	0.81	0.72	0.30	1.91	6.14	0.29
F7J1P	0.033	0.170	2.70	0.77	0.67	0.30	1.67	5.14	0.29
G2I4S	0.032	0.186	4.80	0.87	0.71	0.33	1.73	5.89	0.32
G914S	—	—	4.36	0.84	0.71	0.31	2.00	5.80	0.30
T6T6S	0.048	0.193	1.70	0.5	0.60	0.29	1.33	3.98	0.29
T8S4S	0.061	0.225	1.31	0.41	0.57	0.31	1.24	3.67	0.31
T8T1P	0.037	0.092	1.29	0.48	0.43	0.15	0.80	2.49	0.13
BMMS-1	—	—	2.12	0.53	—	—	—	—	—
G1K9P	0.029	0.154	2.51	0.71	0.69	0.29	1.73	5.36	0.28
T9Q8P	0.038	0.161	2.33	0.55	0.62	0.27	1.41	4.22	0.26
T7T3S	0.046	0.180	2.90	0.67	0.60	0.28	1.36	3.95	0.28
R^2 (LAI)					0.49	0.17	0.54	0.59	0.10
R^2 (FPAR)					0.45	0.14	0.50	0.54	0.08



a) b)

Figure 3.
Dependence of red (a) and NIR (b) reflectances on Leaf Area Index, where the same numbers in (a) and (b) indicate the same stand.

Table 2 cont'd.

Stand	SAVI1	NLI	GEMI (surf.)	GEMI (TOA)	WDVI	SAVI2	crown closure	basal area (m^2/ha)	stand density (stems/ha)
NOJP	0.22	-0.18	0.51	0.47	0.08	0.23	0.43	12	1800
NOBS	0.21	-0.12	0.48	0.45	0.05	0.23	0.53	18	4500
NYJB	0.24	-0.09	0.55	0.51	0.09	0.26	0.30	20	30000
SOJP	0.22	-0.18	0.50	0.47	0.08	0.23	0.31	29	2000
SOBS	0.24	-0.07	0.53	0.49	0.05	0.25	0.42	20	3000
SYJP	0.26	-0.01	0.56	0.52	0.11	0.28	0.43	9	4000
T6R5S	0.23	-0.04	0.50	0.46	0.06	0.24	0.82	29	7900
T7R9S	0.24	-0.10	0.56	0.52	0.03	0.26	0.04	6	7500
T8Q9P	0.23	-0.14	0.51	0.48	0.08	0.24	0.42	14	1600
F70P	0.23	-0.02	0.50	0.46	0.10	0.24	0.55	34	2100
F7J1P	0.29	-0.07	0.52	0.48	0.09	0.25	0.62	28	1150
G2I4S	0.26	0.05	0.55	0.56	0.08	0.28	0.71	36	12500
G9I4S	0.24	-0.02	0.51	0.48	0.07	0.25	0.71	—	—
T6T6S	0.23	-0.13	0.55	0.54	0.02	0.26	0.16	6	5600
T8S4S	0.26	-0.09	0.60	0.55	0.01	0.28	0.08	—	—
T8T1P	0.10	-0.63	0.35	0.50	0.01	0.10	0.24	—	15000
BMMS-1	—	—	—	—	—	—	0.37	—	—
G1K9P	0.22	-0.10	0.49	0.46	0.09	0.23	0.40	20	700
T9Q8P	0.21	-0.19	0.50	0.52	0.07	0.22	0.20	—	300
T7T3S	0.22	-0.17	0.53	0.49	0.02	0.24	0.09	9	7600
R^2 (LAI)	0.11	0.23	0.003	0.05	0.22	0.09			
R^2 (FPAR)	0.08	0.19	0.00	0.19	0.29	0.06			

GEMI (TOA) was calculated using reflectance at the top of the atmosphere because the main purpose of GEMI is to minimize the atmospheric effect. Although GEMI was developed for improving global vegetation monitoring, it is chosen in this study of limited geographical scope because it is a distinct non-linear index.

Figures 3a and **3b** demonstrate the reason for the different performance of the indices, As expected, the reflectance in the red band decreases with increasing LAI. However, the trend of the reflectance in the near infrared band is not discernible because of the noise. The major signal on the vegetation conditions is then carried in the red reflectance, but this does not mean NIR reflectance has no information content. Examining the points in **Figures 3a** and **3b** together, one can find that red and NIR reflectance are correlated. Some of the corresponding points in these two figures are numbered. At LAI= 1. 1, point 1 is considerably larger than point 2 in both plots. In general, at similar LAI values, if red reflectance is above the average values (such as points 1, 3, and 5), NIR reflectance appears correspondingly in the same way, and vice-versa (points 2 and 4). This simultaneous behaviour may have been caused by non-uniformity of the atmospheric conditions, which is not removed using the cross-scene bulk atmospheric correction method. It may have also resulted from shadows of neighbouring pixels or dissimilar surface features within the pixels, such as rocks or small water bodies. The unwanted environmental noise can be effectively removed by taking the ratio of the reflectance in these two bands because the noise generally introduces biases in these two bands in roughly the same proportion.

This error-reduction mechanism using the ratioing technique is critical for boreal forests because the signal is weak with respect to the noise in the individual bands. The noise is mostly retained in indices based on the absolute difference, such as WDVI and PVI, because the noise does not introduce the same absolute bias in red and NIR reflectance, The noise can even be amplified when mathematical operations such as taking the square or square root of the reflectance are used in the calculation of indices (SAVI2, GEMI, and NLI). These noise-amplification operations almost caused a complete loss of the weak signal on the vegetation conditions contained in these two bands, as evident in the R^2 values in **Tables 2** and **3**. SAVI and SAVI1 are also not in accord with the ratioing principle, although to a lesser degree, by introducing the parameter L in the calculation. This parameter not only prevents the exact ratioing of the reflectances, but also reduces the sensitivity of SAVI and SAVI 1 to the variations in LAI and FPAR.

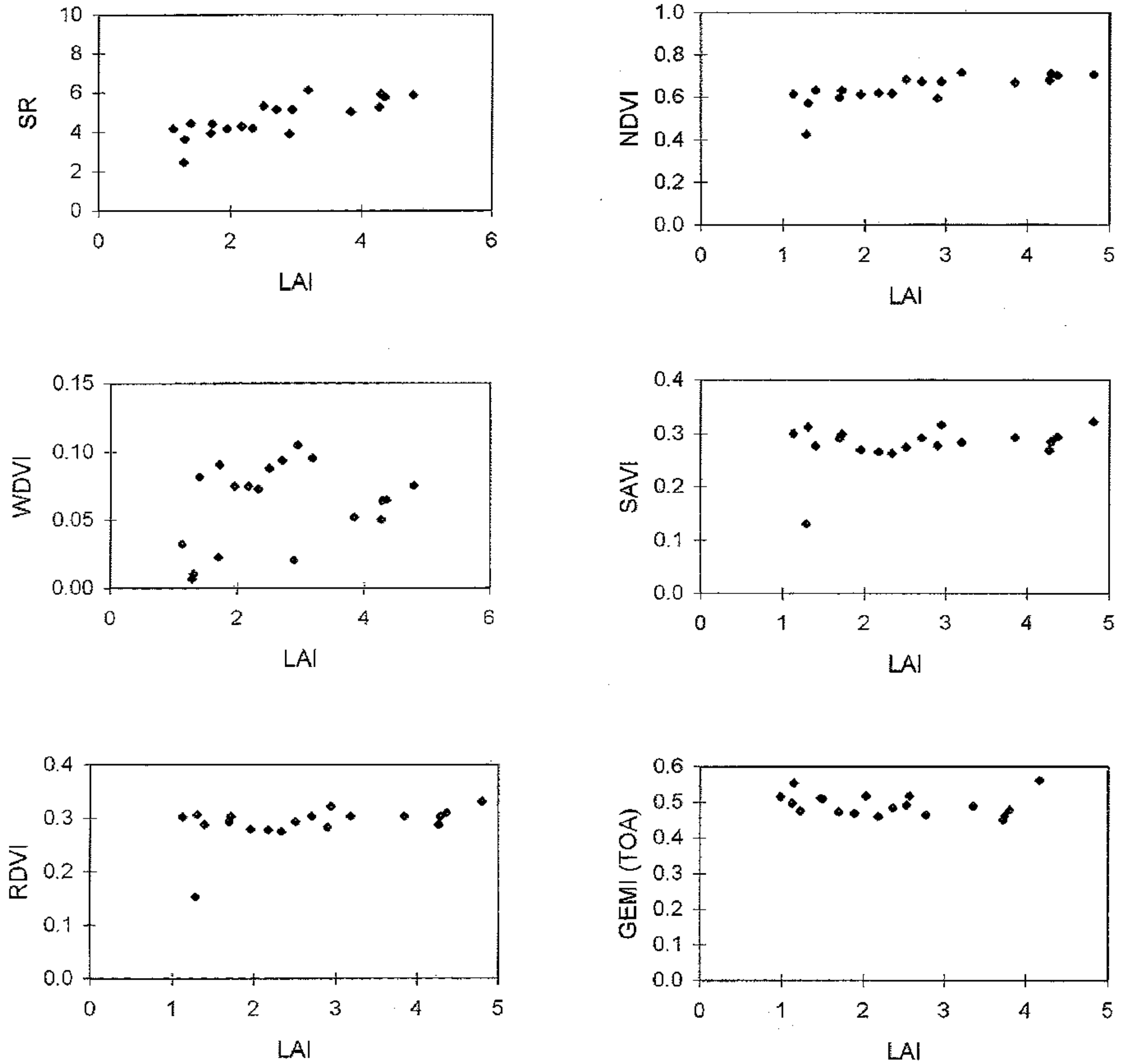


Figure 4.
Late-spring (IFC-1) LAI results versus SR, NDVI, WDVI, SAVI, RDVI, and GEMI (top of the atmosphere) from Landsat-5 TM images.

Figures 4 and 5 display the relationships between the various indices and LAI, as well as FPAR for IFC-1 (late spring). The results for IFC-2 (mid-summer) are similar (not plotted). The sensitivity of NDVI to LAI or FPAR is small because of the understorey contribution to the reflectance and the tree crown shadow effect (Chen and Cihlar, 1996; Chen, 1996b). The sensitivity of SR is larger than that of NDVI, but the scatter of data points on the vertical axis is also larger. SR is also more linearly related to LAI and FPAR than NDVI. Statistically, SR and NDVI make no difference in terms of the significance of correlation because one can be calculated from the other without additional information. However, in formulating remote sensing algorithms, SR may be preferred over NDVI because of its better sensitivity and linearity with respect to surface parameters. Other indices show little or no sensitivity with LAI and FPAR. Although SAVI is similar to NDVI in its form, the small sensitivity of NDVI to LAI and FPAR is lost in SAVI because it retains some of the noise in the data and reduces the sensitivity by the use of the parameter L in the denominator. The same problem exists for SAVI1. The scatter of data points in plots for WDVI is largest because much

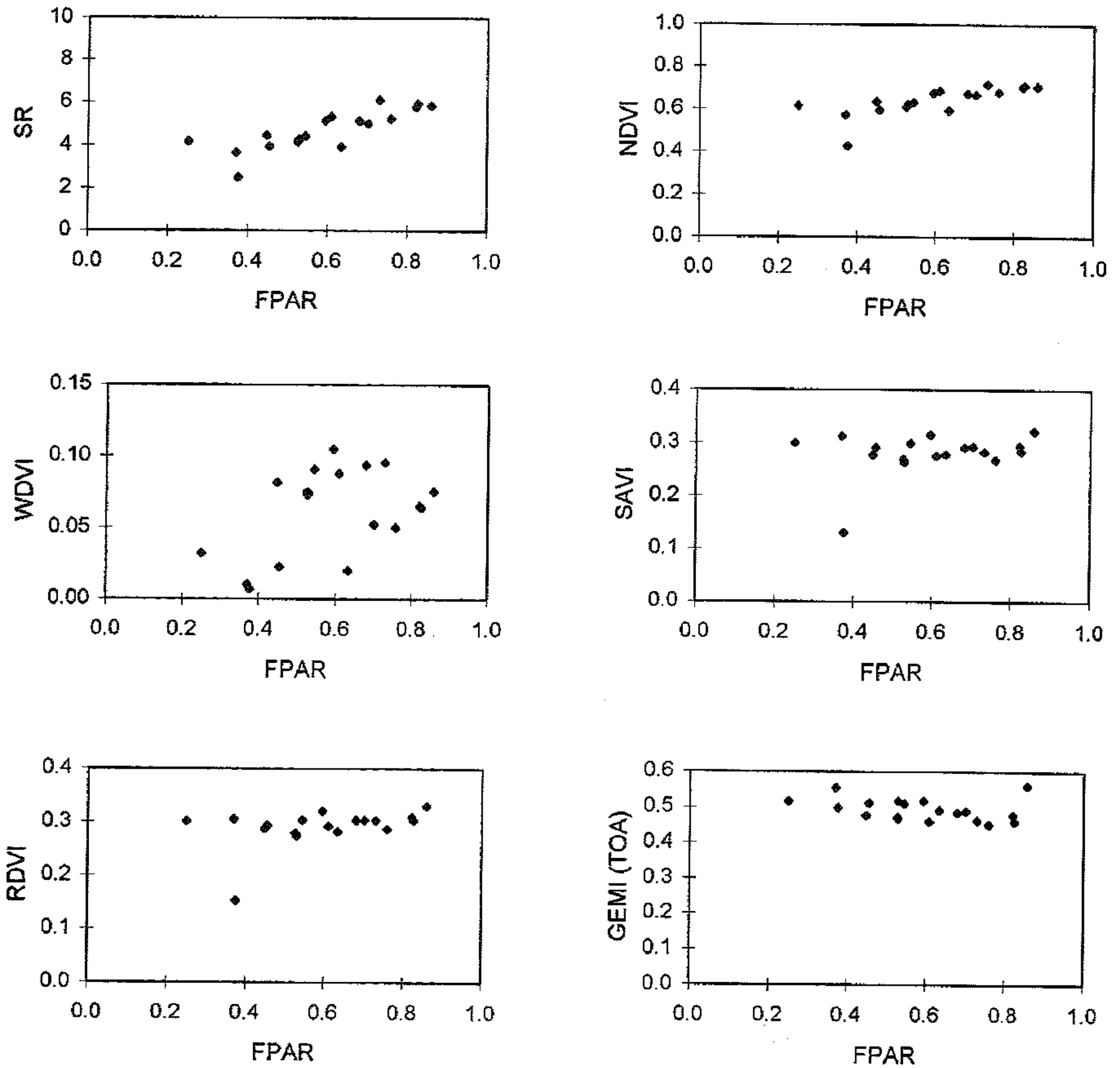


Figure 5.
Late-spring (IFC-1) FPAR results versus SR, NDVI, WDVI, SAVI, RDVI, and GEMI (top of the atmosphere) from Landsat-5 TM images.

measurement noise is retained when absolute rather than relative difference is taken. RDVI does not show any advantage over NDVI in terms of its sensitivity. The loss of sensitivity in RDVI may be the result of the noise amplification involved in taking the square root of the sum of the two reflectances. GEMI, with the most sophisticated mathematical operations, also suffers from a similar noise problem. NLI performs slightly better than GEMI (see R^2 in **Tables 2** and **3**), but much worse than NDVI and SR. **Figure 6** displays the various indices mentioned above in the order of the R^2 value for correlation between the indices and LAI in IFC-1. SR, MSR, and NDVI are the best among all the indices.

If no noise exists in the data sets, RDVI is expected to perform better than NDVI and SR because it is less sensitive to the unknown optical and geometrical properties of the vegetated surface. MSR is an improved version of RDVI. It not only retains the non-linear features of RDVI but is also less sensitive to measurement noise. From the relationship MSR = RDVI / $\sqrt{\rho_r}$, one can see that noise reduction in MSR is achieved by the division of RDVI with $\sqrt{\rho_r}$. This division makes MSR a function of SR. The relationships of MSR to

Table 3.
Summary of stand attributes and VI for mid-summer (IFC-2).

Stand	ρ_r	ρ_n	LAI	FPAR	NDVI	RDVI	MSR	SR
NOJP	0.037	0.164	2.19	0.63	0.63	0.28	1.48	4.47
NOBS	0.021	0.167	4.78	0.78	0.78	0.34	2.33	8.00
NYJB	0.035	0.193	1.93	0.54	0.70	0.33	1.79	5.60
SOJP	0.036	0.160	2.44	0.69	0.65	0.29	1.57	4.77
SOBS	0.026	0.163	4.30	0.72	0.72	0.31	1.94	6.20
SYJP	0.040	0.201	3.30	0.59	0.67	0.33	1.65	5.07
T6R5S	0.024	0.187	4.81	0.84	0.77	0.35	2.26	7.63
T7R9S	0.039	0.223	1.27	0.45	0.70	0.36	1.83	5.77
T8Q9P	0.032	0.166	1.58	0.55	0.67	0.30	1.66	5.10
F70P	0.020	0.152	3.57	0.81	0.77	0.32	2.29	7.79
F7J1P	0.019	0.154	3.02	0.77	0.78	0.32	2.36	8.13
G2I4S	0.023	0.164	5.37	0.87	0.76	0.33	2.16	7.16
G9I4S	0.025	0.178	4.89	0.84	0.75	0.34	2.14	7.08
T6T6S	0.035	0.214	1.91	0.50	0.72	0.36	1.92	6.12
T8S4S	0.066	0.271	1.47	0.41	0.61	0.35	1.37	4.11
T8T1P	0.017	0.087	1.44	0.48	0.67	0.21	1.63	4.99
BMMS-1	0.021	0.171	2.55	0.53	0.78	0.34	2.37	8.18
G1K9P	0.023	0.161	2.81	0.71	0.75	0.32	2.09	6.85
T9Q8P	0.040	0.168	2.61	0.63	0.61	0.28	1.39	4.17
T7T3S	0.036	0.198	3.24	0.67	0.69	0.33	1.75	5.44
R^2 (LAI)					0.34	0.07	0.35	0.36
R^2 (FPAR)					0.31	0.03	0.32	0.32

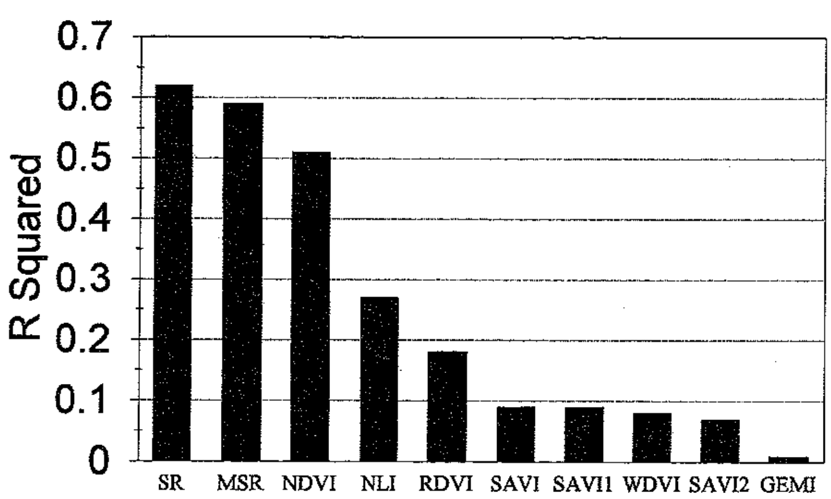


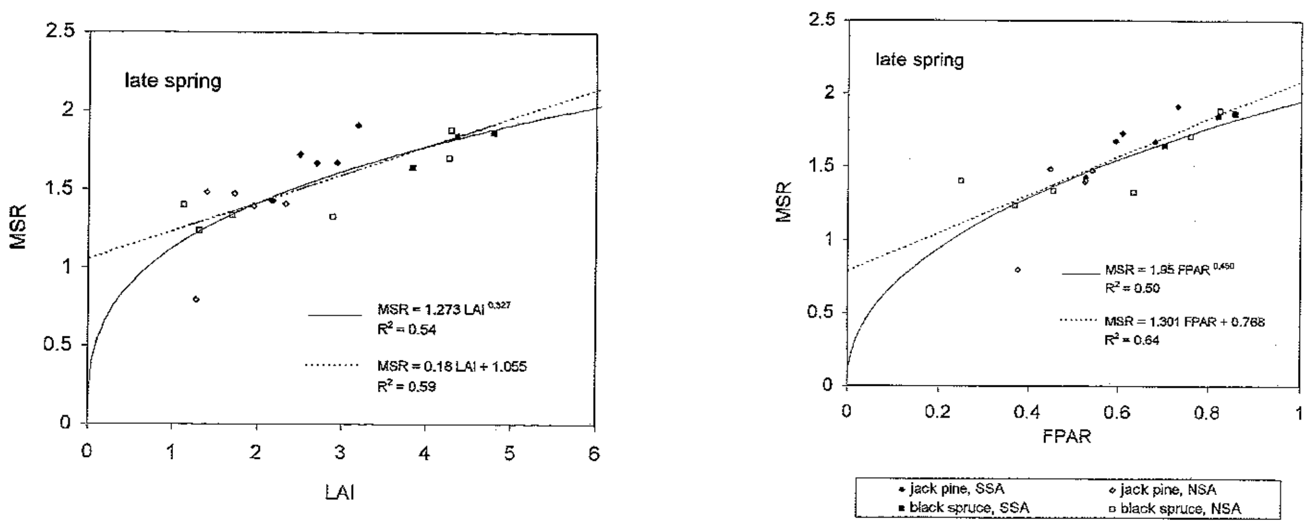
Figure 6.
Correlation coefficient (R^2) between vegetation indices from Landsat TM and LAI in late spring (IFC-1) obtained in BOREAS.

LAI and FPAR in IFC-1 and IFC-2 are shown in **Figures 7** and **8**. The level of significance of the non-linear and linear correlation (R^2) for MSR is similar to those for SR and NDVI. Because there are no obvious saturation points in the relationships between NDVI and LAI or FPAR — that is, the relationships are already approximately linear — full assessment of the advantages of MSR over NDVI and SR is not possible with our data sets. However, the statistics certainly indicate that MSR is superior to RDVI. Based on Roujean and Breon (1995), RDVI has the advantage of being less sensitive to geometrical and optical properties of plant canopies.

MSR is expected to have a similar advantage over other vegetation indices. This advantage is not obvious from our data sets, possibly due to the fact that the Jack Pine and Black Spruce stands included in this study had similar optical properties, as evident from the small difference between them in **Figures 7** and **8**. There was a difference in the foliage angle distribution pattern between these two species —

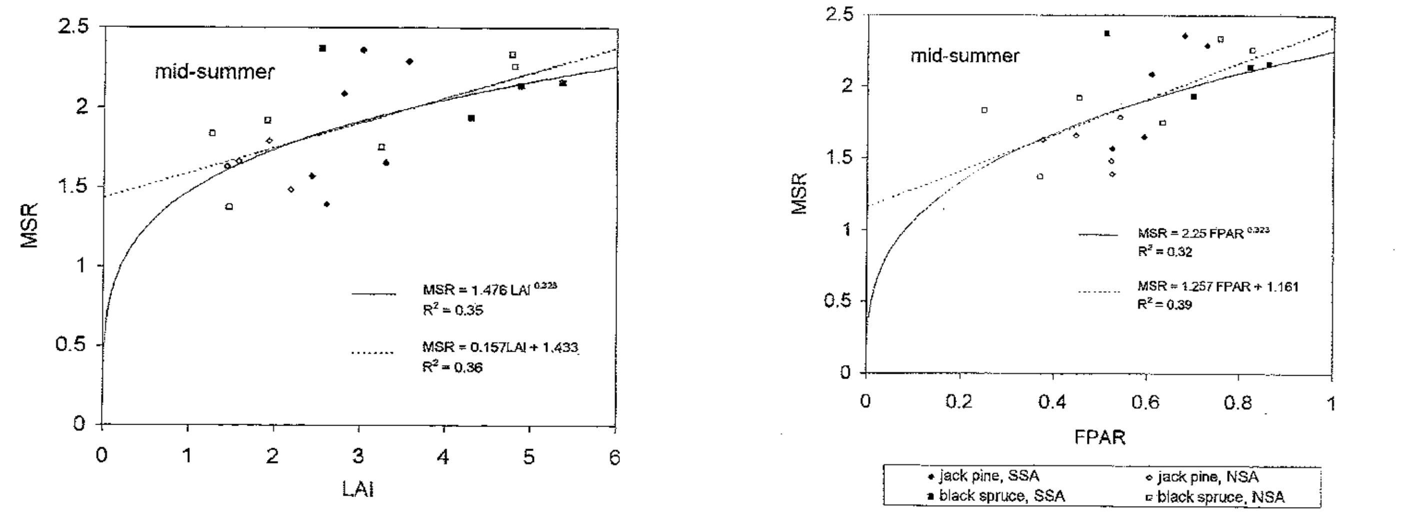
Table 3 cont'd.

Stand	SAVI	SAVI1	NLI	GEMI (surf.)	GEMI (TOA)	WDVI	SAVI2
NOJP	0.27	0.22	-0.16	0.51	0.47	0.02	0.23
NOBS	0.32	0.26	0.15	0.52	0.48	0.03	0.28
NYJB	0.33	0.27	0.04	0.56	0.51	0.02	0.29
SOJP	0.27	0.22	-0.14	0.50	0.47	0.03	0.23
SOBS	0.30	0.24	0.01	0.51	0.48	0.02	0.26
SYJP	0.33	0.27	0.01	0.57	0.53	0.03	0.29
T6R5S	0.34	0.29	0.18	0.56	0.51	0.03	0.30
T7R9S	0.36	0.31	0.13	0.61	0.56	0.01	0.33
T8Q9P	0.29	0.23	-0.08	0.51	0.47	0.03	0.25
F70P	0.30	0.24	0.09	0.49	0.37	0.01	0.25
F7J1P	0.30	0.25	0.12	0.50	0.46	-0.003	0.26
G2I4S	0.31	0.25	0.08	0.51	0.57	0.01	0.27
G9I4S	0.33	0.27	0.12	0.54	0.50	-0.002	0.29
T6T6S	0.36	0.30	0.14	0.60	0.55	0.02	0.33
T8S4S	0.37	0.31	0.05	0.68	0.61	0.05	0.34
T8T1P	0.17	0.13	-0.40	0.35	0.34	-0.02	0.13
BMMS-1	0.33	0.10	0.17	0.53	0.49	0.02	0.28
G1K9P	0.30	0.25	0.05	0.51	0.47	0.03	0.26
T9Q8P	0.27	0.22	-0.18	0.51	0.47	0.01	0.23
T7T3S	0.33	0.27	0.04	0.57	0.52	0.01	0.29
R^2 (LAI)	0.03	0.03	0.18	0.00	0.00	0.15	0.02
R^2 (FPAR)	0.008	0.006	0.12	0.02	0.02	0.19	0.002



a) b)

Figure 7.
The relationships between the new Modified Simple Ratio (MSR) and LAI (a) and FPAR (b) in late spring (IFC-1) measured in the Southern Study Area (SSA) near Candle Lake, Saskatchewan, and in the Northern Study Area (NSA) near Thompson, Manitoba.



a) b)

Figure 8.
The relationships between the new Modified Simple Ratio (MSR) and LAI (a) and FPAR (b) in mid-summer (IFC-2) measured in the Southern Study Area(SSA) near Candle Lake, Saskatchewan, and in the Northern Study Area (NSA) near Thompson, Manitoba.

Table 4.
Linear regression results (VI = a + b*LAI, or VI = a + b*FPAR).

			NDVI	SR	MSR
late spring	LAI	a	0.529	3.04	1.055
		b	0.042	0.626	0.180
		R^2	0.51	0.62	0.59
	FPAR	a	0.463	2.044	0.768
		b	0.3	4.523	1.301
		R^2	0.55	0.67	0.64
mid-summer	LAI	a	0.63	4.2	1.4
		b	0.027	0.648	0.157
		R^2	0.36	0.36	0.36
	FPAR	a	0.585	3.074	1.161
		b	0.212	5.209	1.257
		R^2	0.38	0.39	0.39

Table 5.
Non-linear regression results ($VI = a*LAI^b$, or $VI = a*FPAR^b$).

			NDVI	SR	MSR
late spring	LAI	a	0.542	5.839	1.273
		b	0.181	0.362	0.327
		R^2	0.49	0.59	0.54
	FPAR	a	0.733	6.142	1.95
		b	0.248	0.499	0.45
		R^2	0.45	0.54	0.5
mid-summer	LAI	a	0.635	4.408	1.476
		b	0.107	0.306	0.323
		R^2	0.34	0.36	0.35
	FPAR	a	0.768	7.6	2.25
		b	0.145	0.416	0.323
		R^2	0.31	0.32	0.32

Jack Pine stands being more erectophile than Black Spruce stands — but the difference is significant only when the view zenith angle is larger than 60° (Chen, 1996b). The ranges of variation in the optical and geometrical properties in the stands investigated may be too small to allow the full realization of the advantages of MSR. The usefulness of MSR, therefore, remains to be tested in other environments.

The linear and non-linear regression results for NDVI, SR, and MSR are summarized in **Tables 4** and **5**, respectively. These indices are better correlated to the overstorey LAI and FPAR in late spring than in mid-summer because the strength of the understorey signal increased from spring to summer, reducing the sensitivity of the indices to the overstorey conditions.

The ratioing principle for noise reduction may be applicable to three-band vegetation indices involving an additional blue band, such as the Atmospherically Resistant Vegetation Index (ARVI) (Kaufman and Tanre, 1992), the Soil and Atmospherically Resistant Vegetation Index (SARVI), and the modified SARVI (Huete and Liu, 1994). Further study is needed to apply the ratioing principle to these three-band indices.

CONCLUSIONS

Several two-band vegetation indices, including NDVI, SR, RDVI, SAVI, SAVI1, SAVI2, GEMI, NLI, WDVI, and a new Modified Simple Ratio (MSR), calculated using data from Landsat-5 TM images are evaluated against field data sets of LAI and FPAR in boreal forests. The following conclusions are drawn from this comparative study:

- SR and its associate indices (NDVI and MSR) are better correlated to the field data than all other indices, which cannot be expressed as a function of SR. Many sources of unwanted noise cause simultaneous increases or decreases in red and NIR reflectances in approximately the same proportion, and therefore they can be greatly reduced by taking the simple ratio between the two reflectances. Indices such as NLI, GEMI, and SAVI2 employing mathematical operations other than ratioing would amplify the noise. Indices such as WDVI and PVI based on the absolute difference between the reflectance would retain the noise. The major drawback of SAVI and SAVI1 is the reduction of their sensitivity to surface parameters of interest because of the use of the parameter L in the denominator. This L prevents the exact ratioing and also dampens the background effect at the expense of the sensitivity.
- As a non-linear index, MSR is an improvement over RDVI developed for the purpose of linearizing its relationship with surface parameters. MSR potentially has the advantage of being less sensitive to canopy optical and geometrical properties than NDVI, but this advantage has not been fully shown in this study because of the similarity of the stands investigated.
- Many vegetation indices were developed for idealistic conditions and tested using data sets generated by radiative transfer models without considering measurement errors. All measurements inevitably involve errors, and in most cases indices less subjective to measurement errors should be preferred over those more vulnerable to errors since noise in measurements is generally difficult to assess. However, an evaluation of the indices in this study is based on limited data sets. The indices that performed poorly here may have advantages in other environments or under conditions where all significant environmental noise can be removed.

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