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A Shortwave Infrared Modification to the Simple Ratio for LAI Retrieval in Boreal Forests: An Image and Model Analysis

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In preparation for new satellite sensors, such as VEGETATION on SPOT-4 and the MODerate Resolution Imaging Spectrometer (MODIS), we investigate the potential of the shortwave infrared (SWIR) signal to improve Leaf Area Index (LAI) retrieval in the boreal forests of Canada. Our study demonstrates that an empirical SWIR modification to the simple ratio (SR) vegetation index, termed the reduced simple ratio (RSR), has the potential to unify deciduous and conifer species in LAI retrieval, shows increased sensitivity to LAI, and demonstrates an improved correlation with LAI in individual jack pine and black spruce canopies. The unification of deciduous and conifer species suggests the possibility of not requiring a cover type stratification prior to retrieving LAI information from remotely sensed data, and has impact where no cover type information will be made or where the mix of cover types within a pixel is unknown. We use a geometric–optical canopy reflectance model to quantify the potential variation in jack pine and black spruce canopy reflectance caused by differences in background reflectance. The modeling study supports the results from the image analysis of the RSR showing increased sensitivity to LAI and reducing background effects in these conifer canopies.

INTRODUCTION

Accurate leaf area index (LAI) measurements are critical for understanding biological and physical processes associated with vegetation, and as an input to ecosystem productivity models (Sellers et al., 1986; Bonan, 1993; Liu et al., 1997). The need for LAI information over large areas has prompted investigations of the relationship between ground-measured LAI and vegetation indices derived from satellite-measured reflectance (Franklin, 1986; Spanner et al., 1990; Nemani et al., 1993; Chen and Cihlar, 1996; Fassnacht et al., 1997). The common approach has been to correlate ground-measured LAI against the simple ratio (SR) (Jordan, 1969) or the normalized difference vegetation index (NDVI) (Deering, 1978).

In the boreal forests of Canada, studies investigating the relationship between LAI and satellite-derived vegetation indices have achieved r^2 values between 0.38 and 0.66 (Chen and Cihlar, 1996). However, there is often considerable scatter evident in the relationship. Where a pixel covers more than a single tree, the reflectance is a combination of the forest canopy reflectance and the type and amount of understory observed by the sensor (Robinove et al., 1981; Franklin, 1986). In this situation, there is no single LAI vs vegetation index curve, but rather a family of curves, each a function of canopy closure and the reflectance characteristics of the background (Spanner et al., 1990).

The amount of background observed through a forest canopy is determined mainly by canopy closure (Franklin, 1986; Spanner et al., 1990). To compensate for differences in canopy closure and background reflectance, studies have used shortwave infrared (SWIR) reflectance to quantify canopy closure (Butera, 1986; Baret et al., 1988) and have used the SWIR reflectance as a modification to the NDVI (Nemani et al., 1993). Other vegetation indices including SAVI (Huete, 1988) and modifications of the SAVI (Qi et al., 1994), which have been developed to minimize the effect of background observed may also be used; however, in the boreal forest

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of Canada, Chen (1996) demonstrated that the SR vegetation index was the most correlated with LAI.

The effect of variation in the type and amount of background on canopy reflectance can be understood through canopy reflectance models. Modeling analyses have illustrated the effect of forest age on canopy reflectance (Nilson and Peterson, 1994), the relationship between vegetation indices and the fraction of photosynthetically active radiation absorbed by the canopy (FPAR) (Asrar et al., 1992; Goward and Huemmrich, 1992; Huemmrich and Goward, 1997), and the effects of canopy biophysical and biochemical variability on canopy reflectance (Asner, 1998). For modeling the open boreal forests of Canada, results from the geometric-optical 4-scale model (Chen and Leblanc, 1997; Leblanc et al., 1998) compare well with ground data from boreal black spruce forests and in simulating the directionality of NDVI in boreal forests (Leblanc et al., 1997).

In preparation for the availability of SWIR information from new satellite sensors, such as VEGETATION onboard SPOT-4 and the MODerate Resolution Imaging Spectrometer (MODIS) on the EOS AM1 system, we test whether Nemani et al.'s (1993) SWIR modification of the NDVI will improve the correlation between the SR and LAI in Canada's boreal forest. We also use the 4-scale model to model canopy reflectance in jack pine and black spruce canopies and to understand and quantify the effect of variation in the type and amount of background observed on canopy reflectance, the SR and a SWIR-modified SR.

METHODS

Study Sites

The study sites were tower and auxiliary sites from the Boreal Ecosystem–Atmosphere Study (BOREAS) (Halliwell and Apps, 1997) in Saskatchewan and Manitoba. These sites were located in forest stands of major boreal species: black spruce (*Picea marinana*), jack pine (*Pinus banksiana*), and aspen (*Populus tremuloides*). The undergrowth in jack pine stands typically comprises lichen (*Cladina* spp), alder (*Alnus*), blueberry (*Vaccinium myrtilloides*), and cranberry (*Vaccinium vitis-idaea*). In contrast, the undergrowth in black spruce forest may be completely covered by sphagnum moss (*Sphagnum* sp), feather moss (*Pleurozium schreben*), labrador tea (*Ledum groenlandicum*), and bog cranberry (*Vaccinium vitis-idaea*) (White et al., 1995; Chen, 1996; Walker, 1998).

Leaf area index measurements for all sites were obtained from BOREAS field campaign data. The data collection procedures are discussed in Chen (1996). Briefly, the ground-based optical LAI measurements were obtained from the LAI-2000 instrument (Welles, 1990). The transect length ranged from 150 m to 300 m on the tower sites to 50 m at the auxiliary sites. Because LAI values obtained from LAI-2000 measurements alone do not account for non-random leaf spatial distribution and woody material, they are considered as an effective LAI. The TRAC (Tracing Radiation and Architecture of Canopies) instrument (Chen and Cihlar, 1995) was used to quantify the effect of foliage clumping. Where only the effective LAI was reported in the literature, a conversion factor of 1.3 for mature jack pine and 1.8 for black spruce was used to calculate the LAI from the effective LAI (Chen et al., 1997).

Landsat TM Image Analysis

Two Landsat Thematic Mapper (TM) scenes were used in the study: one (37/22) covering the Saskatchewan study area acquired on 6 June 1991, and the other (34/21) covering the Manitoba study area acquired on 9 June 1994. The red and near-infrared (NIR) bands of these images had been rectified to within one pixel for a previous study (Chen and Cihlar, 1996). For this study, a SWIR band (TM5) was co-registered to the existing images using 25 ground control points distributed widely across each image. Radiometric corrections were made using the gain and offset provided with the images. Surface reflectance was calculated using the 5S code (Tanré et al., 1986), using inputs of a continental airmass, midlatitude summer, a uniform target, and 30 km atmospheric visibility.

The individual sites were positioned on the rectified TM images using latitude/longitude coordinates and aerial photography. The average red, NIR, and SWIR reflectance were extracted from a nine pixel window in the auxiliary sites, and from a transect of seven to nine pixels oriented in the northwest to southeast direction in the intensive sites. The SR and SWIR modification demonstrated by Nemani et al. (1993) were calculated from the reflectance data. We used the SR because previous studies by Chen (1996) demonstrated that the SR has the highest correlation with LAI in boreal forest. In this article, we define the SWIR-modified SR as the Reduced SR (RSR). The RSR is calculated as

$$RSR = SR \cdot \left[1 - \frac{(SWIR - SWIRmin)}{(SWIRmax - SWIRmin)} \right],$$

where *SWIRmin* is the SWIR reflectance obtained from a completely closed canopy and *SWIRmax* is the SWIR reflectance from an open canopy. This term "reduced" is given because the SR is reduced by differing amounts depending on the difference between the site SWIR reflectance and the minimum SWIR reflectance. Although it is preferable not to determine the minimum and maximum SWIR reflectance from the image as the presence of water affects the SWIR reflectance (Nemani et al., 1993); in practice, this is not always possible. In this study, we did not have ground-based information available on canopy closure and therefore used the minimum and maximum SWIR reflectance recorded from the sites as the SWIR reflectance corresponding with a completely closed and an open canopy. Separate minimum and maximum SWIR reflectance were used for the Saskatchewan and Manitoba images to account for possible differences in moisture status. The maximum and minimum SWIR reflectance were 17% and 5% for the Saskatchewan study sites, and 19.5% and 5% for the Manitoba study sites.

Canopy Reflectance Modeling

We used the 4-scale model (Chen and Leblanc, 1997; Leblanc et al., 1998) to model canopy reflectance as a function of the type and amount of background observed. 4-scale is a geometric-optical bidirectional reflectance model that considers four scales of canopy architecture: tree groups, tree crowns, branches, and shoots. The model employed several new modeling methodologies including: simulating the nonrandom, patchy distribution of trees in a forest stand using a Neyman type A distribution (Neyman, 1939); using an angular distribution pattern to define foliage architecture; computing the hotspot both on the ground and on the foliage with gap size distributions between crowns and inside crowns for the foliage; and considering the tree surface (cone, cylinder, or spheroid) as a complex medium, rather than a smooth surface. Considering the effect of all these detailed architectural parameters is important to obtain the correct canopy gap fraction and proportion of sunlit and shaded components.

We used a series of 4-scale simulations to model canopy reflectance as a function of LAI and the amount and type of background observed. For model canopies of black spruce and jack pine, we increased the LAI from 0.5 to 6 in increments of 0.5 LAI. To vary the amount of background observed at each LAI, that is, canopy closure, we varied the tree crown radius (0.4–2 m) and tree density (1000–6000 stems/ha). At each LAI value, the canopy closure could be generated from many combinations of crown radii and tree densities. All other species-specific canopy architecture parameters were taken from Leblanc et al. (1997) and remained constant during the simulations. Any combinations of LAI, crown radius, and tree density that generated a warning from the 4-scale model due to exceeding mathematical or physical limits were not included in subsequent analysis. Gap fractions obtained from the model were limited to an ecologically realistic range between a random canopy and a canopy with a clumping index of 0.4 (Chen and Cihlar, 1996).

We repeated the simulations for backgrounds of lichen, sphagnum moss (moss), and forest soil. Background spectra were obtained from *in situ* spectroradiometric measurements (White et al., 1995). A synthetic background of 50% of water and 50% moss spectra was also included for the black spruce canopy to simulate the effect of wet vegetation and subpixel water bodies beneath the forest canopy. We did not run simulations for an aspen canopy because we had no specific information or experimental data on the reflectance of background components found commonly under aspen canopies or the mid-infrared reflectance of aspen leaves.

The input red (0.63–0.69 μm) and NIR (0.76–0.90 μm) reflectance to 4-scale were taken as the average needle reflectance of the summer adaxial and abaxial surfaces (Middleton et al., 1997) (Table 1). No specific experimental data on the SWIR reflectance (1.55–1.75 μm) of jack pine and black spruce were available. A generic SWIR reflectance of 22% was therefore assumed from the literature (Heois, 1979; Guyot et al., 1989; Dungan et al., 1996). The view zenith angle was at nadir and the solar zenith angle set at 45°.

RESULTS

Landsat TM Analysis

The red canopy reflectance follows an inverse curvilinear relationship that reaches an asymptote at LAI greater than 3 (Fig. 1a). Red reflectance decreases from 5–6% at an LAI of 1, to 2–3% at an LAI of 6. The jack pine, black spruce, aspen, and mixed sites are interspersed, although aspen appears mainly at the bottom of the data group. In the NIR band (Fig. 1b), the reflectance of jack pine and black spruce sites decrease linearly with LAI; however, the decrease is less than observed for the red reflectance. The mean NIR reflectance of the aspen and mixed sites is 30%, noticeably greater than the 17% mean reflectance of the pine and spruce sites. In the SWIR band (Fig. 1c), there is a strong linear decrease in reflectance with increasing LAI. The aspen and mixed sites show slightly larger SWIR reflectance than the pine and spruce for a given LAI, but there is no noticeable separation of the deciduous and coniferous data.

Figures 2a and 2b compare use of the SR with the RSR on the combined jack pine, black spruce, and aspen data. The correlation coefficients are summarized in Table 2. In Figure 2a, there are two distinct groups of points: one for aspen, and one for jack pine and black spruce. The points for mixed forest types are interspersed in between these two groups. When the RSR is applied (Fig. 2b), the aspen and the mixed forest types are no longer separate, but are interspersed with the conifers. The respective r^2 values are 0.12 for SR, and 0.55 for the RSR.

In the jack pine stands (Figs. 2c and 2d), application of the RSR increases the r^2 value from 0.54 to 0.70, a 30% increase over the SR vs. LAI relationship. The RSR also demonstrates increased sensitivity at low LAI compared to the SR, that is, for a small change in LAI, the change in the RSR is greater than for the SR. In the black spruce stands (Figs. 2e and 2f), the r^2 increases from 0.50 to 0.58 when the RSR is used, a 15% relative

Table 1. Input Red, NIR, and SWIR Reflectance for Jack Pine and Black Spruce Needles, and Various Backgrounds Used in the 4-Scale Modeling

	Needle Reflectivity (%)		*Background Spectral Signature (%)*			
Spectral Band	*Jack Pine*	*Black Spruce*	*Lichen*	*Forest Soil*	*Moss*	*Water*
Red (0.63–0.69 mm)	8.3	9.1	13.7	6.0	7.0	3.0
NIR (0.76–0.90 mm)	53.5	45.1	31.4	16.8	33.3	0.1
SWIR (1.55–1.75 mm)	22.0	22.0	28.1	29.9	31.4	0.1

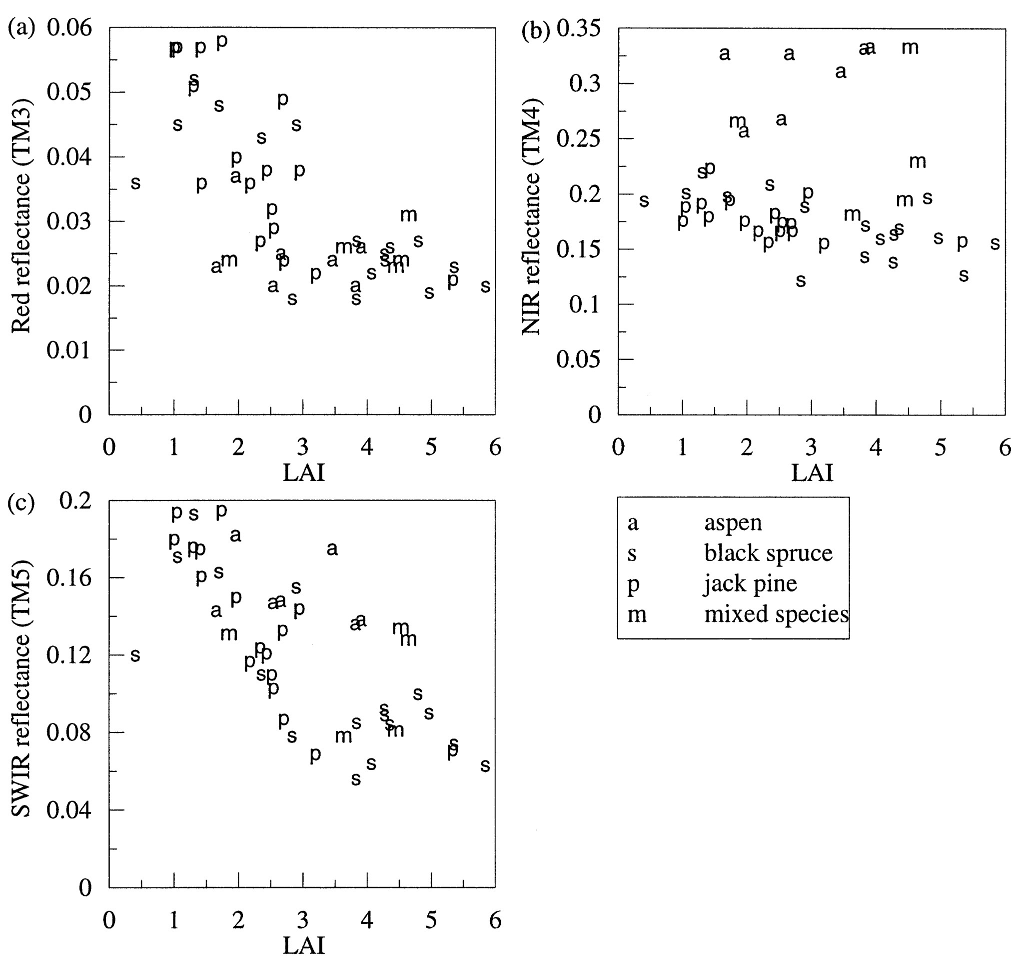
change. The black spruce stands also demonstrate the increased sensitivity of the RSR at low LAI values.

Modeled Canopy Reflectance

As observed in the TM analysis, both jack pine and black spruce canopies demonstrate an inverse curvilinear relationship of red reflectance with increasing LAI (Figs. 3a and 3b). At low LAI (0.5), the red reflectance of a jack pine canopy can range from 5.0% to 10.1%, a relative range of 50% depending on understory composition. The reflectance curve reaches an asymptote at an LAI of approximately 3. At high LAI (6), there is minimal effect from the understory, with canopy reflectance ranging from 2.6% to 3.0%. Similar values are observed for the vegetative and soil backgrounds in the black spruce canopy.

In the NIR (Figs. 3c and 3d), there are different curves for the forest soil and the vegetative backgrounds, caused by the relatively low NIR reflectance of soil compared to the lichen and moss backgrounds (Table 1). At LAI values less than 2, the canopy NIR reflectance for vegetative backgrounds decreases with increasing LAI, but, as LAI increases, the NIR reflectance increases. This increase is more pronounced in the jack pine can-

Figure 1. Red (a), NIR (b), and SWIR (c) canopy reflectance against LAI. Reflectance values are from Landsat TM imagery, and LAI values are from BOREAS tower and auxiliary sites.



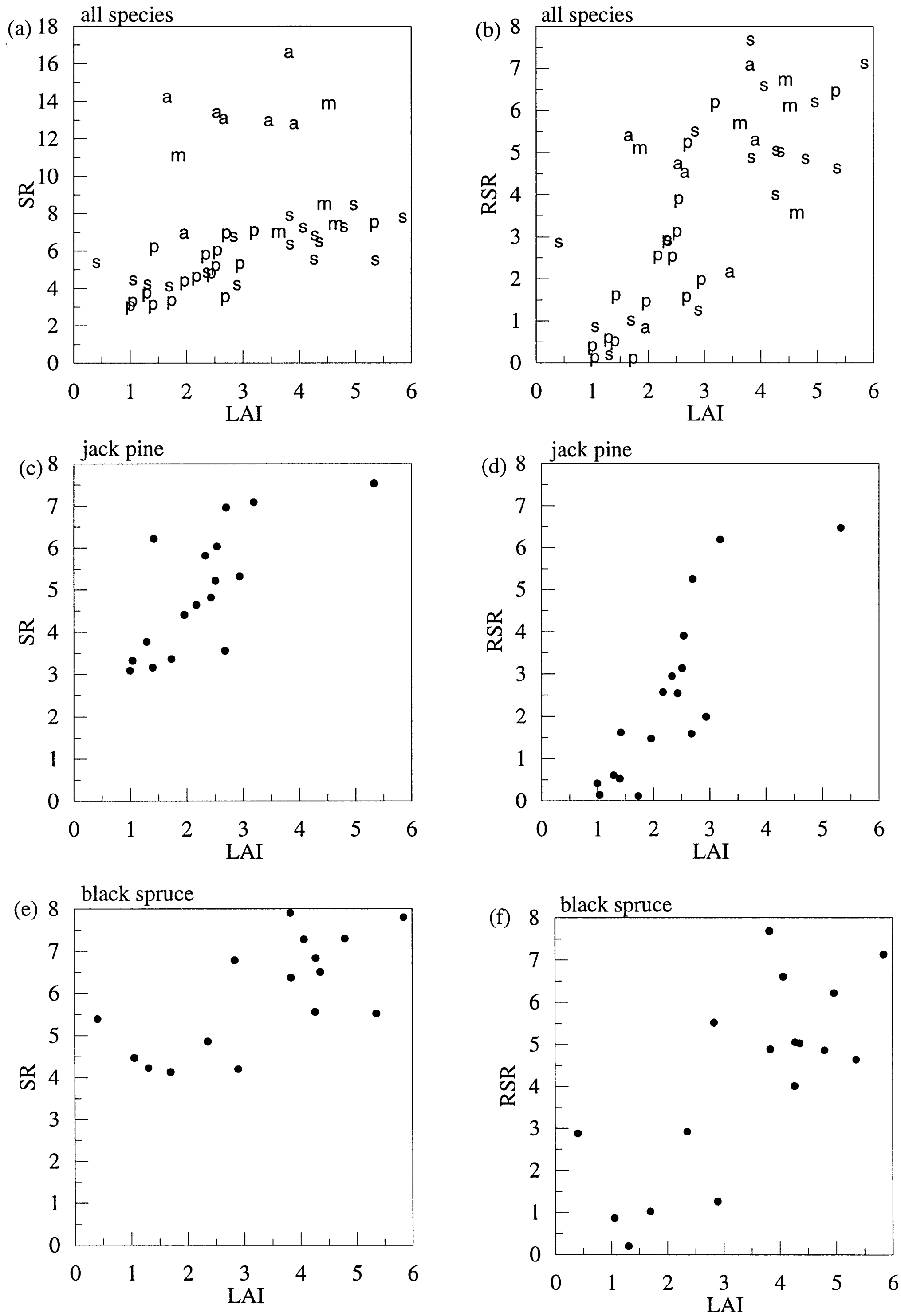


Figure 2. The Landsat TM-derived SR and RSR against ground-measured LAI for all species (a and b), jack pine (c and d), and black spruce (e and f).

opy (Fig. 3c) than in the black spruce (Fig. 3d) because of the greater needle reflectivity input to the 4-scale model (Table 1). The canopy NIR reflectance for the soil background increases over the complete range of LAI. As with the red reflectance, the range in NIR reflectance caused by the different backgrounds decreases with increasing LAI. In the black spruce canopy, the absolute reflectance values at high LAI are less than in the jack pine; however, the soil and vegetative background curves follow the same pattern.

Table 2. Correlation Coefficients for Regressions between SR and RSR with LAI for Different Boreal Species

Species	*SR* (r^2)	*RSR* (r^2)
All (jack pine, black spruce, aspen)	0.122	0.551
Jack pine	0.536	0.703
Black spruce	0.501	0.578
Jack pine and black spruce	0.554	0.662

The canopy SWIR reflectance (Figs. 3e and 3f) demonstrates the same inverse curvilinear trend with increasing LAI as red reflectance. However, because of the similar SWIR reflectance of all backgrounds (Table 1), there is only minimal variation in canopy SWIR reflectance at low LAI. This similarity of SWIR reflectance across different backgrounds compared to the range shown in the red and NIR reflectance, and the large sensitivity of the SWIR to LAI are the main reasons for the better performance of the RSR compared with the SR. The SWIR reflectance in the black spruce canopy is almost identical with only small differences caused by minor variations in the canopy gap fraction.

Figures 4a–d illustrate the effect of background reflectance on the SR and the RSR. The results demonstrate that the RSR reduces the effect of background reflectance and shows increased sensitivity at low LAI values. Figure 4e quantifies the possible range in SR and RSR caused by differences in background reflectance. For both the SR and RSR, the possible range reaches a maximum at an LAI of 2–3, but then decreases with increasing LAI. The maximum possible range is slightly greater in the jack pine canopy compared to the black spruce canopy. At LAI less than 3, the possible range in RSR for a given LAI is less than the range SR; however, at LAI greater than 3, the possible range in RSR and SR is similar.

The curves for the mixed water and moss background in a black spruce canopy (Fig. 3b, 3d, and 3f) illustrate that a damp background will have a large effect in canopy reflectance in the individual bands. The effect is greatest at low LAI; however, the effects visible in the individual bands are minimized in both the SR and RSR (Figs. 4b and 4d).

DISCUSSION

One of the most intriguing results is the ability of the RSR to unify different cover types for potential LAI retrieval. This is demonstrated graphically in the merging of the aspen and mixed species plots with the jack pine and black spruce data (Figs. 2a and 2b). The result suggests the possibility of not requiring a prior cover type stratification for LAI retrieval, and has impact where no cover type information will be made or where the mix of cover types within a pixel is unknown. An explanation for the unification is that aspen leaves have a both larger NIR and SWIR reflectance compared to the conifer reflectance (Figs. 1b and 1c) (Williams, 1991). The SWIR modification compensates for the higher NIR reflectance of the aspen leaves.

Even where cover type information is available, use of the RSR would improve LAI retrieval accuracy by reducing the effect of background or understory reflectance and increasing sensitivity to change in LAI. In comparison, the SAVI (Huete, 1988) also minimizes the effect of background reflectance but decreases sensitivity compared to the SR (Chen, 1996). It is interesting that a greater improvement was observed in the jack pine stands (30%) compared to the black spruce stands (15%). This difference may be attributed to variation in understory composition in the typically more open jack pine stands (Chen, 1996). In well-drained jack pine stands, the predominate understory is lichen, changing to alder shrubs on the lower parts of slopes and moss on wet stands, whereas, in black spruce sites, the background maybe completely covered by sphagnum moss, feather moss, labrador tea, and bog cranberry (White et al., 1995; Chen, 1996; Walker, 1998).

Results from the 4-scale modeling analysis can be interpreted in terms of variation in four canopy components: the probability of observing sunlit canopy, sunlit background, shaded canopy, and shaded background. The inverse curvilinear relationship of red reflectance with increasing LAI is consistent with results published by Peterson et al. (1987), Spanner et al. (1990), and Nemani et al. (1993). As the LAI and canopy closure increase, the red reflectance decreases as less of the highly reflective sunlit background is observed (Chen et al., 1998). The large variation in red reflectance at low LAI that can be attributed to variation in background agrees with the modeling analyses of Nilson and Peterson (1994).

An initial decrease of NIR at low LAI may be attributed to an increase in the probability of observing shadowed background. At low LAI and a nadir view, tree shadows tend to fall on the background rather than on neighboring trees, therefore decreasing the amount of the highly reflective sunlit background visible. Although the canopy needle NIR reflectance input to the model (Table 2) was greater than the background NIR reflectance, clumping in shoots, whorls, and canopies greatly reduces the NIR reflectance (Williams, 1991). An increasing NIR canopy reflectance at LAI greater than 2.5–3, reflects the increasing LAI of the conifer overstory (Spanner et al., 1990) with proportionally more sunlit and shaded canopy contributing to the canopy reflectance.

The large range in SR at low LAI (Figs. 4a and 4b) supports the conclusion of Nemani et al. (1993) that the NDVI alone cannot be used to estimate LAI in open forest canopies, and the statement by Chen and Cihlar (1996) that the scatter observed in the LAI vs. SR relation may be attributed to variation in background reflectance. At low LAI (0.5), there is a high probability of

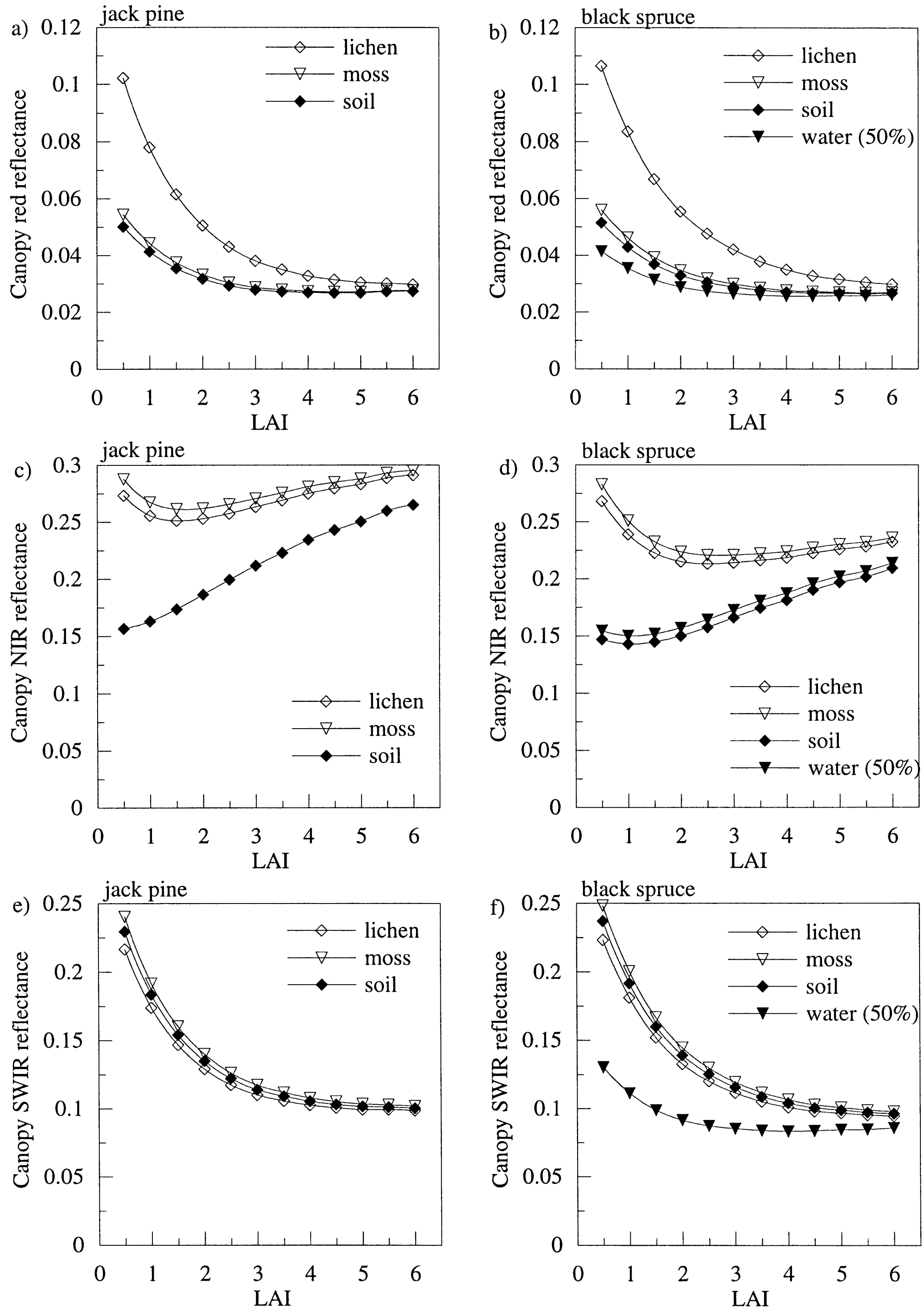


Figure 3. Canopy reflectance simulations using the 4-scale model of a jack pine and black spruce canopy in the red (a and b), NIR (c and d), and SWIR (e and f) against LAI for backgrounds of lichen, sphagnum moss, and forest soil. A 50% water/moss background was also included for the black spruce canopy.

observing sunlit background, and the SR is affected by variation in the reflectance properties of different backgrounds. As the LAI increases, there is progressively more shaded background, and sunlit and shaded canopy visible (Chen et al., 1998). The variation in SR peaks when the canopy architecture creates the largest number of possible combinations of sunlit and shaded background and canopy. In this study, this occurred at an LAI value

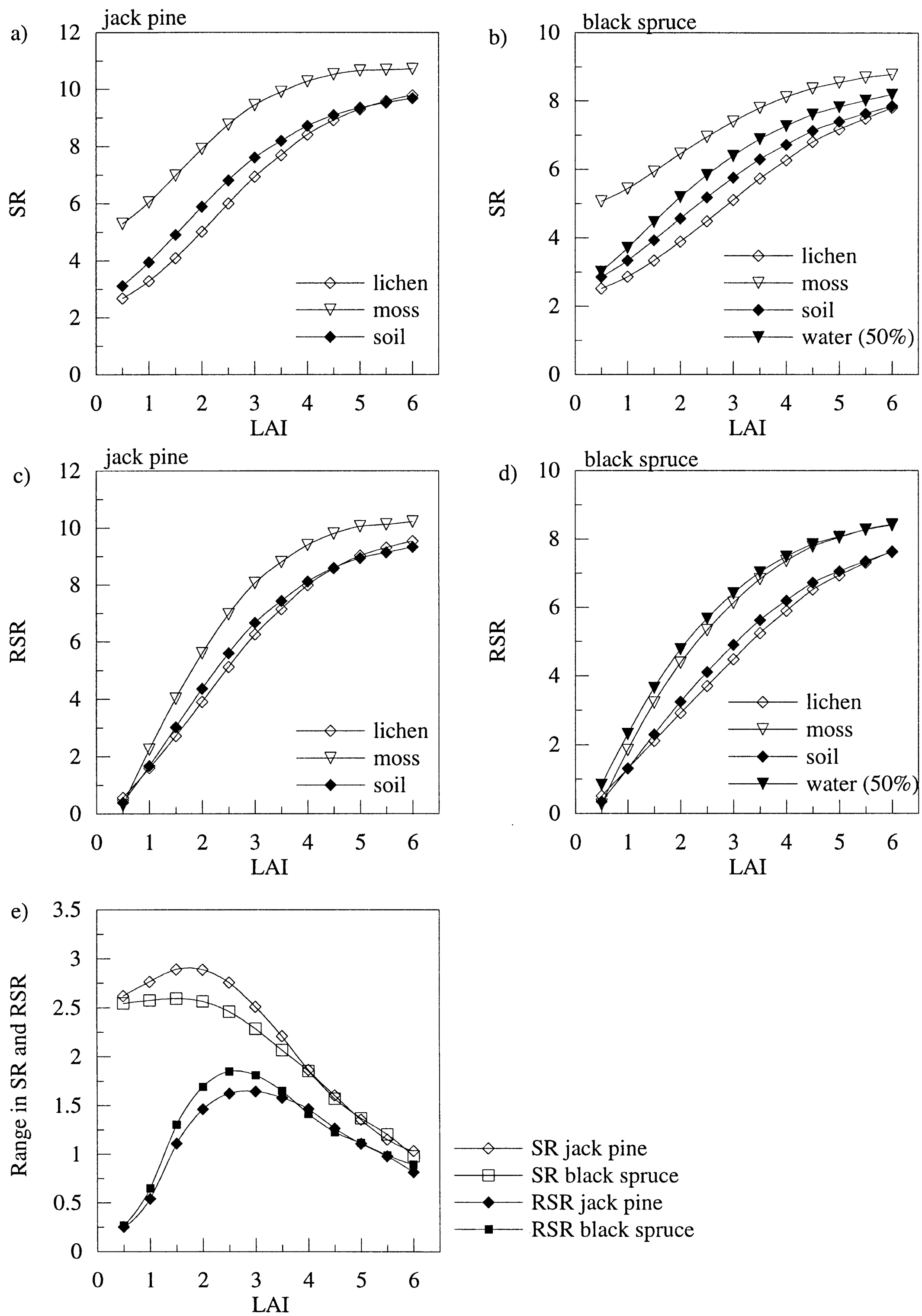


Figure 4. Modeled results of the effect of different backgrounds on the SR (a and b) and on the RSR (c and d) at different LAI values in a jack pine and a black spruce canopy. Figure 4e quantifies how the difference in background observed affects the possible range in the SR and RSR.

of 2.5–3. As the LAI increases from this point, the canopy reflectance is increasingly dominated by sunlit and shaded canopy (Chen et al., 1999) and the range in SR decreases.

The SWIR modification applied (Nemani et al., 1993) is a scalar which reflects the shape of the SWIR reflectance vs. LAI curve. The inverse curvilinear relationship between SWIR and LAI means that low LAI canopies will generate a small scalar, and cause a large decrease in the SR. In high LAI canopies, the scaling factor will approach unity. In our modeling simulation using a mixed water and moss background, both the SR and RSR appeared to negate the effect of the damp background conditions. However, this simulation assumed an equal effect of water in all spectral bands, which is simplistic and probably not the case *in situ*. Nevertheless, the simulation indicates the shape of canopy reflectance vs. LAI curves for increased surface moisture conditions. If we now assume the effect of water to be different in each band, ratio vegetation indices such as the SR will not correct for moisture conditions. In addition, the shape of the SWIR vs. LAI curve, and the SWIR modification, will be different depending on the surface moisture conditions. The more moist the conditions, the less effect the SWIR modification will have on the SR at low LAI. Future developments may be able to use more sophisticated methods to consider the surface moisture and weather conditions, especially in rainfall events prior to image acquisition.

CONCLUSIONS

A SWIR modification has been shown to improve the correlation between the SR and LAI in boreal forests. The modification reduces the effect of background reflectance and demonstrates increased sensitivity to change in LAI. Use of the RSR also negates the effect of higher NIR reflectance in deciduous canopies, and unifies deciduous and coniferous species for LAI retrieval. This unification suggests that a prior cover type stratification may not be required to retrieve the LAI from data acquired with the MODIS and VEGETATION sensors. Although this needs further evaluation, not requiring a cover type stratification will be especially valuable in regional and global scale studies, where accurate cover type information is not available, or where the mix of cover types within a pixel is unknown.

Analyses with the 4-scale geometric optical model illustrated the large range in canopy reflectance and vegetation indices that can be caused by variation in background reflectance. These results provide an explanation for the scatter observed in LAI vs. vegetation index relationships in boreal forests and indicate the uncertainty in LAI values retrieved from satellite-derived vegetation indices based on red and NIR reflectance. The modeling study supports the results from the TM analysis of the RSR showing increased sensitivity to LAI and reducing background effects.

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