Retrieving Leaf Area Index of Boreal Conifer Forests Using Landsat TM Images.

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ABSTRACT[1]

Vegetation indices, including the Simple Ratio (SR) and the Normalized Difference Vegetation Index (NDVI), from Landsat TM data were correlated to ground-based measurements of LAI, effective LAI, and the crown closure in boreal conifer forests located near Candle Lake and Prince Albert, Saskatchewan and near Thompson, Manitoba, as part of the Boreal Ecosystem-Atmosphere Study (BOREAS). The measurements were made using two optical instruments: the Plant Canopy Analyzer (LAI-2000, LI-COR) and the TRAC (Tracing Radiation and Architecture of Canopies). The TRAC was recently developed to quantify the effect of canopy architecture on optical measurements of leaf area index. The stands were located on georeferenced Landsat TM images using global positioning system (GPS) measurements. It is found that late spring Landsat images are superior to summer images for determining overstory LAI in boreal conifer stands because the effect of the understory is minimized in the spring before the full growth of the understory and moss cover. The effective LAI, obtained from gap fraction measurements assuming a random distribution of foliage spatial positions, was found to be better correlated to SR and NDVI than LAI. The effective LAI is less variable and easier to measure than LAI, and is also an intrinsic attribute of plant canopies. It is therefore suggested to use effective LAI as the most important parameter for radiation interception considerations.

Keywords: LAI, crown closure, vegetation index, Landsat, boreal forest, canopy architecture

INTRODUCTION

Leaf area index (LAI) quantifies the amount of foliage area per unit ground surface area. It is therefore an important parameter controlling many biological and physical processes associated with vegetation on the Earthÿs surface, such as photosynthesis, respiration, transpiration, carbon and nutrient cycle, and rainfall interception . LAI is a required input to many climate and ecological models (Sellers et al. 1986, Dickinson et al. 1993, Running and Coughlan 1988, Bonan 1993).

Satellite remote sensing provides a unique way to obtain the distributions of LAI over large areas. Green leaves are selective absorbers of solar radiation. Compared with non-vegetative surfaces, green leaves absorb more visible radiation for photosynthesis and less near infrared radiation. Reflectance in red and near infrared wavebands, denoted by ÿ$_n$ and ÿ$_r$, have therefore been used to formulate various vegetation indices as indicators of the conditions of vegetated surfaces (Jordan 1969, Deering 1978, Huete 1988, Baret et al. 1989, Kaufman and Tanre 1992, Qi et al. 1994, Liu and Huete 1995, and Roujean and Bréon 1995). Among the various vegetation indices, the Normalized Difference Vegetation Index (NDVI) (Deering 1978), (ÿ$_n$ - ÿ$_r$)/(ÿ$_n$ + ÿ$_r$), and the Simple Ratio (SR) (Jordan 1969), ÿ$_n$ /ÿ$_r$, are most frequently used to derive LAI and other surface parameters from spaceborne and airborne remote sensing data, in spite of their limitations in removing the effects of background (Sellers et al. 1994, Running et al. 1994).

Numerous studies have been done to relate vegetation indices to LAI of agricultural crops (e.g., Asrar et al. 1985, Best and Harlan 1985, Curran and Williamson 1987, Shibayama and Akiyama 1989, and Wiegand et al. 1988). There have also been several investigations on this relationship between satellite-derived vegetation indices and LAI in conifer stands (Badhwar et al. 1986, Spanner et al. 1990a, 1990b and 1994). The uncertainties in the relationship were found to be large due to the complexity of the radiation environment in forest stands and errors in ground-based measurements. The data for boreal forests appear to be lacking, and much work needs to be done to understand remotely measured spectral signals from forested surfaces.

One way of improving our understanding of remote sensing measurements is to simulate the radiative transfer processes using numeric models. There has been a wealth of models of various types (see review by Myneni et al. 1995). Valuable insights into the fundamental processes governing the relationships between vegetation indices and LAI or other surface parameters have been gained through model simulations and sensitivity tests (Goel and Qin 1994, Huete and Liu 1994). However, models are always, to some extent, abstract or simplified mathematical descriptions of the physical reality. Model results can only be trusted to the extent of validation using ground truth data. Extrapolated model predictions are useful only when the model assumptions are not violated. Experimental data also help examine the assumptions. Another way of understanding remote sensing signals is by correlating the signals with ground-base measurements. Conclusions drawn from such statistical analysis depend very much on the accuracy of ground-based and remote sensing data. Improving the accuracy of ground-based data is therefore critical to the advancement of remote sensing applications. This paper addresses several issues related to retrieving LAI using satellite-borne vegetation indices from the perspective of ground-truthing methodology. By a combined use of the LAI-2000 Plant Canopy Analyzer (Welles 1990) and a new sunfleck-LAI instrument TRAC (Tracing Radiation and Architecture of Canopies) recently developed by Chen and Cihlar (1995 a & b), we were able to quantify several key attributes associated with forest canopies: (1) canopy gap fraction distribution with zenith angle; (2) canopy closure; (3) effective LAI (obtained from canopy gap fraction assuming the foliage spatial distribution is random); and (4) LAI. The TRAC instrument quantifies the effect of foliage spatial distribution pattern (non-randomness) on indirect measurements of LAI and can therefore measure LAI rather than the effective LAI measured by previous optical instruments. The objectives of this paper are twofold: (1) to fill in the data gap for boreal forests; and (2) to investigate the content of remote sensing signals by correlating vegetation indices from high resolution Landsat data with the various attributes of boreal conifer canopies mentioned above.

THEORY

LAI presented in this paper is defined as half the total leaf area per unit ground surface area. In many previous papers, especially remote sensing papers, LAI has been defined on the basis of projected area. These two definitions can differ by a factor of 2 for spheres (often used to approximate conifer shoots) and square bars (like some spruce needles), 1.57 for cylinders representing branches, and 1.28 for hemicircular cylinders representing some conifer needles. Chen and Black (1992) demonstrated that in order to use 0.5 as the projection coefficient when the leaf angle distribution is spherical (random), LAI must be defined on the basis of half the total leaf area. They suggested that the definition based on the projected area be abandoned. The concept is easily understood by comparing two objects with the same diameter: disk and sphere. They have the same projected area, but the sphere intercepts twice as much light as the disk with random angular distribution when averaged for all radiation incidence angles. The confusion in the definition arises largely because it has not been fully appreciated that all optical instruments including LAI-2000 respond to half the total area of foliage elements rather than to the projected area. Since the foliage elements can be oriented in all directions, the projected area in one direction does not carry all the necessary information.

Radiation regimes in plant canopies are affected by two essential attributes (Chen 1995): foliage angular distribution and foliage spatial distribution. The foliage angular distribution determines the variation of canopy gap fraction with the zenith angle. It can therefore be derived from multiple angle measurements of the gap fraction through measurements of radiation transmittance. The LAI-2000 instrument is designed for this purpose. The foliage spatial distribution determines the amount of radiation transmitted through the canopy for the same LAI. In highly organized conifer stands, needles are grouped in shoots which in turn are confined in space to structures at higher levels such as branches, whirls and crowns. The clumping of foliage not only results in more radiation transmission (larger gap fraction) than the random case but also alters the gap size distribution. A clumped canopy with large structures like tree crowns exhibits large gaps between tree crowns and branches, which are absent in a canopy with randomly positioned foliage elements. The canopy gap size distribution therefore contains the architectural information and can be measured indirectly using optical methods. The TRAC instrument is designed to measure the canopy gap size using the solar beam as a probe (Chen and Cihlar 1995a and 1995b). From the measured canopy gap size distribution, canopy architectural parameters can be derived and a foliage element clumping index can be calculated as a correction to the effective LAI. Conifer needles are generally closely grouped together in shoots, and the small gap within individual shoots can not be detected using the solar beam because of the penumbra effect. As a result of this, the element clumping index derived from a gap size distribution includes the effects of foliage clumping at scales larger than the shoots. The effect of clumping within the shoots can be obtained by laboratory analysis of shoot samples. The formula for calculating LAI, denoted by L, is as follows (Chen 1995):

(1)

where L_e is the effective leaf area index calculated from canopy gap fraction measurements assuming the foliage spatial distribution is random; ÿ$_E$ is the needle-to-shoot area ratio quantifying the effect of foliage clumping within shoots; ÿ $_E$ is the element clumping index quantifying the effect of foliage clumping at scales larger than shoots (i.e. elements), and ÿ is the woody-to-total area ratio used to remove the contribution of the supporting woody material to the total area including foliage, branches and tree trunks affecting ground-based optical measurements.

L_e was taken as the readings from the LAI-2000 Plant Canopy Analyzer (PCA). ÿ$_E$ was calculated as the ratio of half the total needle area in a shoot to the area of an imaginary surface enveloping the shoot. The imaginary surface area of a shoot was obtained from multi-angle projections of the shoot, being four times the average projected area if the shoot shape is approximated by a sphere. ÿ$_E$ was measured using the TRAC, and ÿ was obtained from destructive sampling (see Ground-Based Measurements for detail).

LAI-2000 measures gap fraction *P(ÿ)* in five zenith angle (ÿ) ranges with the mid-points of 7^o, 23^o, 38^o, 53^o and 67^o (Welles 1990). The calculation of L_e from the gap fraction measurements is based on the following Miller's (1967) theorem:

(2)

Although the original Miller's theorem was used for the calculation of LAI, Chen and Black (1991) regarded the calculated result as L_e rather than LAI because of the assumption of a random foliage spatial distribution used in the calculation.

The crown closure, C, was also obtained from the gap fraction in the first angle range from 0^o to 15^o i.e.

(3)

The crown closure is defined as the percent vegetation cover viewed in the vertical direction. Gap fraction of a plant canopy decreases with zenith angle because the pathlength through the canopy is greater at larger zenith angles. It is therefore expected that $P(7^o)$ would be slightly larger than $P(0^o)$ in the vertical direction by a factor of $Exp(-0.5L_e)/Exp(-0.5L_e/\cos(7^0))=1.01$ at $L_e = 2.0$.

GROUND-BASED MEASUREMENTS

LAI was measured in black spruce (*Picea Mariana*) and jack pine (*Pinus banksiana*) stands located in the BOREAS Southern Study Area (SSA) near Candle Lake, Saskatchewan, and in the Northern Study Area (NSA) near Thompson, Manitoba. This paper uses measurements made in 25 stands, of which 6 are intensive sites and 19 are auxiliary sites. The intensive sites are the BOREAS flux tower sites. They are SOJP (south old jack pine), SYJP (south young jack pine) and SOBS (south old black spruce) in the SSA, and likewise NOJP, NYJP and NOBS in the NSA. Details of LAI measurements at the intensive sites are given in Chen (1995), but is briefly described here. At each intensive site, three parallel transects of equal length, 150 m to 340 m, were located 10 m apart and oriented in the southeast and northwest direction. Along each transect, a forestry flag was placed every 10 m to serve as a distance marker. Optical measurements of LAI were made at the beginning, middle and end of the growing season in 1994 corresponding to the BOREAS Intensive Field Campaigns (IFC-1, IFC-2 and IFC-3, Sellers et al. 1995). IFC-1 (24 May to 16 June) and IFC-2 (19 July to 8 August) are referred to as late spring and mid-summer respectively. Measurements in IFC-3 (30 August to 19 September) are not used in this paper because of lack of cloud-free Landsat data for this period.

LAI-2000 measurements were taken at each flag position, either at dusk or under overcast conditions to avoid the effect of direct sunlight on the sensor and to reduce the light scattering effect. To improve the efficiency of measurements, three LAI-2000 units were used. One was placed on the top of the flux tower or in a large opening nearby (where the obstruction occurred only below the view elevation angle of 15^{o}) to obtain the above-stand reference readings in a remote mode. The other two units were used inside the stand by two persons. The LAI values calculated after merging the reference readings with in-stand readings were taken as the effective LAI (L_e). A mean L_e value for a stand is the average of 60 to 90 LAI-2000 measurements along the transects.

The TRAC was used along the same transects on clear days. The instrument consists of three quantum sensors (LI-COR, Lincoln, NE, Model LI-190SB, 10 ms time constant) for measuring the photosynthetically active radiation (PAR), a data logger (Campbell Scientific, Logan, UT, Model CR10) and a storage module (Model SM716). Two of the sensors measure the downwelling total and diffuse PAR, and one measures the reflected PAR from the forest floor. For the diffuse sensor, a vertical shading strip was used on the side to obstruct the direct light. The sensors were supported by a holding arm and connected to the data logger operated at a sampling frequency of 32 Hz. The whole system was hand-carried by a person walking along the transects. With a walking pace of 1 m every three seconds, a sampling interval of 10 mm for each sensor could be achieved. Measurements of the downwelling components are used to calculate the transmitted direct PAR for LAI estimation. The reflected PAR measured by the downward facing sensor is for the calculation of absorbed PAR by the canopy and is not used in this paper. These closely-spaced measurements on long transects are used to determine the canopy gap size distribution from which to derive the element clumping index.

The needle-to-shoot area ratio was measured for each intensive site for all IFCs. An average ratio was obtained for each stand from 27 to 45 shoot samples removed from three trees (dominant, co-dominant and suppressed) at three heights (top, middle and lower crown portions). The shoot imaginary surface area was obtained from multiple angle projections using a video camera system (AgVision, Decagon Devices Inc., P.O. Box 835, Pullman). The needle surface area was measured using a volume displacement method described in Appendix C of the BOREAS Experimental Plan. The woody-to-total area ratio was measured in two mature jack pine stands (SOJP and NOJP), and one black spruce stand (SOBS). In each stand, three or four trees of different height classes were felled and the foliage, branch and stem areas measured (Chen 1995).

Two perpendicular 50 m transects were established at each auxiliary sites. The transects were oriented in south-north and east-west directions and crossed in the middle to form a “+” shape. The spacing between the marking flags along the transects was also 10 m. LAI-2000 measurements were made on both transects for all sites and TRAC data were acquired along one or both transects at each site. No data were collected for the needle-to-shoot area ratio and the woody-to-total area ratio for the auxiliary sites. Since these ratios do not vary much between mature stands of the same species, the results from the intensive sites were used for these auxiliary sites.

The geographic locations of the stands were determined using a dual-receiver global positioning system (Trimble Pathfinder) with a nominal absolute accuracy of ±10 m. However, the accuracy deteriorated substantially when the measurements were taken in closed stands with a portable antenna extended to just below tree crowns. The error for closed stands is estimated to be about ±100 m. This large error occurred for 3 sites. For these sites, road maps with site locations provided by the BOREAS staff team were used to assist in locating them in the image according to road turning features and distance from the road.

SATELLITE IMAGE PROCESSING

Four Landsat TM scenes were used in this study: two covering part of the BOREAS southern study area near Candle Lake, Saskatchewan (row number: 37/22-23, and dates: 6 June 1991 and 11 August 1986), and the other two covering the northern study area located in between Nelson House and Thompson, Manitoba (row number 34/21, and dates: 9 June 1994 and 19 August 1985). These scenes were acquired at solar zenith angle of 35.9^{o}, 43.2^{o}, 37.3^{o} and 43.9^{o}, respectively. The images were provided in a systematically georeferenced format (Murphy 1982). Over 20 ground control points were used for each scene to improve the accuracy of pixel registration to within one pixel (30 m). Radiometric corrections were made using coefficients (gains and offsets) provided with the images. Vegetation indices at the surface were calculated from the reflectances in bands 3 and 4 after atmospheric corrections using the FIVES model (Tanre et al. 1986, Teillet and Santer 1991). In running the model, the options of continental airmass, midlatitude summer and uniform targets were chosen, and the atmospheric visibility was set to 30 km for these cloudless scenes. It was found that the model output was not sensitive to the visibility larger than 10 km and the type of targets chosen. The average NDVI value for a site was taken from 9 pixels in a square for the auxiliary sites and from 7-9 pixels on a line oriented in the northwest and southeast direction for the intensive sites to match the ground transects.

These images have the least cloud cover among all images available to this study over the past 10 years for late spring and mid-summer at these two locations. All the stands investigated are mature forests more than 50 years old except for two 29 year old young jack pine stands (Apps et al. 1994). We expect the change in the vegetation conditions with time is small for all the stands.

RESULTS AND DISCUSSION

The ground-based measurements and some stand attributes for IFC-1 (late spring) are summarized in Table 1, where the first six are the intensive sites and the rest are auxiliary sites. The stand density and basal area are also included in the table for reference. L_e ranged from 0.6 to 3.5, ÿ$_E$ from 1.28 to 1.43, and ÿ$_E$ from 0.67 to 0.97. Values of ÿ were 0.14, 0.28 and 0.32 for SOBS, NOJP and SOJP, respectively. LAI of all the stands was calculated with these measurements using Eq. 1. On average, LAI in mid-summer exceeded late spring values by 12%.

Figs. 1(a) and 1(b) show the relationships between NDVI and LAI for late spring and mid-summer, respectively. The curve-fitting results are (the non-linear regression line was forced through zero):

Late spring (IFC-1): $\text{NDVI} = 0.5520\, L^{0.1844}$ (R^2=0.52)

or $\text{NDVI} = 0.519 + 0.051\, L$ (R^2=0.50)

Mid-summer (IFC-2): $\text{NDVI} = 0.6539\, L^{0.1057}$ (R^2=0.38)

or $\text{NDVI} = 0.635 + 0.032\, L$ (R^2=0.42)

The sensitivity of NDVI to LAI is larger in late spring than in mid-summer and the regressions are also better (higher R^2 value) in late spring. Similar spring-summer difference was also found by Badhwar et al. (1986). This is because the measured LAI values included only the overstory foliage while the NDVI responded to both the overstory and understory. In the summer, when the understory was abundant, the contribution from the understory increased. The increase was larger for stands with smaller LAI which provided better light environment for the understory growth, resulting in the decrease in sensitivity from spring to summer. These regression results thus suggest that spring images are more useful for estimating the overstory LAI for forest stands.

Compared with similar relationships for cropland or grassland, NDVI from boreal forests does not show an obvious saturation point with increasing LAI. Since conifer canopies are highly clumped, they do not cover as much ground surface as agricultural crops and grasses with the same LAI. The total foliage clumping index for the stands investigated was about 0.6. This effectively reduces LAI by about half in terms of their ability to cover the background having lower NDVI. Therefore, if saturation occurs at LAI=2.5 for agricultural crops, it would occur at LAI=5 for conifer forests. However, the major problem in deriving LAI from NDVI for boreal forests is the contribution from the understory. According to spectral signatures acquired in the summer by White et al. (1995), the average NDVI for the forest floor covers in SOBS and NOBS was about 0.6 and 0.5, respectively. SOBS forest floor cover was predominantly labrador tea (*Hylocomium splendens*) and Sphagnum moss (*Sphagnum fuscum*), and NOBS had less labrador tea and more Sphagnum. NDVI for the major ground cover lichens (*Cladina* spp) in jack pine stands was calculated to be about 0.4 from the measurements of White et al. (1995). In many jack pine stands, there were also abundant Alder (*Alnus* spp) shrubs with similar NDVI values to that of the overstory canopy. The measured NDVI of the background (ground cover and understory) was in the range of 0.35-0.50 in the spring and 0.40-0.60 in the summer. These values are smaller than the respective offsets obtained from the linear regression (Fig. 1), indicating the relationship between NDVI and LAI is non-linear, However, in the usual range of LAI from 1 to 5, the relationship is essentially linear, and different curve-fitting techniques do not make much difference (as evident in the R^2 values).

The difference in NDVI between the background and the overstory was about 0.15-0.25 in the summer for both conifer species . In the spring, the difference was estimated to be 0.25-0.35. This difference is still considerably larger than the error in NDVI , suggesting that vegetation indices from red and NIR bands are useful in determining LAI of boreal forests. If careful radiometric and atmospheric corrections are made, it is possible to reduce the absolute error in NDVI to 0.05 for Landsat images. This error in NDVI is translated into an error of about 20% in LAI. The Landsat images used in this study were acquired at a small solar zenith angle range from 36^{o} to 44^{o}. Therefore no specific attention was given to the solar zenith angle effect. To apply the NDVI-LAI relationship to other geographic areas, some considerations must be given to the dependence of NDVI on solar zenith angle (Hall, et al. 1995). Precautions should also be taken when using this NDVI-LAI relationship for other spaceborne and airborne sensors because the NDVI difference between sensors is often substantial (Spanner, et al. 1994).

The sensitivity to LAI is improved when SR is used instead of NDVI (Figs. 2(a) and (b)). Similar improvements were also found by Running et al (1986). Since SR can be calculated from NDVI without additional information, i.e. SR=(1+NDVI)/(1-NDVI), the correlation between SR and LAI has the same level of statistical significance as that between NDVI and LAI. Because the relationship between SR and NDVI is nonlinear, i.e. the increment in SR per unit increment in NDVI is greater at larger NDVI. the sensitivity to LAI is improved using SR. However, the trade-off is that the error in SR becomes relatively larger than that in NDVI at large NDVI values. Statistically, SR and NDVI makes no significant difference in terms of the accuracy in retrieving LAI. Based on White el al. (1995), the background SR was about 2.3 for jack pine and 3.5 for black spruce in the summer. The difference in SR between the overstory and the background was 4.5-5.5. In this paper, SR is chosen for analysis with other stand attributes.

Figs. 3(a) and 3(b) show the relationships between SR and L_e . These relationships are statistically more significant (larger R^2 values) than those between SR and LAI. Since L_e is calculated directly from gap fraction measurements without additional information, conversely it is a better predictor for the gap fraction, or light interception by the canopies, than LAI. It is therefore expected that SR are better correlated with L_e than with LAI. For the same gap fraction, or L_e, the value of LAI can be quite different, depending on the foliage spatial distribution pattern in the canopy. The effect of the distribution pattern on LAI measurements is quantified using the element clumping index. From Table 1, it can be seen that the element clumping index was not constant even for the same species. Foliage clumping in conifer canopies occurs at several levels: shoots, branches, and tree crowns. Because boreal forests are open, the gaps between tree crowns contribute about 50% to the total canopy gap fraction (Chen 1995), and therefore crown level clumping is often the dominant factor of the total foliage clumping. This level of clumping varied with the canopy openness or the crown closure. Table 1 shows that the element clumping index decreased with decreasing L_e, indicating that a conifer canopy was more clumped when it was more open (less L_e). The element clumping index illustrates that open boreal conifer forests, consisting of isolated trees with needle leaves closely attached to the main stem, are highly clumped. As the stem density or the tree crown size increases, the gaps between tree crowns reduces and the element clumping index increases (less clumped). In closed canopies, the element clumping index approaches unity (a case of random shoot distribution) (Chen and Cilhar 1995a), but foliage clumping within shoots still remains. In this case, the ÿ$_E$ becomes the major factor to convert from L_e to LAI. Since the crown closure varied widely among the stands investigated here, the element clumping index also varied in a wide range. This explains the significant statistical improvement when SR is correlated with L_e rather than LAI. According to our analysis of old and new needles in shoot samples (Chen 1995), LAI of evergreen conifers varied by about 10-30% in the course of a year, while L_e remained virtually unchanged (less than 5%). LAI changed because of new growth in the spring and senescence in the fall, whereas the effective LAI did not change much because the new needles grew on top of the old needles and did not reduce the canopy gap fraction significantly.

In many applications, LAI is used to predict radiation interception absorption by the canopies. It is therefore suggested that L_e rather than LAI be used for this purpose. L_e has several advantages: (1) it can be used to calculate radiation interception without information on foliage clumping; (2) it is better correlated to NDVI and SR; (3) it is less variable than LAI; and (4) it is easy to measure. The LAI-2000 is best used for measuring L_e rather than LAI and is reliable and easy to operate. However, for detailed photosynthesis and rainfall interception considerations, the true LAI is also required. It can be obtained by applying a correction factor to L_e. The major part of the correction factor, the element clumping index, can be obtained from the TRAC based on a gap size distribution theory.

Landsat views the surface in the vertical direction. Therefore, there is a reason to expect that vegetation indices from Landsat are best correlated with the crown closure. However, the correlations between SR and crown closure were not better than those with L_e (the solid line in Figs. 4(a) and 4(b)). This is largely due to the effect of the background because SR became virtually insensitive to changes in crown closure once it was smaller than about 0.2. Since the curve is forced to the zero point, these large SR values at small crown closure incur large errors in the regression. R^2 increases considerably when the four stands enclosed in the square in Figs. 4(a) and 4(b) are excluded from the regression analysis. This means that SR is incapable of determining crown closure when it is smaller than 20% under the condition that the backgroundÿs SR value is not substantially smaller than the overstory foliage. We believe that the regression lines without the four stands seriously affected by the background are more reliable than those from all stands for the estimation of crown closure. To reduce subjective errors caused by the forced curve fitting, linear regression analysis was conducted (not plotted in Fig. 4). The regression results are:

Late spring: SR = 3.046 + 4.348 C (all points, R^2=0.66)

SR = 2.508 + 5.312 C (without 4 points, R^2=0.63)

Mid-summer SR = 4.152 + 6.273 C (all points, R^2=0.44)

Most R^2 values of these linear regressions are larger than those shown in Fig.4 from non-linear regression, suggesting again that a simple linear regression line is more useful for retrieving crown closure information.

Other factors may have also affected the relationships between SR and the crown closure. First, the measurement error in crown closure was larger than that in L_e because crown closure was determined by the gap fraction at one zenith angle whereas L_e was calculated from gap fractions at five zenith angles. The relative error in crown closure is estimated, from the magnitude of variation along transects and the number of measurements, to be 10% at the intensive sites and 25% at the auxiliary sites. Second, vegetation indices are proportional to sunlit green leaves viewed by radiometers (Hall et al. 1995). At a certain solar zenith angle, the amount of sunlit leaves seen in the vertical direction depends not only on the crown closure, but also on the transmittance of the solar beam. The zenith angle distribution pattern of the canopy gap fraction, which determines the solar beam transmission, was variable among stands with different crown closure (Figs. 5(a) and 5(b)). Fig. 5(a) shows the gap fraction distribution for three black spruce stands. The curvature of the distribution varies with crown closure or the overall canopy openness determined from the gap fractions at all angles. The stand T7R9S has the characteristics of planophile foliage angle distribution, whereas the stand T4U9S, and T6T6S to some extent, appears to be erectophile. Fig. 5(b) shows the similar variation in the distribution pattern for jack pine stands. Although the visual appearance of the architecture of individual trees of the same species did not change significantly with stand openness, the distribution pattern of the gap fraction changed. This implies that in conifer canopies, radiation transmission is determined not only by the angle of foliage elements and the structures at higher level, such as tree crowns and branches but also by the spatial distribution of trees. Boreal conifer tree crowns are small with foliage tightly attached to the tree trunk and can be approximated by long vertical cylinders. In denser stands, such as T4U9S, the gaps between these vertical structures were small compared with tree height, and therefore the gap fraction decreased rapidly with view zenith angle. In open stands, such as T7R9S, the spacing between the trees may be larger than or comparable to the tree height, and the gap fraction did not decrease with the view zenith angle significantly until it reached a critical value which depends on the relative dimensions of gap size and tree height. Because of this variation in the gap fraction distribution pattern, the amount of sunlit leaves viewed in one direction may not be exactly proportional to the crown closure, causing some errors in the correlation between SR and the crown closure. The fact that gap fraction distribution pattern changed with crown closure suggests that any radiative transfer models with assumptions on the foliage angle distribution pattern without considering the tree crown structure and the distribution pattern would bear little relevance to boreal conifer forests.

Many satellite sensors, including the Advanced Very High Resolution Radiometer (AVHRR), acquire data at multiple view zenith angles. Vegetation indices derived from off-nadir measurements are expected to correlate better with L_e than with crown closure.

CONCLUSIONS

Our overall conclusion is that vegetation indices obtained from Landsat TM data are useful for determining LAI of boreal forests. However, the useful ranges of the indices are small, and signals must be processed to a high degree of accuracy. The specific conclusions are as follows:

1. Landsat images acquired in late spring, when the understory vegetation in open boreal forests has not fully grown, are more useful for estimating the overstory LAI than summer images in which the contribution of the understory to satellite measurements becomes important. The difference in NDVI between the overstory and the background (understory and moss layer) was in the range from 0.25 to 0.35 in the spring. This becomes the range of NDVI from which to determine the overstory LAI. To retrieve LAI within 20%, NDVI needs to be accurate to at least 0.05.
2. The effective LAI was better correlated to the Simple Ratio (SR) than LAI. Ground truthing data on the effective LAI can be easily obtained from canopy gap fraction measurements using optical instruments, and is the best predictor for radiation interception by plant canopies. It is also less variable with time than LAI. It is therefore suggested that the effective LAI be used as the basic stand parameter for radiation considerations.
3. SR from Landsat in the nadir view direction is also a good predictor of the crown closure larger than 20%. Because of the contribution of the background signals, SR was found to be insensitive to crown closure under 20%. The gap fraction distribution

with the zenith angle varied with the stand openness (or crown closure), indicating that crown closure is not a better predictor than the effective LAI for the intercepted radiation by the canopies.

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List of Figures

Fig. 1. Relationships between NDVI and LAI for boreal conifer forests in (a) late spring and (b) mid-summer. The surface NDVI is calculated from Landsat TM band 3 (red) and band 4 (near infrared) reflectances at the surface level after atmospheric corrections. The LAI is obtained based on optical measurements with considerations for the foliage clumping and the contributions from the supporting woody material.

Fig. 2. Relationships between SR and LAI in (a) late spring and (b) mid-summer. SR is calculated from the surface NDVI shown in Fig. 1.

Fig. 3. Relationships between SR and the effective LAI in (a) late spring and (b) mid-summer. The effective LAI is obtained from canopy gap fraction measurements assuming a random foliage spatial distribution.

Fig. 4. Relationships between SR and the crown closure in (a) late spring and (b) mid-summer. The solid lines are obtained using all data points, while the dotted lines exclude the 4 data points enclosed in the square or rectangle. The crown closure equals one minus gap fraction in the vertical direction.

Fig. 5. Gap fraction angular distribution patterns for (a) black spruce stands and (b) jack pine stands. Table 1. Summary of field data for late spring (IFC-1). The first six are the intensive sites and the rest are the auxiliary sites. The last letter of the site name is either “S” for black spruce or “P” for jack pine. Spring Landsat data were not available for BMMS-1, BMMS-2 and BMMS-3.

Stand	L_e	ÿE	ÿE	1-ÿ	LAI	crown closure	basal area (m2 /ha	stand density (stems /ha.)
NOJP	1.40	0.82	1.38	0.72	1.70	0.43	12	1800
NOBS	2.31	0.71	1.36	0.84	3.71	0.53	18	4500
NYJP	1.09	0.95	1.35	0.97	1.50	0.30	20	30000
SOJP	1.54	0.71	1.28	0.68	1.89	0.31	29	2000
SOBS	2.04	0.70	1.41	0.84	3.34	0.42	20	3000
SYJP	1.31	0.71	1.43	0.97	2.56	0.43	9	4000
T6R5S	2.95	0.93	1.4	0.84	3.73	0.82	29	7900
T7R9S	0.57	0.73	1.4	0.84	0.92	0.04	6	7500
T8Q9P	1.12	0.87	1.35	0.7	1.22	0.42	14	1600
F7J0P	2.7	0.92	1.35	0.7	2.77	0.55	34	2100
F7J1P	2.32	0.93	1.35	0.7	2.35	0.62	28	1150
G2I4S	3.44	0.97	1.4	0.84	4.17	0.71	36	12500
G9I4S	3.00	0.93	1.4	0.84	3.79	0.71	--	--
T6T6S	0.95	0.75	1.4	0.84	1.48	0.16	6	5600
T8S4S	0.71	0.73	1.4	0.84	1.14	0.08	--	--
T8T1P	0.89	0.75	1.35	0.7	1.12	0.24	--	15000
BMMS-1	1.1	0.75	1.4	0.9	1.84	0.37	--	--
BMMS-2	2.72	0.92	1.4	0.84	3.73	0.48	--	--
BMMS-3	2.8	0.91	1.4	0.84	3.48	0.49	--	--
G1K9P	1.89	0.82	1.35	0.7	2.18	0.40	20	700
T9Q8P	1.44	0.67	1.35	0.7	2.03	0.2	--	300
T7T3S	1.62	0.75	1.4	0.84	2.52	0.09	9	7600