ALGORITHMS FOR RETRIEVING LAI AND FPAR OF BOREAL CONIFER FORESTS USING LANDSAT TM IMAGES

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ABSTRACT

Algorithms have been developed for calculating leaf area index (LAI) and the fraction of photosynthetically-active radiation (FPAR) absorbed by boreal forests using satellite-measured vegetation indices. This study is part of the Boreal Ecosystem-Atmosphere Study (BOREAS). In the summer of 1994, ground-based measurements of LAI and FPAR were made in more than 30 forest stands near Candle Lake and Prince Albert, Saskatchewan and near Thompson, Manitoba. The measurements were made using optical instruments including the Plant Canopy Analyzer (PCA, LI-COR LAI-2000) and the TRAC (Tracing Radiation and Architecture of Canopies). The TRAC was recently developed by us to quantify the effect of canopy architecture on optical measurements of leaf area index and to obtain average PAR transmitted through the forest canopies. The stands with the ground-truth data were located on georeferenced Landsat TM images using global positioning system (GPS) measurements. Algorithms for LAI and FPAR are based on the correlation of the ground-based measurements with vegetation indices calculated using Landsat TM data. It is found that late spring Landsat images are superior to summer images for determining overstory LAI and FPAR in boreal conifer stands because the effect of the understory is minimized at that time.

INTRODUCTION

Leaf area index (LAI), defined as half the total leaf area per unit ground surface area (Chen and Black 1992), is an important parameter controlling many biological and physical processes associated with vegetation on the earth's surface. FPAR is used to convert the incident photosynthetically active radiation (PAR) into absorbed PAR by vegetation (APAR). Both LAI and FPAR are required inputs to many climate and ecological models. Remote sensing provides a unique way to obtain the distributions of these biophysical parameters over large areas. In several US studies, satellite-borne vegetation indices (VI) were correlated with LAI in conifer stands (Badhwar et al. 1986, Spanner et al. 1990a, 1990b and 1994). In these studies, the uncertainties in the relationships between VI and LAI were large due to the complexity of radiation environment in forest stands and errors in ground-based measurements. In this paper, similar relationships for both LAI and daily green FPAR were established for Canadian boreal forests based on improved ground measurement techniques.

THEORY

Leaf Area Index

Optically-based methods were used to measure LAI of conifer forests. The methods are described in detail by Chen and Cihlar (1995 a & b) and Chen (1995). The formula for calculating LAI, denoted by L, is as follows:
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 (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 obtained from laboratory analysis on shoot samples. It was calculated as the ratio of half the total needle area in a shoot to the area of an imaginary shoot surface enveloping the shoot. The imaginary surface area of a shoot was obtained from multi-angle projections of the shoot. ÿ$_E$ was measured using a sunfleck-LAI instrument named TRAC (Tracing Radiation and Architecture of Canopies) recently developed by us based on a new canopy gap size analysis theory (Chen and Cihlar 1995a). ÿ was obtained from destructive sampling (see Ground-Based Measurements for detail).

Daily Green FPAR

The instantaneous FPAR, denoted by F(ÿ) at the solar zenith angle ÿ, for a plant canopy is defined as follows:

where R_0 is the incident PAR above the canopy, R_{r0} is the reflected PAR above the canopy,
R_t is the transmitted PAR through the canopy to the ground surface, and R_{ru} is the reflected
PAR from the forest floor. R_0 and R_{r0} were measured on towers above the forest stands, and
R_t and R_{ru} were measured in the stands using the TRAC. In this paper, only the overstory is considered in the FPAR calculation, and both R_t and R_{ru} were measured above the understory (herbaceous and shrubs) when present.

The following equation is used to calculate daily green FPAR, denoted by F_g

where ÿ$_{min}$ is the minimum solar zenith angle at the solar noon as a function of latitude and the date, and F_g(ÿ) is the instantaneous green FPAR calculated from F(ÿ) with the contribution of woody material removed according to measured woody-to-total area ratio. This formula performs a cos(ÿ) weighting scheme for FPAR acquired at different times during the course of the day. FPAR is the smallest at solar noon and increases with solar zenith angle because of the increase in the path-length of the solar beam through the canopy. Since the solar irradiance on a horizontal surface varies closely with cos(ÿ), it becomes necessary to use the weighting scheme for the calculation of daily FPAR. In this way, the daily FPAR can be used to convert the daily incident PAR to daily APAR.

GROUND-BASED MEASUREMENTS

LAI and FPAR were measured using optical instruments, the PCA and the TRAC, near Candle Lake in Saskatchewan and Thompson in Manitoba as part of BOREAS. The PCA was used to measure L_e in 6 conifer tower flux sites and 25 auxiliary sites. The measurements were made at about 90 locations along three 300 m parallel transects at the tower flux sites and at 11 locations along two 50 m perpendicular transects at the auxiliary sites. The TRAC measurements were also made on the same transects. The TRAC consists of three quantum sensors (LI-COR, Lincoln, NE, Model LI-190SB, 10 ÿs time constant), a data logger (Campbell Scientific, Logan, UT, Model CR10) and a storage Module (Model SM716). Two of the sensors face upwards to measure the downwelling total and diffuse PAR, and one faces downward to measure 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 per three seconds, a sampling interval of 10 mm for each sensor could be achieved. These closely-spaced measurements along long transects can be used to derive the canopy architectural parameters and the element clumping index. This type of measurements is also crucial for obtaining good spatial averages of the transmitted and reflected PAR beneath the canopy. The woody-to-total area ratio was measured in two mature jack pine stands (SOJP near Candle Lake and NOJP near Thompson) and one black spruce stand (SOBS near Candle Lake). In each stand, three or four trees of different height classes were felled and the foliage and branch areas measured (Chen 1995). The geographic locations of the stands were determined using a dual-receiver global positioning system (Trimble Pathfinder) with an absolute accuracy of ±10 m.

SATELLITE IMAGE PROCESSING

NDVI data presented in this paper were obtained from four Landsat TM scenes: 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). The images were provided in a systematically georeferenced format. Over 20 ground control points were used 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. NDVI values at the surface were calculated from the reflectances in bands 3 and 4 after atmospheric corrections using a 5S software package (Teillet and Santer, 1991).

RESULTS AND DISCUSSION

The ground-based measurements in the 31 stands can be summarised as follows: L_e ranged from 0.7 to 3.5, $\ddot{y}_E$ from 1.38 to 1.68, and $\ddot{y}_E$ from 0.70 to 0.98. Values of ÿ were 0.14, 0.28 and 0.32 for SOBS, NOJP and SOJP, respectively. L_e and $\ddot{y}_E$ were measured in all stands, but $\ddot{y}_E$ and ÿ in only 6 and 3 stands, respectively, because they are conservative for the same species of the same age. LAI of all the stands was calculated with these measurements using Eq. 1.

Figs. 1(a) and 1(b) show the relationships between NDVI and LAI for late spring (June) and mid-summer (August), respectively. The regression line was forced through zero and the results were

Late spring: $NDVI = 0.5463\ L^{0.1870}$ (R^2=0.51)

Mid-summer: $NDVI = 0.6552\ L^{0.1168}$ (R^2=0.38)

The sensitivity of NDVI to LAI is larger in late spring than in mid-summer and the regression is also better (higher R^2 value) in late spring. This is because the measured LAI values included only the overstory foliage while the NDVI responds to both the overstory and understory. In the summer, when the understory is abundant, the contribution from the understory increases. The increase is larger for stands with smaller LAI which provide better light environment for the understory growth, resulting in the decrease in sensitivity from spring to summer. The regression results thus suggest that spring images are more useful for estimating the overstory LAI for forest stands.

Figs. 2(a) and 2(b) show similar results for daily green FPAR, F_g. The regression results are:

Late spring: $NDVI = 0.7695\ F_g^{0.3342}$ (R^2=0.62)

Mid-summer: $NDVI = 0.8021\ F_g^{0.1875}$ (R^2=0.38)

Again, the late spring result shows better sensitivity and correlation than the summer result for the same reasons as mentioned above for LAI. In comparison between the LAI and FPAR results, it is interesting to note that in late spring, the regression for daily green FPAR is better than that for LAI, and that the sensitivity of NDVI to daily green FPAR is also better than that to LAI. The comparison reveals that NDVI gives better estimates for FPAR than for LAI. This is because for the same amount of radiation intercepted by the canopy, the foliage area of the canopy can be different, depending on the architecture of the canopy. If a canopy is more clumped, it will intercept less PAR with the same LAI. Since NDVI is largely proportional to the sunlit leaf area, it is expected to be better correlated to FPAR than to LAI. The results suggest that for the purpose of estimating radiation absorbed by plant canopies, it is better to use direct relationships between vegetation indices and FPAR, and it is unadvisable to estimate LAI first and then calculate FPAR from LAI.

CONCLUSIONS

1. NDVI values from Landsat TM images are more highly correlated with daily green FPAR than with LAI, suggesting that reflected solar radiances from boreal conifer forests respond more to the sunlit leaf area than to the total leaf area.

2. 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 and FPAR than summer images in which the contribution of the understory to satellite observations becomes important.

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Fig. 1. Relationships between leaf area index (LAI) and NDVI at the surface level in (a) late spring (June) and (b) mid-summer (August) for boreal conifers. The LAI was measured using optical instruments assisted with shoot sample analysis. The surface NDVI values were obtained from Landsat TM images after atmospheric corrections.

Fig. 2. Relationship between daily green FPAR and the surface NDVI in (a) late spring (June) and (b) mid-summer (August) for boreal conifers.