Mapping leaf area index heterogeneity over Canada using directional reflectance and anisotropy canopy reflectance models.

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***Abstract*-Leaf area index (LAI) retrieval from remote sensing is a very active research field. In heterogeneous canopies, simulations with the canopy reflectance model Five-Scale show that nadir view vegetation indices, such as NDVI and Simple Ratio (SR), based on near infrared and red reflectance are more closely related to the gap fraction at the solar zenith angle than the LAI. The gap fraction is important in canopy light interception. At the solar zenith angle, it can be used to estimate the amount of sunlit LAI. But the knowledge of LAI and foliage heterogeneity are both needed to estimate shaded leaves that are also important in the carbon cycle. In our previous studies, we developed a methodology to retrieve the foliage heterogeneity, represented by a clumping index, from remote sensing. The retrieval is accomplished with an anisotropy index using broadband directional reflectance at the hotspot and at the darkspot. The combination of nadir, hotspot, and darkspot views allows the LAI retrieval for a given cover type. However, directional measurements are not usually acquired with the same sun-target-sensor geometry, so the anisotropy kernel-based Four-scale Linear model for AnIsotropy Reflectance (FLAIR) is used to interpolate the directional reflectance from ADEOS-POLDER data to acquire hotspot and darkspot reflectance at a common geometry in the near infrared band. A landcover map at 1-km based on SPOT-VGT data acquired in 1998 and directional POLDER data acquired over Canada in June 1997, are used to map the clumping index. The results show consistent clumping index values compared to *in-situ* values, and that SR and the anisotropy index are not correlated to each other, indicating that both indices are related to different canopy properties.**

I. INTRODUCTION

The retrieval of biophysical parameters from remote sensing data is an ongoing activity that has shown great potential. One important parameter that has been retrieved and validated is the leaf area index (LAI) [1]. LAI defines the area that interacts with solar radiation and is responsible for carbon absorption and exchange with the atmosphere. In the retrieval of LAI from nadir view imagery, the spatial distribution of the foliage is not considered. The production of maps that describe how the foliage is distributed within a pixel is important in carbon exchange models that need separation of shaded and sunlit leaves. A clumping index [2] has been used to describe the deviation of foliage distribution from the random distribution in the canopy gap fraction calculated with Beer's law at a view zenith angle θ:

$$P(\theta) = e^{-G(\theta)\Omega(\theta)L/\cos\theta}, \qquad (1)$$

where $G(\theta)$ is the projection of unit leaf area in direction θ; L is the LAI; and $\Omega(\theta)$ is the clumping index:

$$\Omega(\theta) = \frac{\ln[P(\theta)]}{\ln[P_R(\theta)]}, \qquad (2)$$

where $P_R(\theta)$ is the gap fraction of a random canopy with no clumping (i.e. (1) with $\Omega(\theta)=1$).

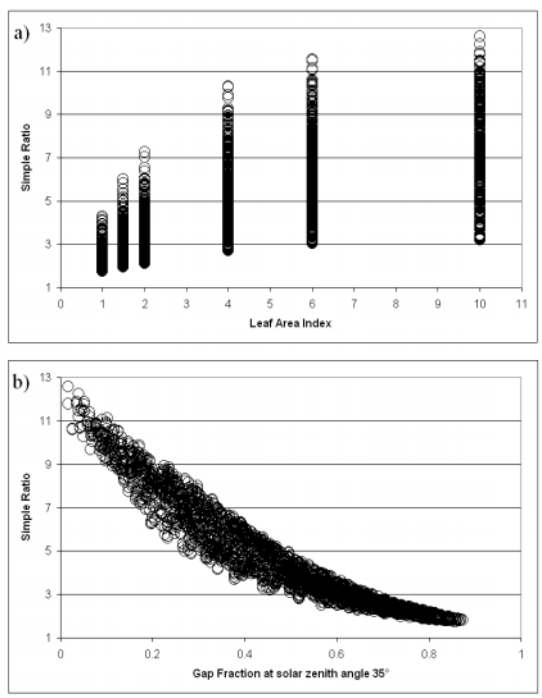

Fig. 1. a) Nadir SR versus LAI simulated with Five-Scale, b) Nadir SR versus gap fraction at the solar zenith angle (35°). The simulations are for a density of 2500 stems/ha over a wide range of crown dimension, with shoot and flat leaves as foliage element. The optical properties were fixed.

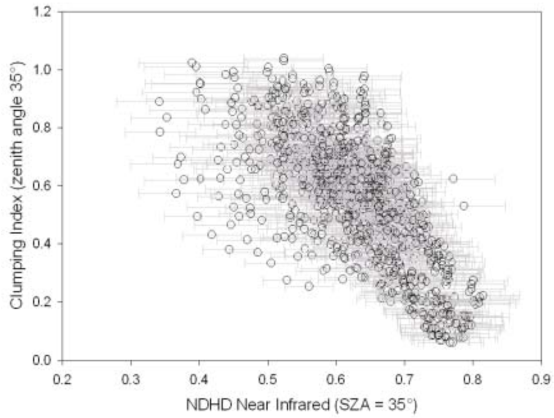

Fig. 2. Simulation of clumping Index versus the NDHD at the solar zenith angle of 35°. The horizontal lines represent the standard deviation of 32 optical property sets.

II. SIMULATIONS

The radiative transfer model Five-Scale [3][4] is used in this study to simulate reflectances based on different canopy structures. Five-Scale is well suited for studying foliage heterogeneity since it was develop to consider the interaction of solar radiation with foliage by considering many levels of foliage clumping: 1) foliage clumped in crowns; 2) non-random distribution of crowns; 3) foliage clumped in branches; and 4) foliage clumped in shoots for conifers.

A) *Nadir view reflectance*

Generally, LAI retrieval is done from nadir (or nadir-normalized) reflectance in two or more bands. Fig. 1a shows the Simple Ratio (SR) of the near infrared and red bands of many simulated conifer canopies using Five-Scale. The optical properties and stem density were kept constant and the LAI was varied while allowing different crown sizes, shoots or flat leaves foliage, and crown distributions (Poisson and Neyman [3]). The variation of the input parameters may be larger than what is found in real forests. Nevertheless, the test indicates that although the LAI increases with SR (see Fig. 1a), many SR values exist for a given LAI. Fig. 1b shows that nadir SR is strongly related to the gap fraction at the solar zenith angle. A weaker relationship was found with gap fraction from nadir view. This suggests that the LAI retrieved from nadir view is the equivalent of the so-called effective LAI at the solar zenith angle. Although good relationships have been found between nadir SR and field LAI measurements (e.g. [1][7]), it was shown in [7] that SR was more correlated to the crown closure (zenith gap fraction) and the effective LAI than the LAI.

B) *Directional reflectance*

The bidirectional reflectance distribution function (BRDF) of vegetated surfaces has maximum and minimum values referred as hotspot and darkspot, respectively [6]. The hotspot is found at the viewing geometry where sun and view angles coincide, and the darkspot is found on the forward scattering view geometry where shadows are predominant. Our previous study [5] showed that the Normalized Difference Hotspot DarkSpot Difference:

$$NDHD = \frac{\rho_H - \rho_D}{\rho_H + \rho_D}, \qquad (3)$$

where ρ_H and ρ_D are the reflectances at the hotspot and darkspot, respectively, was more linearly related to the clumping index than other anisotropy indices such as the ratio of hotspot to darkspot reflectance [6].

Five-Scale was used to simulate the hotspot and darkspot of thousands of canopies with LAI ranging from 1 to 10. An average was done over 32 sets of optical properties for the anisotropy index. Fig. 2 shows an example of NDHD clumping index relationship. As a comparison, the simulated hotspot reflectance had a mean relative Standard Deviation (S.D) of 45% while the NDHD only shows a 7% relative mean S.D. This makes the NDHD relatively independent of the optical properties of the canopy and understory. The NDHD values, based on ADEOS-POLDER acquired in June 1997, have similar values for conifer and deciduous cover types, although they generally have different clumping indices. Different foliage element (leaves for deciduous and shoots for conifers) phase functions seem responsible for the difference NDHD relationships with clumping. Improvement of the phase functions used by Five-Scale has yielded two relationships for the clumping index retrieval. The following linear mixing relationship is used to retrieve the clumping index:

$$\Omega = X \cdot A_N + A_B(1-X) - \left[X \cdot B_N + (1-X)B_B\right] \cdot NDHD \qquad (4)$$

where X is the percentage of conifer within the pixel and the A and B's are values found from fitting the clumping index to the NDHD from Five-Scale simulations.

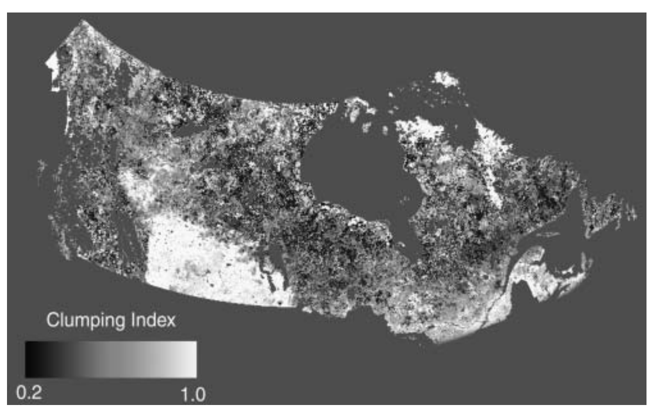

Fig. 3. Map of clumping index at zenith angle of 35° based on POLDER data taken over Canada from June 15-30, 1997.

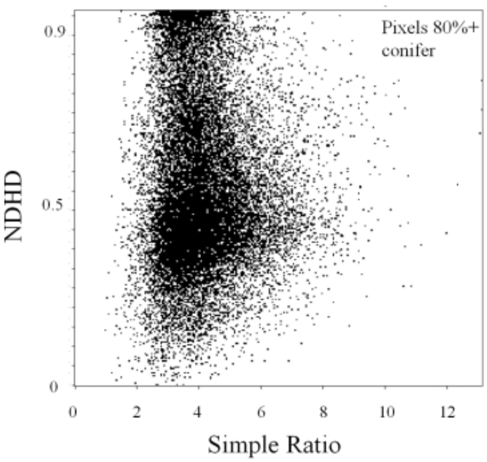

Fig. 4. NDHD for solar zenith angle of 35° versus nadir Simple Ratio, both extracted with the FLAIR model from POLDER data taken over Canada from June 15-30, 1997. Only the pixels with proportion of 80% and more conifers based on a SPOT-VGT landcover map are displayed.

The NDHD was compared with Five-Scale input parameters and it was found that the NDHD is strongly correlated ($R^2 > 0.9$) to the relative difference in sunlit foliage seen at the hotspot and darkspot. The understory seems to have a very small effect on the NDHD based on the Five-Scale simulations.

III. APPLICATION

Directional POLDER data (latitude 45-65°) taken over Canada in June 1997 are used to map the clumping index. Since the nadir footprint of the POLDER data is about 6×7 km, a 1-km resolution landcover map of Canada based on 1998 SPOT-VGT data is used to assess the percentage of conifer cover in 7x7 km areas centred at the POLDER pixel location. All view angles from the POLDER pixels from June 15 to 30 are used. Because the POLDER data are acquired at different view and sun geometries, the Four-Scale Linear Model for AnIsotropic Reflectance (FLAIR) [8] is used to extract the hotspot, darkspot and nadir view of each pixel. FLAIR is a linear kernel-like model developed from the Four-Scale Model [4]. The Powell method was used to retrieve FLAIR parameters. By using FLAIR, the hotspot and darkspot reflectances can be obtained at a common solar zenith angle. Only the near infrared band (865 nm) is used based on previous studies [5][6] that showed better results with both simulated and measured values. Using (4) with the retrieved NDHD, a map of clumping index at 35° from zenith is produced (see Fig. 3). Fig.4 shows that there is no relationships between the retrieved NDHD and the nadir SR, implying that they may contain different information. Retrieved clumping index analysis segmented by cover type from VGT showed that for FLAIR fit with large R^2, the clumping index follows more closely a normal distribution centred at a reasonable mean for both coniferous and non-coniferous cover types. Extreme low clumping index values (less than 0.2) are mainly from pixels that the FLAIR model had low R^2 (less than 0.5).

IV. DISCUSSION-CONCLUSIONS

The Five-Scale simulations showed that 1) vegetation indices such as SR or NDVI are more related to the gap fraction at solar zenith angle than to LAI. 2) The anisotropy index NDHD, based on the hotspot and darkspot reflectance, is related to the clumping index; and 3) the NDHD is related to the proportional difference of sunlit foliage viewed by sensor at the hotspot and darkspot. The data analysis showed that SR and NDHD have different information content. Our results suggest that the gap fraction estimated from SR combined with the NDHD could be used to retrieve more accurate LAI.

It must be noted that the simulation sets were done without any a priori knowledge of the canopies and without any relationships that may or may not exist between gap fraction and clumping index. As more field measurements become available and the effects of correlations among input parameters are better understood, it is anticipated that the relationship between clumping and anisotropy indices will be improved.

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