Use of Multiple Scattering Fraction to Estimate Leaf Area Index of Grass Canopies

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Abstract - Multiple scattering intensity is mainly determined by the total area of scatterers and their scattering coefficients. In a vegetation canopy, it is more directly correlated to leaf area index (LAI) than to other structure parameters. In this study, multiple scattering fraction (MSF) of the total canopy reflectance is used as an index to derive LAI. The method is evaluated by both field measurement data and BRDF model simulations. Results in this study show that, compared to NDVI, MSF is less influenced by other factors such as spatial heterogeneity of canopy structure, sun and view geometries, and soil background brightness, and is not saturated with increasing LAI as quickly as NDVI does. Therefore, MSF is a good replacement for NDVI for LAI estimation, especially for cases when LAI is high.

BACKGROUND

Quantitative assessment of vegetation properties through remote sensing technology has been a long-term goal of remote sensing of vegetation. Efforts having been made toward this goal in the past decades include use of vegetation indices (VIs), spectral mixture analysis, BRDF (bidirectional reflectance distribution function) model inversion, and LUT (lookup-table) techniques. The most common VI method is the normalized difference vegetation index (NDVI) which is extensively used to assess leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (fAPAR). However, its performance is significantly affected by other factors including background brightness, BRDF effect (i.e., sun and view angle dependent) and spatial heterogeneity of vegetation structure [1]. Recent studies have revealed that NDVI is much more sensitive to changes in sunlit vegetation fraction than to LAI and is controlled by sunlit scene components, while LAI is almost linearly proportionally related to shaded foliage fraction [2]. But the relationship between LAI and shaded foliage fraction is still subject to BRDF effect. Since reflected radiation from shaded vegetation component is generated entirely through multiple scattering, the mean value (or hemispherical average) of multiple scattering reflectance over different view directions seems to be a good replacement for shaded foliage fraction for LAI estimation. In this study, we propose to use multiple scattering fraction (MSF), a ratio between reflectance by multiple scattering and the total reflectance in the near-infrared region (NIR) as an index to estimate LAI. The mean value of MSF is determined by the total area of scatterers (which is identical to LAI, or effective LAI for heterogeneous vegetation canopies) and their scattering coefficients (reflectivity + transmittance), no matter how the scatterers are distributed in space. Multiple scattering reflectance is much less angular dependent compared to first order scattering reflectance, and its angular dependence can be further minimized by taking the angular average or hemispherical integration from all available angles and dividing the result by the total reflectance of the canopy. The purpose of this study is to investigate the feasibility of deriving LAI from MSF using both field measurements and model simulations. Then the impact of other optical and structural factors on this method is simulated and the results will be analyzed in the following sections.

METHODOLOGY

A strategy to use both field measurements and a BRDF model is adopted in this study since MSF cannot be obtained without a canopy BRDF model that can separate between first order scattering reflectance and multiple scattering reflectance. The field measurements used here are from the FIFE (first ISLSCP field experiment) dataset for Konza prairie grass and include measured LAI, LAD (leaf angle distribution), optical properties of leaf and the soil background, and canopy reflectance at different view angles. Specifically, spectral reflectance in red (675nm) and NIR (750nm) acquired with two SE590 spectroradiometers in the solar principal plane (PP) with a sensor field-of-view of 15° under relatively clear-sky conditions are used. These two SE590s were operated on two different goniometer systems by two teams (GSFC – Goddard Space Flight Center, NASA, and UNL – University of Nebraska-Lincoln) at different sites with LAI ranging from 0.6 to 2.1, and sun zenith angles (SZAs) between 26° and 60°. The details about instrumentation and measurements are described in [3-5].

An analytical BRDF model [6] is applied here to accurately calculate single scattering reflectance from both foliage elements (leaf + stem) and the soil background. The reason for choosing this specific BRDF model is because (1) the sensor’s FOV is explicitly included when calculating reflectance; (2) it can account for nonleaf foliage components such as stem, branch, etc.; (3) non-random dispersion of foliage elements is allowed for by incorporating a Markov clumping model [7]; (4) the hot spot effect is rigorously incorporated by considering foliage shape, size and orientation; (5) it is totally analytical and runs very fast,
and can explicitly separate the reflectance by single scattering from foliage and the soil, and that by multiple scattering from both. In addition, the module for soil reflectance component is modified to use either direct measurements of soil bidirectional reflectance for a given SZA or a soil BRDF model [8, 9] if field measurements are not available. However, multiple scattering reflectance components are only approximately and analytically estimated.

Thus, we estimate the multiple scattering reflectance by subtracting the corresponding single scattering reflectance calculated with the BRDF model from the measured canopy reflectance. Since the analytical BRDF model is able to produce more accurate estimation of first order scattering reflectance than multiple scattering reflectance, the subtraction should be a good estimate of multiple scattering reflectance. Due to the narrow range of LAI (0.6-2.1) in the measurements, we add simulation data with LAI up to 7.0 to investigate the method. To achieve this goal, we first examine the performance of the BRDF model by comparing modeled results against measured reflectance data for a given set of input parameters (including LAI, LAD, ratio of leaf size to canopy height, and optical properties of leaf and soil). Generally speaking, the modeled reflectances match the measured data pretty well for all cases of LAI and most of SZAs. Fig.1 shows a sample of comparison with UNL SE590 measured data acquired under four SZAs in the two bands at LAI of 1.7. The good agreement is achieved, especially at low view zenith angles (VZAs) under low SZAs or at high VZAs on the backscattering side, by taking into account the non-random spatial dispersion feature of leaves and stems and by introducing a small fraction of stem (less than 10% of the total LAI). Although there were no direct measurements on stem fraction or foliage clumpness, from the photos taken in the field one can see that there is a fraction of stem at the lower part of the canopy, and leaves are clustered so that large gaps exist between grasses. Also, in the afternoon as the soil was drying out, some water stress was developed which caused leaf rolling, resulting in a reduction of the effective LAI in the afternoon. That increased (decreased) the measured reflectance in red (NIR) at low SZAs in the afternoon, because a higher portion of soil background is visible and soil reflectance is usually higher (lower) than leaf reflectance in red (NIR).

Although grass canopies are generally considered to be homogeneous, our results indicate that the Konza tallgrass canopy is a non-random canopy with leaves clumped together, producing large gaps between grass clumps. Also, the role of stems cannot be ignored even when the stem area is only a fraction (<10%) of leaf area.

Fig. 1 demonstrates the ability of the analytical model to reproduce the measured reflectance data. Now we are in a position to simulate canopy reflectance and its single and multiple scattering components for a variety of LAIs of the canopy. We vary LAI from 0.5 to 7.0 with an interval of 1.0. In order to examine the influence of other factors, such as soil brightness, LAD and non-random dispersion of foliage, on the relationship between multiple scattering fraction and LAI, we change these parameters for the canopy with the same LAI. Specifically, we increase soil single scattering albedo by 0.1 to simulate a bright soil background; consider two more LADs: spherical and planophile; and change the clumping index to simulate regular and clumping canopies. The full range of solar zenith angle is covered by considering four SZAs: 60°, 45°, 33° and 28°. The view zenith angles (VZAs) vary within ±60° with an interval of 10° in the principal plane ("." stands for the forward scattering directions). The simulation results for all the scenarios are presented and analyzed below.

RESULTS AND ANALYSIS

Fig.2 plots the mean MSF for all SZAs against LAI, with the error bar indicating the standard deviation (STDEV) from the mean value. For comparison purposes, the results for NDVI are also shown in the figure. It is obvious that in such a narrow range of LAI, MSF almost linearly increases with LAI. While NDVI also performs well because LAI is less than 2.1, its STDEV (2.6%-4.0%) is larger than that of MSF (1.2%-2.4%).

To examine the performance of MSF over a wider range of LAI (0.5 to 7.0) and to consider the impact of other factors such as canopy structure, background brightness and sun and view angles, etc., a simulation and sensitivity analysis are conducted with the analytical BRDF model [6]. The modeling results illustrate that taking the average over all the scenarios described in the preceding section can effectively reduce the influence of all the factors mentioned above. And the mean value of MSF is quite stable, with very small STDEVs (<3.8%). Although an increase of soil brightness does increase the multiple scattering reflectance, MSF is hardly affected because it is a ratio to the total reflectance. From Fig.3, the advantage of MSF over NDVI is obvious as the saturation point of MSF is much higher than that of NDVI (which is near 3.0), even though both indices change nonlinearly with LAI. Thus, MSF can detect changes in LAI even at large LAIs (up to 7.0), while NDVI is limited to LAIs below 3.0. Even with LAIs below 3.0, its STDEV is much higher (2.2% - 6.6%) than that of MSF (which is within 3.8%). This implies that NDVI is more susceptible than MSF to other factors such as LAD, foliage spatial dispersion pattern, sun and view angles etc. Therefore, MSF should be more useful for extracting LAI from remote sensing data.

CONCLUSIONS

In this study, the multiple scattering fraction (MSF) is proposed to derive LAI. Both field measurement data at FIFE sites and BRDF model simulations have proven that MSF is more directly and strongly related to LAI than NDVI, and does not saturate as quickly as NDVI. Further, MSF is less affected than
NDVI by other factors, such as LAD, soil brightness, canopy structure and sun and view angles. However, since MSF cannot be obtained without using a canopy BRDF model that can separate first order scattering contribution and multiple scattering contribution from the total reflectance, the best way to use this method to infer LAI is to combine BRDF model inversion with measured spectral data.

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