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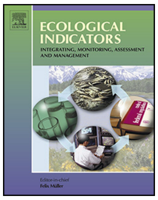

Developing and validating novel hyperspectral indices for leaf area index estimation: Effect of canopy vertical heterogeneity

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ABSTRACT

Leaf area index (LAI) is one of the key biophysical parameters for understanding land surface photosynthesis, transpiration, and energy balance processes. Estimation of LAI from remote sensing data has been a premier method for a large scale in recent years. Recent studies have revealed that the within-canopy vertical variations in LAI and biochemical properties greatly affect canopy reflectance and significantly complicate the retrieval of LAI inversely from reflectance based vegetation indices, which has yet been explicitly addressed. In this study, we have used both simulated datasets (dataset I with constant vertical profiles of LAI and biochemical properties, dataset II with varied vertical profile of LAI but constant vertical biochemical properties, and dataset III with both varied vertical profiles) generated from the multiple-layer canopy radiative transfer model (MRTM) and a ground-measured dataset to identify robust spectral indices that are insensitive to such within canopy vertical variations for LAI prediction. The results clearly indicated that published indices such as normalized difference vegetation index (NDVI) had obvious discrepancies when applied to canopies with different vertical variations, while the new indices identified in this study performed much better. The best index for estimating canopy LAI under various conditions was *D*(920,1080), with overall RMSEs of 0.62–0.96 m^2/m^2 and biases of 0.42–0.55 m^2/m^2 for all three simulated datasets and an RMSE of 1.22 m^2/m^2 with the field-measured dataset, although it was not the most conservative one among all new indices identified. This index responded mostly to the quantity of LAI but was insensitive to within-canopy variations, allowing it to aid the retrieval LAI from remote sensing data without prior information of within-canopy vertical variations of LAI and biochemical properties.

1. Introduction

Leaf area index (LAI) is a critical parameter for understanding biological and physical processes associated with vegetation, and a premier-required input in ecosystem productivity models (Bonan, 1993; Colombo et al., 2003; Liu et al., 1997). Generally, it is defined as one half of the total surface leaf area of the vegetation per unit area of soil (background) surfaces (Chen and Black, 1992). In situ measurements of LAI can be time-consuming, expensive and often unfeasible, which leads to the striking possibility of using remote sensing data to estimate LAI (Wang et al., 2005).

Recent developments in hyperspectral remote sensing and imaging spectrometry fields have allowed new ways to quickly estimate vegetation LAI. A common approach of estimating LAI from remote sensing data has relied on vegetation indices based on the relationship between field-measured LAI and spectral reflectance. As a result, a large number of vegetation indices have been established (Haboudane et al., 2004), e.g. the Normalized Difference Vegetation Index (NDVI, Thenkabail et al., 2000), Ratio Vegetation Index (RVI, Stenberg et al., 2004), Modified Simple Ratio (MSR, Chen, 1996), Modified Chlorophyll Absorption Ratio Index (MCARI, Haboudane et al., 2004), Triangular Vegetation Index (TVI, Broge and Leblanc, 2000), Modified TVI (MTVI, Haboudane et al., 2004), Modified Soil-Adjusted Vegetation Index (MSAVI, Qi et al., 1994), and D_{LAI} (le Maire et al., 2008). These indices can be easily parameterized and are known to be precise in certain studies. However, they all have apparent shortcomings since their calibration depends on particular experimental datasets. Whatever the index, its success depends preliminarily on the quality of the training dataset, the selection of the wavelengths and the number of independent datasets available for validation (le Maire et al., 2008). Various factors, such as atmospheric quality, vegetation types, leaf biochemical properties, understory vegetation, and background soil reflectance, will all affect canopy scale reflectance, thus blur the generality and significance of the vegetation indices' relationships with LAI, making it difficult to apply them generally to large areas. Among them, some factors have already been demonstrated in

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numerous studies (e.g. Broge and Leblanc, 2000; Chen and Cihlar, 1996; Colombo et al., 2003; Gitelson et al., 2005), while others have yet to be addressed and studied sufficiently. These unaddressed factors include vertical variations of LAI and biochemical properties within the canopy, which significantly impacted the canopy scale reflectance as revealed in a recent study (Wang and Li, 2013).

The main reason for the lack of studies on the effects of vertical variations of LAI and biochemical properties within the canopy is due to the scarce availability of field measurements, as well as a lack of radiative transfer modeling that deals with such within canopy variations. Recently, a multiple-layer canopy reflectance model (MRTM) was developed to embrace such within canopy variations of biophysical and biochemical properties (Wang and Li, 2013). Based on this model, the vertical variations of LAI and leaf biochemical properties have been clearly demonstrated to greatly affect canopy scale reflectance, e.g. canopy reflectance changed greatly with the same amount of total LAI but under different vertical distributions, which was also true with other biochemical components (e.g. leaf chlorophyll, equivalent water thickness, and leaf mass per area). Therefore, in this study we will challenge the effect of within canopy vertical variations of LAI and biochemical components on their effectiveness, robustness and estimating accuracy of LAI with various vegetation indices.

The current study was based on three simulated datasets generated from the multiple-layer canopy reflectance model (MRTM), as well as one field-measured dataset. In this study, simulated datasets were used to identify potential robust indices for LAI, which were then validated against the field-measured dataset containing the seasonal change of LAI in four sites of a typical cold-temperate mountainous landscape in Japan. Such an approach of using simulated datasets from radiative transfer models is a popular and advanced way of allocating effective and general vegetation indices developed in recent years (le Maire et al., 2004, 2008; Wang and Li, 2012). Since the variation effect in biophysical and biochemical properties on canopy reflectance are explicitly through canopy reflectance models (Asner, 1998), such an approach has many advantages: Most canopy properties can be represented in detail (via thousands of spectra); the influence of a specific property can be decoupled from others; and the effect of a particular property on the spectra is based on physical and physiological processes. As a result, well established indices obtained through such a large simulated database may potentially be applied to a wide range of spectra. However, it is worth noting that the accuracy of the approach relies on the capacity of applied radiative models to correctly simulate canopy reflectance under various conditions. Thus, it is essential to validate such indices with experimental measurements.

The objective of the present study is to develop a potentially general and robust vegetation index that is insensitive to within canopy vertical variations of LAI and biochemical components used to estimate LAI. We described the multiple-layer canopy radiative transfer model (MRTM) simply at first for generating simulated datasets as well as experimental protocols for field measurements. The spectral indices from precious studies were then validated, along with a proposal to design a method and determine new types of indices. Those newly identified indices were then validated with simulated and measured datasets.

2. Material and methods

2.1. Simulated datasets

Three simulated datasets were generated via the multiple-layer model MRTM using the 5 vertical-layer mode, as previous studies revealed that 5-layer mode can cover large LAI for accurate reflectance simulation (Wang and Li, 2013). A detailed description of this model can be referred to Wang and Li (2013). Among the three datasets, dataset I was generated with the model when both LAI and biochemical properties distributions were treated identically along the vertical canopy profile, while dataset II was generated from simulations with various LAI vertical profiles but with constant vertical distribution of biochemical properties along the canopy. For comparison, dataset III was generated considering the vertical changes of LAI and biochemical properties along the canopy. Parameter settings for generating these datasets are presented in Table 1, where reflected spectra were simulated for every combination of these parameters within the input ranges. To ensure that representative results were obtained, a uniform distribution was set for each varying parameter so that a reflectance spectrum obtained with extreme parameter values had the same weight as other spectra on the indices' calibration procedure. However, some parameters have been treated as constants (see Table 1 legend). In order to reproduce the observed radiometric noise of real measured reflectance in the simulations, a random noise was added to each spectrum of both databases (leaf and canopy). This step was important for eliminating noise sensitive indices and indices with artificially close wavelengths (le Maire et al., 2004). An additive random Gaussian noise with a standard deviation of 3% of the reflectance amplitude was applied on all wavelengths of each reflectance spectrum of the simulated datasets in this study.

2.2. Field-measured dataset

The field measured dataset was compiled from synchronous measurements of leaf biophysical and biochemical parameters, as well as leaf and canopy reflectance data at Naeba Mountain (36°51′N, 138°40′E), a typical cold-temperate, mountainous landscape in Japan. Beech (*Fagus crenata*) is the dominant species in this region and is widely distributed along altitudes from 550 to 1500 m on the northern slope of the mountain. In four typical stands (the 550 m, 900 m (X1), 900 m (X5), and 1500 m sites) at 550, 900 and 1500 m a.s.l., representing the lower-, mid- and upper-limits, respectively, of the *F. crenata* ecosystems, four towers served as platforms for meteorological sensors and canopy access (canopy reflectance and LAI vertical variation). The upper-canopy at each elevation consisted mainly of *F. crenata* with sporadic occurrence of other species such as *Quercus mongolica* Fisch. ex Ledeb. var. *grosseserrata* (Blume) Rehder & E.H. Wilson, *Magnolia obovata* Thunb. and *Acanthopanax sciadophylloides* at the 550 and 900 m sites, and *Betula grossa* Siebold & Zucc. and *Betula ermanii* Cham. at the 1500-m site. The mean tree heights (and diameter at breast height, DBH) were 34 m (37 cm), 31 m (18 cm), 32 m (19 cm) and 22 m (17 cm) for the 550 m, 900 m (X1), 900 m (X5), and 1500 m sites, respectively. Detailed descriptions of the Naeba Site can be referred to Wang et al. (2008a, b). It is also an important site in the SpecNet (Gamon et al., 2006). The field-measured dataset was acquired during the 2009 growing season at the 550 m, 900 m (X1), 900 m (X5), and 1500 m sites.

Both leaf and canopy properties, e.g., contents of various pigments, leaf water, leaf dry matter, leaf thickness, leaf angle, leaf size and leaf area index, and leaf and canopy reflectance were simultaneously measured. Canopy directional–hemispherical reflectance spectra were measured by a field spectroradiometer (ASD FR, USA) covering wavelengths from 400 to 2500 nm. It has been attached with a 5° field of view and set perpendicularly over the canopy to ensure both view nadir angle and view azimuth angle were 0°, while sun zenith angle was calculated by the measuring time (Wang and Li, 2013). Leaf area index (LAI) during the growing season was estimated through litter trap method (Wang et al., 2008b; Kojima et al., 2009). The LAI vertical variation within the canopy was obtained in situ similar to Iio et al. (2011). The sampling