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Estimating light absorption by chlorophyll, leaf and canopy in a deciduous broadleaf forest using MODIS data and a radiative transfer model

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Abstract

In this paper, we present a theoretical and modeling framework to estimate the fractions of photosynthetically active radiation (PAR) absorbed by vegetation canopy ($FAPAR_{canopy}$), leaf ($FAPAR_{leaf}$), and chlorophyll ($FAPAR_{chl}$), respectively. $FAPAR_{canopy}$ is an important biophysical variable and has been used to estimate gross and net primary production. However, only PAR absorbed by chlorophyll is used for photosynthesis, and therefore there is a need to quantify $FAPAR_{chl}$. We modified and coupled a leaf radiative transfer model (PROSPECT) and a canopy radiative transfer model (SAIL-2), and incorporated a Markov Chain Monte Carlo (MCMC) method (the Metropolis algorithm) for model inversion, which provides probability distributions of the retrieved variables. Our two-step procedure is: (1) to retrieve biophysical and biochemical variables using coupled PROSPECT + SAIL-2 model (PROSAIL-2), combined with multiple daily images (five spectral bands) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor; and (2) to calculate $FAPAR_{canopy}$, $FAPAR_{leaf}$ and $FAPAR_{chl}$ with the estimated model variables from the first step. We evaluated our approach for a temperate forest area in the Northeastern US, using MODIS data from 2001 to 2003. The inverted PROSAIL-2 fit the observed MODIS reflectance data well for the five MODIS spectral bands. The estimated leaf area index (LAI) values are within the range of field measured data. Significant differences between $FAPAR_{canopy}$ and $FAPAR_{chl}$ are found for this test case. Our study demonstrates the potential for using a model such as PROSAIL-2, combined with an inverse approach, for quantifying $FAPAR_{chl}$, $FAPAR_{leaf}$, $FAPAR_{canopy}$, biophysical variables, and biochemical variables for deciduous broadleaf forests at leaf- and canopy-levels over time.

Keywords: MODIS; PROSPECT; SAIL-2; FAPAR; Markov Chain Monte Carlo (MCMC) method

1. Introduction

Gross primary production (GPP) is a key terrestrial ecophysiological process that links atmospheric composition and vegetation processes. One of the most important of these processes, plant photosynthesis, requires solar radiation in the 0.4–0.7 μm range (also known as photosynthetically active radiation or PAR), water, carbon dioxide (CO_2), and nutrients. The fraction of PAR absorbed by the vegetation canopy ($FAPAR_{canopy}$) is therefore an important biophysical variable and is widely used in satellite-based Production Efficiency Models (Potter et al., 1993; Prince & Goward, 1995; Ruimy et al., 1996; Running et al., 2004) to estimate GPP or net primary production (NPP). In remote sensing studies, $FAPAR_{canopy}$ is usually estimated as a linear or non-linear function of Normalized Difference Vegetation Index (NDVI) (Prince & Goward, 1995; Tucker, 1979). $FAPAR_{canopy}$ is also related to leaf area index (LAI), and is estimated as a function of LAI and a light extinction coefficient in a number of process-based biogeochemical models (Ruimy et al., 1999). The LAI-$FAPAR_{canopy}$ and NDVI-$FAPAR_{canopy}$ relationships have been the dominant paradigm in the literature for estimating GPP and NPP of terrestrial vegetation at various spatial scales (Field et al., 1995; Running et al., 2004).

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A vegetation canopy is composed primarily of photosynthetically active vegetation (PAV) and non-photosynthetic vegetation (NPV; e.g., senescent foliage, branches and stems). The presence of NPV has a significant effect on $FAPAR_{canopy}$. For example, in forests with an LAI less than 3.0, an earlier study (Asner et al., 1998) found that stems increased canopy FAPAR by 10–40%. There is then, in principal, a need to partition $FAPAR_{canopy}$ into the fractions of PAR absorbed by green leaves and by NPV.

Furthermore, it is important to note that a green leaf is composed of chlorophyll and various proportions of non-photosynthetic components (e.g., other pigments in the leaf, primary/secondary/tertiary veins, and cell walls). Non-photosynthetic absorption in PAR wavelengths can vary in magnitude (e.g., 20–50%) among different species, leaf morphology, leaf age and growth history (Hanan et al., 1998, 2002; Lambers et al., 1998). We argue that $FAPAR_{canopy}$ should be partitioned into the fractions of PAR absorbed by chlorophyll ($FAPAR_{chl}$) and by NPV ($FAPAR_{NPV}$, including all the non-chlorophyll pigments in leaf, cell walls, veins, branches and stems).

Only the PAR absorbed by chlorophyll (a product of $FAPAR_{chl} \times PAR$) is used for photosynthesis. Therefore, remote sensing driven biogeochemical models that use $FAPAR_{chl}$ in estimating GPP are more likely to be consistent with plant photosynthesis processes (Xiao et al., 2004a,b). It is important to understand to what extent $FAPAR_{canopy}$ can be partitioned into $FAPAR_{chl}$ and $FAPAR_{NPV}$ given imperfect models and data. In an earlier study (Depury & Farquhar, 1997), a process-based leaf photosynthesis model estimated PAR effectively absorbed by PSII system per unit leaf area. However, the partitioning issue has not been studied extensively in both remote sensing and ecological communities that focus on large scales.

Quantifying the temporal evolution of $FAPAR_{chl}$ for a forest ecosystem represents an important challenge for remote sensing and ecology researchers, as it is extremely difficult to directly measure $FAPAR_{chl}$ and $FAPAR_{NPV}$ at the leaf and canopy levels on large scales over plant growing seasons. To our knowledge, no field and laboratory experiments to measure $FAPAR_{chl}$ at the leaf and canopy levels over plant growing seasons have been reported, and similarly we found no published efforts to calculate $FAPAR_{chl}$ with physics-based radiative transfer models.

In this study, we aim to develop a theoretical and technical framework for quantifying and evaluating the fractions of PAR absorbed by chlorophyll, leaf and canopy. The specific objectives of this study are twofold: (1) to clarify the concepts of $FAPAR_{chl}$, $FAPAR_{leaf}$ and $FAPAR_{canopy}$; (2) to explore the potential of estimating $FAPAR_{canopy}$, $FAPAR_{leaf}$ and $FAPAR_{chl}$, using a coupled leaf-canopy radiative transfer model with multiple daily images from the MODerate resolution Imaging Spectroradiometer (MODIS) onboard NASA Terra satellite. We used a coupled leaf-canopy radiative transfer model (PROSPECT model + SAIL-2 model) to calculate $FAPAR_{chl}$, $FAPAR_{canopy}$ and $FAPAR_{leaf}$. These models have been discussed extensively in the published literature, both separately and in combination (Bacour et al., 2002; Baret & Fourty, 1997; Braswell et al., 1996; Combal et al., 2002; Di Bella et al., 2004; Gond et al., 1999; Jacquemoud & Baret, 1990; Jacquemoud et al., 1996, 2000; Kuusk, 1985; Verhoef, 1984, 1985; Verhoef & Bach, 2003; Weiss et al., 2000; Zarco-Tejada et al., 2003). As a case study, we selected a deciduous broadleaf forest at the Harvard Forest in Massachusetts, USA, where earlier studies reported field-based observations of leaf chlorophyll content (Waring et al., 1995) and LAI (Cohen et al., 2003; Xiao et al., 2004b). This radiative transfer based modeling exercise will help us to address an important scaling issue—light absorption from chlorophyll to leaf and to canopy. Our analysis also provides guidance for designing and conducting field measurement and observations of forest canopies in the near future.

2. Description of the radiative transfer model and the inversion algorithm

2.1. Brief description of the PROSPECT + SAIL-2 model

The PROSPECT model is a leaf radiative transfer model. Previous studies used the PROSPECT model with four variables—leaf internal structure variable (N), leaf chlorophyll content (C_{ab}), leaf dry matter content (C_m), and leaf water thickness (C_w) (Demarez et al., 1999; Hosgood et al., 1995; Jacquemoud & Baret, 1990; Newnham & Burt, 2001). A number of other studies used the PROSPECT model with five variables—leaf internal structure variable (N), leaf chlorophyll content (C_{ab}), leaf dry matter content (C_m), leaf water thickness (C_w) and leaf brown pigment (C_{brown}) (Baret & Fourty, 1997; Di Bella et al., 2004; Verhoef & Bach, 2003). We used the five-variable PROSPECT model in this study because the addition of brown pigment is useful for discriminating between photosynthetic and non-photosynthetic light absorption.

The SAIL (Scattering from Arbitrarily Inclined Leaves) model is a canopy radiative transfer model. The SAIL model has been developed by several earlier researchers, evolving gradually over time with minor changes reflecting individual study objectives (e.g., Andrieu et al., 1997; Badhwar et al., 1985; Braswell et al., 1996; Goel & Deering, 1985; Goel & Thompson, 1984; Jacquemoud et al., 2000; Kuusk, 1985; Major et al., 1992; Verhoef, 1984, 1985). In this study we used the version of SAIL presented by Braswell et al. (SAIL-2; Braswell et al., 1996). The SAIL-2 model decomposes a vegetation canopy into stems and leaves. In a typical parameterization, stems have spectral properties that are more similar to soil and litter than leaves. Leaf and stem mean inclination angles and the self-shading effect of both leaves and stems are also considered.

In this study, we coupled the modified PROSPECT model with the SAIL-2 model (hereafter called PROSAIL-2) by replacing the leaf reflectance component in the SAIL-2 model with the five-variable PROSPECT model. The coupled PROSAIL-2 model was used to describe optical characteristics (reflectance, absorption and transmittance) of the canopy and its components. The PROSAIL-2 model has three groups of variables: (1) observation viewing geometry variables; (2) an