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Leaf area index estimation with MODIS reflectance time series and model inversion during full rotations of *Eucalyptus* plantations

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A B S T R A C T

The leaf area index (LAI) of fast-growing *Eucalyptus* plantations is highly dynamic both seasonally and inter-annually, and is spatially variable depending on pedo-climatic conditions. LAI is very important in determining the carbon and water balance of a stand, but is difficult to measure during a complete stand rotation and at large scales. Remote-sensing methods allowing the retrieval of LAI time series with accuracy and precision are therefore necessary. Here, we tested two methods for LAI estimation from MODIS 250m resolution red and near-infrared (NIR) reflectance time series. The first method involved the inversion of a coupled model of leaf reflectance and transmittance (PROSPECT4), soil reflectance (SOILSPECT) and canopy radiative transfer (4SAIL2). Model parameters other than the LAI were either fixed to measured constant values, or allowed to vary seasonally and/or with stand age according to trends observed in field measurements. The LAI was assumed to vary throughout the rotation following a series of alternately increasing and decreasing sigmoid curves. The parameters of each sigmoid curve that allowed the best fit of simulated canopy reflectance to MODIS red and NIR reflectance data were obtained by minimization techniques. The second method was based on a linear relationship between the LAI and values of the GEneralized Soil Adjusted Vegetation Index (GESAVI), which was calibrated using destructive LAI measurements made at two seasons, on *Eucalyptus* stands of different ages and productivity levels. The ability of each approach to reproduce field-measured LAI values was assessed, and uncertainty on results and parameter sensitivities were examined. Both methods offered a good fit between measured and estimated LAI ($R^2 = 0.80$ and $R^2 = 0.62$ for model inversion and GESAVI-based methods, respectively), but the GESAVI-based method overestimated the LAI at young ages.

1. Introduction

Leaf area index (LAI) is a key parameter involved in a variety of ecosystem processes, such as light and rain interception, transpiration, photosynthesis, plant respiration, and soil heterotrophic respiration (through litter fall). Its precise temporal and spatial estimation is crucial for the understanding of forest processes and for the parameterization of ecosystem models that quantify carbon, water, and energy fluxes.

Field estimations of LAI are often performed using optical (LICOR LAI-2000, hemispherical photographs), direct and semi-direct methods (litter collection, allometric methods, and destructive sampling). Routine in-situ measurements of LAI are, however, time-consuming and even unfeasible for large scale studies. For this reason, numerous studies have attempted to characterize LAI with remotely sensed data (North, 2002; Rouse et al., 1973). The reflectance deduced from satellite measurements contains information on canopy structural and biochemical characteristics. In particular, reflectance in the visible and near-infrared wavelengths is highly sensitive to green LAI, thus offering the challenging opportunity of quantifying LAI using reflectance values. Two types of methods have classically been used for this purpose:

– *Spectral Vegetation Indices and/or multiple regressions*: mathematical combinations of well-chosen spectral band reflectances are designed to correlate with particular characteristics of the observed surface. These methods are simple, but their use is limited to the representativeness of the experimental calibration

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dataset. Moreover, indices and multiple regressions may be sensitive to more than a single characteristic. They are also more or less sensitive to vegetation type, atmospheric conditions, viewing geometry, spatial resolution, and therefore they must generally be calibrated for each image (Thenkabail et al., 2000; Turner et al., 1999; Walthall et al., 2004).
– *Inversion of Radiative Transfer Models (RTM)* that simulate reflectance spectra from canopy and soil characteristics. Existing RTM belong to a range of types (simple turbid-medium, geometrical models, hybrid models, and discrete or ray-tracing models), each offering a different representation of the spatial heterogeneity of a scene.

Inversion techniques are based on minimization algorithms, or on pre-computed reflectance databases using either Look-Up Tables (Knyazikhin et al., 1998) or Neural Networks (Bacour et al., 2006; Baret et al., 2007; Fang & Liang, 2005). The inversion of such reflectance models often gives a large number of different possible solutions and therefore needs to be constrained. Moreover, uncertainties on measurements and models may result in a large variability in the results (Combal et al., 2003).

These two methods have their advantages and drawbacks, and the choice of a method highly depends on the characteristics of the vegetation and on the objective of the study.

In this study, we focus on the particular case of *Eucalyptus* plantations. *Eucalyptus* trees, which are the most widely planted hardwood genus in tropical regions (FAO, 2006), provide an increasing share of the global wood supply. The fast-growing *Eucalyptus* plantations of São Paulo State (Brazil) have a rotation length of typically 5 to 7 years (Laclau et al., 2010). Large structural changes of the canopy occur during this time: the rapid growth from seedlings to high trees (up to >25 m) is accompanied by changes in LAI, crown cover, leaf angles, specific leaf area (SLA), etc. (Laclau et al., 2009, 2010; Marsden et al., 2010). Plantations also experience seasonal changes mainly because of the dry season when trees are water limited (Almeida et al., 2007). The LAI of *Eucalyptus* plantations largely determines plantation carbon and water cycles (du Toit, 2008; Marsden et al., 2010), and hence wood production and water consumption. The retrieval of LAI time series is therefore an important objective both for plantation managers (who are now increasingly using process-based models to monitor and predict production), and for scientists interested in biogeochemical modeling to address carbon sequestration, water use and sustainability issues. The methods currently available involve a great deal of field and interpretation work (regular visits of inventory plots with some optical device to measure gap fractions), and are therefore unsatisfactory regarding time- and cost-effectiveness, but also accuracy and spatial representation. LAI estimation using remote sensing is therefore highly relevant but also challenging for this ecosystem, because the canopy experiences strong structural changes with time.

The main objective of this study was to develop reliable approaches for the monitoring of green LAI *over complete rotations* of eucalypt plantations. For this purpose, we used a RTM, which has the advantage of taking into account changes in canopy structure and biochemistry with time. An original aspect of our methodology was the inversion procedure, which was constrained using a series of sigmoid curves to describe the time course of LAI. We compared these results with a simpler methodology based on vegetation indices. The specific objectives were therefore to (i) invert a RTM to estimate the LAI on one to seven years of MODIS reflectance time series of several stands, (ii) validate these LAI estimations with field measurements, (iii) compare the applicability and the performance of the RTM inversion approach with those of a simple vegetation index method, and (iv) analyse the uncertainty of both methods, and gain insight into the variables that are important for LAI estimations by means of a sensitivity analysis.

Section 2 gives an overview of the “biological” and radiometric data that were used, Section 3 describes the RTM, the inversion methodology, the vegetation index calibration and the uncertainty and sensitivity analysis procedure, and Section 4 presents the results. Section 5 discusses the objectives presented above in the light of the results, and offers some perspectives for future studies.

2. Data

2.1. Study site and stand selection

Eucalyptus plantations occupied approximately 4.3 million ha in Brazil in 2008 (ABRAF, 2009). In typical plantation management, soil is prepared with mechanical disking and harrowing a few months after each clear-cut harvest. New cuttings or seedlings are planted in rows at a density of ~1300 trees ha^{-1} and fertilized, and chemical weeding is carried out during the first year of growth. Harvesting occurs about six to seven years after planting, and foliage and branches are left on the ground. Leaf area index changes with stand age, with a maximum value generally attained during the second or third year. During the dry season, water stress causes a more or less marked seasonal decrease of LAI (up to ~50%), depending on soil water holding capacity and the age of the plantation.

Sixteen *Eucalyptus* stands belonging to the International Paper of Brazil Company, and two additional stands managed by the Duratex Company, were selected for our study in São Paulo State, southeastern Brazil (Table 1).

The first 16 stands were planted with company-improved clones of *E. grandis* (W. Hill ex Maiden) * *E. urophylla* (S.T. Blake) hybrids and managed on six or seven-year rotations. The chosen stands were of different ages (aged 1 to 5 years) and productivity levels (30 to 53 m^3 commercial wood ha^{-1} yr^{-1}), but were genetically similar (commercial clone H13 and two stands of the closely-related clone H18) and exhibited very homogeneous canopies. They were larger than 30 ha and of compact shape. Eight stands were located close to the town of Brotas (28.22°S, 48.15°W, 647 m altitude), on relatively unfertile sandy soils (~90% sand, 8% clay, and 2% silt). The remaining stands were about 125 km east of Brotas in the vicinity of Mogi Guaçu (22.35°S, 46.97°W, 591 m altitude), on more fertile soils with a higher percentage of clay (~62% sand, 32% clay, and 6% silt).

The two Duratex stands were planted with *E. grandis* seedlings of a common controlled origin, and were 7 years old at the time of measurement. They presented contrasted productivity levels, as one stand (IT1) was planted on soil that was more fertile and clayey than that of the other (IT2) (see Table 1). These stands were part of the EucFlux Project experimental site close to Itatinga (22.97°S, 48.72°W, 740 m altitude).

The climate in the three zones is very similar, displaying a mean annual rainfall of ~1200 mm between 2000 and 2008 (ranging from 1044 mm in 2003 to 1345 mm in 2002). More than 80% of precipitation occurs during the wet season between October and April. Mean monthly air temperatures range from about 17 °C to 25 °C with an annual mean of 20 °C during the nine year period.

2.2. Destructive measurements of leaf biomass, LAI, and SLA

Three permanent inventory plots (400 m^2 each) were chosen in nine stands. The diameter at breast height (DBH, at 1.3 m above ground level) of each tree of the inventory plot was measured. These measurements were conducted 1) in order to ensure that trees for destructive measurements (chosen outside the permanent inventory plot) were sampled across the range of tree sizes, and 2) to enable upscaling of tree leaf area and other characteristics to the plot level with empirical models based on DBH (Fig. 1). Destructive sampling was carried out at two dates in 2008, on 7 stands during the wet season, close to the seasonal peak of LAI, and on 9 stands at the end of the dry season, when LAI was low. Four additional measurements were made at IT1 and IT2 stands in the 2007 and 2008 dry seasons and 2008 and 2009 wet seasons