Calibration of a vegetation index to monitor *Eucalyptus* plantation leaf area index with MODIS reflectance time-series

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Abstract. Leaf area index (LAI) of *Eucalyptus* plantations is an important variable, linked to different biophysical processes: carbon assimilation, water consumption, litter production, etc. *Eucalyptus* LAI is highly variable in time throughout the stand rotation. After planting, LAI increases rapidly to reach a maximum value at the age of about 2 years. Then LAI fluctuates seasonally, with a small decrease with stand age, till the clear-cut which occurs at age 6-7. In addition to these variations with time, differences in space may arise from local soil and meteorological conditions. In this study, we propose a method to retrieve spatial and temporal values of *Eucalyptus* stand LAI during entire rotations based on Moderate Resolution Imaging Spectroradiometer (MODIS) near-infrared and red reflectance time-series. This work capitalizes on a recently published methodology based on radiative transfer model (RTM) inversion, which achieved good LAI retrieval results (r^2=0.80, RMSE= 0.41) but was computationally intensive. We propose here to use the radiative transfer model results to calibrate a dedicated *Eucalyptus* plantation vegetation index which would give a similar result to RTM inversion, but in a simpler way. This vegetation index takes the form of a soil adjusted vegetation index. When using only red and NIR reflectance, r^2 is 0.68 and RMSE is 0.49 on an independent validation dataset of destructive LAI measurements. The additional use of stand age and day of year increases the performance of the index (r^2=0.75 and RMSE=0.43). This simple index opens the way to the operational retrieval of *Eucalyptus* LAI from MODIS data.

Keywords: remote sensing; eucalypt; MOD13Q1; radiative transfer model; PROSAIL

1. Introduction

Short rotation tropical plantations of fast-growing *Eucalyptus* trees are expanding rapidly and have provided an increasing share of the global wood supply in the last decades. In south-eastern Brazil these plantations are a particularly dynamic tree crop, with rapid growth and large structural changes occurring within a rotation length of just 5 to 7 years (Laclau *et al.* 2010). Their leaf area index (LAI) is a critical variable both for scientists interested in carbon and water balance and sustainability issues, and for plantation managers wishing to gain insight into plantation productivity. It is also highly variable in time and space, and difficult and time-consuming to measure with the currently available destructive or optical field methods. The development of a method allowing the simple retrieval of LAI time series from freely available satellite data is therefore of considerable interest.

A recent study by le Maire et al. (in press) has shown that it is possible to retrieve the LAI of *Eucalyptus* stands by inverting a well calibrated radiative transfer model (RTM), which explicitly takes into account stand structural characteristics (specific leaf area, LID, crown cover, etc.). This method is however difficult to apply, as it initially requires detailed field data and is computationally intensive. RTM inversion performed better than a simpler LAI retrieval method based on a soil adjusted index, the GESAVI (Gilabert *et al.* 2002), which nevertheless showed promising results. The reader is referred to le Maire et al. (in press) for a complete description of the method and results, but a brief description of the principal aspects relevant to the present study has been included in this paper.

The objective of the present study is to take advantage of the calibrated RTM model to create a new – and simple – vegetation index dedicated to be used on *Eucalyptus* plantations. This species-specific index can be complemented by information on stand age and period of the year which may improve the accuracy of the retrieved LAI. This index is tested on an independent dataset of destructive LAI measurements.

2. Methodology

2.1 Study site and stand selection

The 18 commercial stands (16 belonging to International Paper do Brasil, 2 to Duratex) selected for this study are located in São Paulo State, south-eastern Brazil (Table 1 of le Maire et al. in press), and managed on six to seven-year rotations. They are all larger than 30 ha and of compact shape. The International Paper stands are genetically similar (*E. grandis* (W. Hill ex Maiden) **E. urophylla* (S.T. Blake) hybrids from two closely-related commercial clones), but present contrasted productivity levels (30 to 53 m^3 commercial wood ha^{-1} yr^{-1}) and ages (1 to 5 years). The two 6 to 7 year old Duratex stands, planted with *E. grandis* seedlings, are part of the EucFlux Project experimental site close to Itatinga, and also present contrasted productivity levels due to higher soil clay contents on stand IT1 than on stand IT2.
Annual rainfall in the studied zone ranged from 1044 mm to 1345 mm between 2000 and 2008, with more than 80% of precipitations occurring during the wet season (October to April). Mean annual temperature was 20°C with a monthly low of ~17°C and high of ~25°C.

2.2 Destructive measurements of LAI

Destructive LAI measurements were carried out at two dates in 2008, on 9 stands during the wet season, close to the seasonal peak of LAI, and on 11 stands when LAI was low at the end of the dry season. On the IT1 and IT2 stands LAI was also measured in the 2007 dry season and the 2009 wet season. The methodology is described in Nouvellon et al. (2010) and le Maire et al. (in press), and involved felling 6 to 10 trees of different sizes per stand for the measurement of total tree leaf biomass and specific leaf area, to establish the stand- and season-specific relationships between diameter at breast height (DBH, at 1.3 m above ground level) and tree leaf area. These relationships were then applied to DBH data measured on three permanent inventory plots (400 m^2 each) per stand to obtain stand LAI. Note that such a procedure is considered as the reference method allowing robust LAI estimations in regular tree plantations (Gower *et al.* 1999, Macfarlane *et al.* 2007), but it is time- and labour-intensive.

2.2 Stand-scale MODIS reflectance time series

We used the MODIS/Terra MOD13Q1 products (Vegetation Indices 16-Day L3 Global 250m, Collection 5), which also contain 16-day red and near-infrared reflectances and sun and view angles. We extracted the reflectance time-series of the 18 MODIS pixels selected to represent each stand (cf. le Maire et al. (in press) for details on the pixel selection procedure). The extracted data covered the period from early 2000 to March 2009. An additional filtering step was applied to the “16-day best value” data, by excluding data that did not have good NDVI quality or pixel reliability flags, and by correcting the time-series for remaining outliers like in Soudani et al. {, 2008 #1158}.

2.3 LAI retrieval using radiative transfer model inversion

Previous work (le Maire et al. (in press)) described a method to retrieve the LAI of *Eucalyptus* plantations through the mathematical inversion of the PROSAIL radiative transfer model. This RTM simulates canopy reflectance by coupling the PROSPECT4 (Feret *et al.* 2008), SOILSPECT (Jacquemoud *et al.* 1992), and 4SAIL2 (Verhoef and Bach 2007) models which represent the optical properties of leaves, soils and the canopy, respectively. The PROSAIL model had to be constrained for most of its parameters to be able to invert the LAI: i.e. all model parameters were forced to carefully-chosen values, except the LAI which was the “free” adjusting variable. The inverted LAI was the LAI that gave the best fit of simulated versus measured red and NIR reflectances. The other parameters were either forced to a constant value or were a function of stand age or location, or were linkend to the sun and view geometry of the measurements. These parameters were measured on the sites described above.

2.3 LAI retrieval using a vegetation index

Vegetation indices are combinations of reflectances in different spectral bands. Their calculation is very easy, and is based only on the measured reflectance, without information on satellite and sun geometries, or other surface properties. In the present study, we focus on vegetation indices that are known to be correlated with LAI, and using only the red and NIR bands (i.e. the only 2 bands available in MODIS 250 m resolution data). We can mention the simple ratio SR (Jordan 1969), normalized difference vegetation index NDVI (Rouse *et al.* 1973), soil adjusted vegetation index SAVI (Huete 1988), transformed TSAVI (Baret and Guyot 1991), modified MSAVI, weighted difference vegetation index WDVI (Clevers and Verhoef 1993), optimized OSAVI (Rondeaux *et al.* 1996), and generalized GESAVI (Gilabert *et al.* 2002). All these indices can be written in the synthetic form :

$$VI = \frac{aNIR + bRED + c}{dNIR + eRED + f} \qquad \text{(Eq.1)}$$

with NIR and RED being the reflectance in near infrared and red, respectively, and [*a, b, c, d, e, f*] being parameters. For instance, these parameters take the values [1, -1, 0, 1, 1, 0] for the NDVI. The study of le Maire et al. (in press) showed that the GESAVI index calibrated for our *Eucalyptus* stands (using information about post-harvest soil reflectance and leaf area index at 2 seasons), had the vector [1, -1.505, -0.034, 0, 1, 0.0383].

These indices can be calibrated by finding the parameter vector which gives the best correlation with measured LAI values, but a large amount of data is necessary to represent different ages, soil conditions, viewing geometry, etc. (le Maire *et al.* 2008). It is also possible to calibrate indices on a simulated database, which has the advantage of taking into account a large range of conditions (le Maire *et al.* 2008, le Maire *et al.* 2004). However, the creation of the simulated database on which the index is calibrated can be difficult, because the distribution of variables should represent (i) the range that is observed in reality and (ii) the correlation between the parameters that are observed in reality. To overcome these possible issues, we used here the database of the 18 stand reflectance time series together with the parameters used in PROSAIL simulations, including the inverted LAI values. There are 2620 pairs of measured MODIS reflectance together with the inverted LAI. This database encompasses many real measurement configurations, stand properties, age, and soil conditions, which satisfy the points (i) and (ii) mentioned above. The calibration of the 6 parameters of Eq. 1 was carried out on this database with a Powell algorithm (Press *et al.* 1996), with the NDVI parameters as the initial parameter state, by minimizing the squared difference between VI and LAI. The obtained VI is called EucVI since it is specific to *Eucalyptus* plantations. Since the EucVI is calibrated on LAI, its value is directly in units of LAI. It means that a linear correlation between LAI and EucVI is preferred, although studies have shown that most of the time the relationships are non-linear. However, the use of non-linear relationships results in more parameters to adjust and did not improve the results, which are therefore not presented here.

2.3 Corrections for age and period of the year

In the RTM inversion methodology, age and seasons are indirectly taken into account through the prescribed variations of the forced parameters (SLA, LID, crown cover). It is therefore logical that age and season can be used to correct the VI adjustments. This was done through a simple residual analysis of the calibrated EucVI and LAI scatterplot. The residuals were first plotted as a function of age, and a third order polynomial was fitted. This polynomial was used to correct the general trend of the residuals with age. The new residuals were then plotted as a function of day of year (DoY), and another third order polynomial fit was used. The two successive corrections of the EucVI led to a new index named $EucVI_{corr}$.

2.4 Smoothing and comparison with LAI destructive measurements

NIR and RED reflectances used for the calculation of EucVI and $EucVI_{corr}$ were not smoothed, and therefore neither were these VIs. EucVI and $EucVI_{corr}$ time-series were therefore smoothed in a second step, for three main reasons: i) smoothing is consistent with the gradual production and shedding of leaves ii) it enables the interpolation of the results at daily time-steps and iii) it allows to compare the results with the LAI destructive measurements at a given date. The spline function avoids artificial variations of estimated LAI due to residual atmospheric effects, view angle and noise in the reflectance data. Once smoothed, the VIs were compared to destructive field measurements of LAI on the subset of nine stands, and r-square (R^2) and root mean squared error (RMSE) were calculated. Values of R^2 and RMSE obtained with the inversion method, GESAVI, EucVI and $EucVI_{corr}$ were compared.

3. Results and discussion

3.1 New vegetation index calibration

The calibration of Equation 1 in the synthetic PROSAIL database gave the parameters [4.95, -9.32, 0.005, 0.46, 6.97, 0.0911] for EucVI. Figure 1a shows the calibrated EucVI as a function of LAI. Note that in this figure, LAI is the LAI obtained from PROSAIL inversion, and EucVI is not smoothed. The correlation between EucVI and inverted LAI is high, with an R^2 of 0.87 and a RMSE of 0.48. This result shows that it is very difficult with a single vegetation index, even well calibrated, to retrieve the LAI obtained from RTM inversion. Indeed, many other variables influence the results in the inversion process, like the satellite view angles, the sun angle, etc.

The use of age and DoY to correct the VI slightly improves the results: the R^2 reaches 0.90 while the RMSE decreases to 0.42 (Figure 1, right). These two variables are easy to obtain at large scales from forest inventories (or from visual examination of NDVI time series) and reflectance acquisition date. The final equation of EucVIcorr is therefore:

$$EucVI_{corr} = EucVI - (0.0207\mathrm{AGE}^3 - 0.1786\mathrm{AGE}^2 + 0.3215\mathrm{AGE})...$$
$$- (-1.2\times10^{-7}\mathrm{DOY}^3 + 5.6\times10^{-5}\mathrm{DOY}^2 - 0.0054\mathrm{DOY}) + 0.0298 \qquad \text{Equation 2.}$$

with AGE in years and DoY in days. The correction for age and DoY is comprised between -0.45 and +0.6 LAI units, which is rather low and leaves a large scatter in Figure 1b. Other empirical corrections for the different view and sun angles or for site specificities (soils) could have been added, but the aim of this study was to remain as simple as possible for the practical use of remote sensing for LAI estimation.

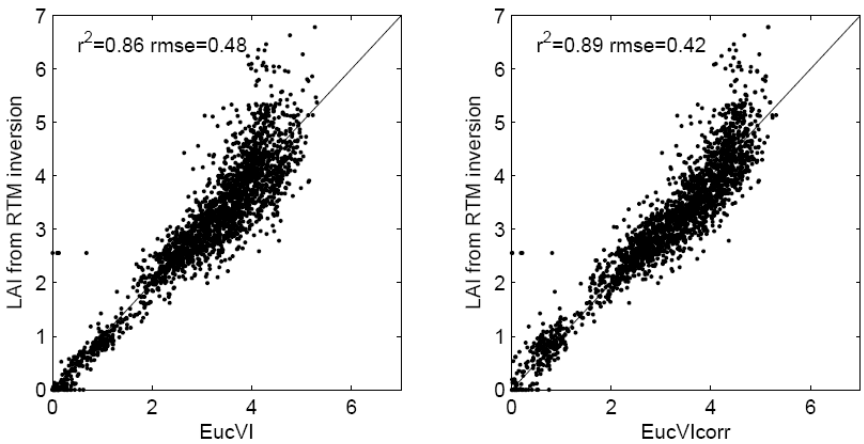

Figure 1. Results of the calibration of EucVI on left (Equation 1) and $EucVI_{corr}$ on right (with age and DoY taken into account) on the LAI obtained from PROSAIL inversion. The 2620 data belong to 18 different stands of different ages and soil conditions, from their planting date up to year 2009.

3.2 Comparison with destructive measurements

Figure 2 shows the LAI retrieved with the four different methodologies. Fig 2a and 2b are taken from le Maire et al. (in press). Figure 2c and 2d are the results of EucVI and $EucVI_{corr}$ after having smoothed the time-series. The RTM inversion, which is our reference method, has an R^2 of 0.8 and RMSE of 0.41. The GESAVI index, which was constructed using only the determination of the soil line, gave the lowest R^2 and highest RMSE. EucVI improved the results both for R^2 and RMSE. Finally, the $EucVI_{corr}$ index gave a high R^2 and a low RMSE, approaching the RTM inversion results.

One of the data points is outside the general tendency (LAI of ~5.5). This high LAI value point, which was well inverted with the RTM, is difficult to retrieve with any of the EucVI. This highlights one of the advantages of using RTM model inversion: it tends to be more precise than EucVIs for high LAI values. This is also visible in Figure 1, where the residuals of EucVI versus LAI from inversion show heteroscedasticity, meaning that the errors are higher with VI for high LAI values.

Figure 3 shows the time-series of LAI retrieved from RTM inversion and with $EucVI_{corr}$, together with destructive sampling.

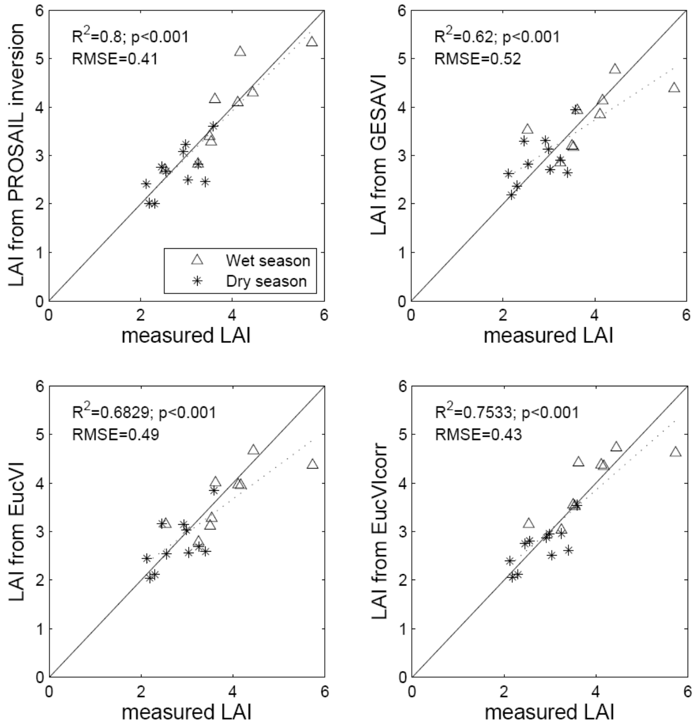

Figure 2. Comparison of measured and estimated LAI from PROSAIL inversion (top left), from GESAVI (top right), from EucVI (lower left) and $EucVI_{corr}$ (lower right). Top figures are taken from le Maire et al. (in press). Measured LAI was obtained from destructive sampling.

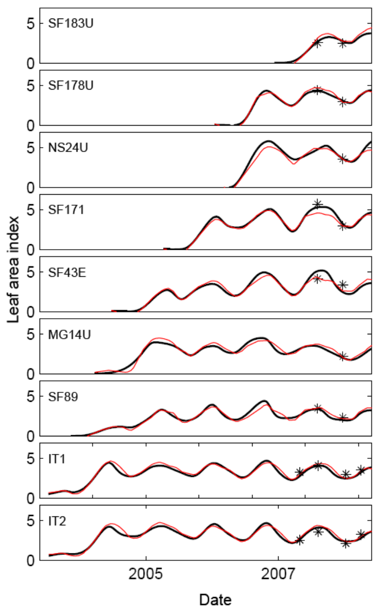

Figure 3. LAI time-series on 9 stands of different ages, since the beginning of the rotation. In black are presented the results of the RTM inversion (le Maire *et al.* in press), and in red the results of the $EucVI_{corr}$ index.

3.3 Applicability of the method for large scale LAI monitoring

LAI is a very important variable involved in a variety of ecosystem process. Its estimation throughout entire rotations is an important step for understanding ecosystem functioning using process-based models. Such models take explicitly into account soil properties and meteorology through the calculation of gross photosynthesis, autotrophic respiration, allocations, litterfall, etc. They are used routinely by some companies (Almeida *et al.* 2004). LAI is one of the key variables simulated by such models. LAI retrieved by remote-sensing can be used for comparison with the LAI simulated by the model, or as a model forcing variable. It has been shown that forcing leaf carbon allocation in a process-based model to reach the target remotely-sensed LAI improved the simulations of the G'Day carbon, water and nitrogen cycling model (le Maire *et al.* 2010).

In view of estimating the LAI of an entire forest (i.e. at the landscape/regional scale) over a decade, our EucVI methodology would require parameterization/calibration and testing on other clones and seedling plantations. In addition, reflectance time series would be needed for every stand in the forest, even those of small size, which is not possible with the methodology currently used. This could however be achieved through stand-scale unmixing of MODIS data (Zurita-Milla *et al.* 2009).

Finally, the vegetation index we have developed is specific to the MODIS sensor and to the sites studied here, i.e. it is dependent on the soil conditions, clonal properties, conditions of illumination at the moment when the satellite takes the measurements, etc. Concerning soil properties, the 18 stands used to calibrate the EucVIs are very different, ranging from very sandy to most clayey types. It would be interesting to test such an index in other contexts.

4. Conclusion

We have developed in this study a *Eucalyptus* specific vegetation index called EucVI. The use of a synthetic database to calibrate the VIs has proven to be an efficient method. It aimed at increasing the number of data points for the calibration, while still considering realistic cases, i.e. real stands with all the correlations between their biophysical and biochemical properties. The vegetation index has the properties of a soil adjusted vegetation index. This vegetation index gave good results in most of the LAI range found for eucalypt stands in SP state, Brazil. However, high LAI values are still difficult to retrieve with such index. The use of age and day of year as additional easily available information improved the results. These indices have been calibrated on a dataset showing a large range of age and soil conditions. Validation on other locations is yet necessary to confirm their genericity.

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