Spatial and temporal variability of the carbon budget of tropical eucalyptus plantations assessed using ecosystem modelling and remote-sensing

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Abstract: The role of managed forests will be essential in addressing the challenges of climate change mitigation by adaptive forest management and enhancement of carbon sinks. The first step is the quantification of the forest carbon budget at large scales, which is an issue at the center of forest landscape ecology. In the aim of estimating regional-scale carbon budgets of Eucalyptus plantations in south-eastern Brazil, the G'Day ecosystem model was combined with remotely-sensed estimates of leaf area index. The spatialization potential of G'Day was assessed through simulations on 16 stands, which encompassed a large range of age and fertility levels. In parallel, the leaf area index (LAI), a key model variable, was obtained for the 16 sites by inversions of MODIS remotely-sensed reflectance time series. These inversions involved the coupling of a hybrid-type canopy radiative transfer model with a soil reflectance model and a leaf reflectance and transmittance model. The inverted LAI was highly variable, both seasonally and interannually. The inverted LAI is used as a forcing variable of G'Day. Results show that the G'Day model is efficient at simulating stand biomass over a wide range of values. Stem biomass increments are also fairly well simulated at different ages, and improved when we use the inverted LAI. A limitation is that inter-stand variability in biomass increment is not well reproduced for the oldest stands. We will discuss the implications of our work for the carbon budget monitoring of Eucalyptus plantations at large scales.

Keywords: Process-based model; Eucalyptus plantation; MODIS; Leaf area index; Biomass

Introduction

Regional carbon budgets and the spatial and temporal distribution of CO_2 sinks and sources are likely to be strongly impacted by land-use changes. In many tropical regions the rapid expansion of highly productive Eucalyptus plantations, conducted on short rotations, is a significant example of these changes (ca. 350000 new ha planted per year in Brazil for example). In the context of carbon mitigation policy, it is acknowledged that highly productive Eucalyptus plantations, well managed, established on former degraded land like pasture, can contribute to reduce logging pressure on native forests. It is therefore essential to have reliable methods for assessing the carbon stocks and plantation productivities at different scales, and in a changing environment. A relevant scale for stakeholders is the landscape or regional scale. The principal carbon sink in these fast-growing forests is the exportation of wood, representing up to 100 t C ha^{-1} at the end of a six-year rotation, but stand productivity is highly variable both temporally and spatially. For the establishment of landscape carbon budgets it is important to gain insight into carbon fluxes in the principal ecosystems, and in the case of Eucalyptus plantations to understand how long-term intensive management or climate change scenarios can affect current and future net ecosystem productivity.

The objective of this study is to test if a simple process-based ecosystem model, applied using meteorological data and easily available spatial information (soil maps, remote sensing), is able to simulate the spatial and temporal variability of stand biomass and biomass increment at the landscape scale, with a mosaic approach. A second objective is to test if forcing the model with LAI time-series derived from remote sensing can improve the simulations.

1. Forest ecosystem model

We adopted a modelling approach to study the interrelated water, carbon and nitrogen fluxes of a plantation stand. The G'DAY (Generic Decomposition And Yield (Comins & McMurtrie, 1993; Corbeels et al., 2005)) model was adapted for application on a daily time-step to the case of Eucalyptus plantations of São Paulo state in south-eastern Brazil. This model is based on a simple but comprehensive description of principal plant and soil mechanisms and simulates the coupled evolution of carbon, nitrogen and water content of plant, litter and soil pools, as well as the fluxes between them. We have adapted the model to Brazilian ferralsol conditions, where Eucalyptus have deep roots (>10m). We have also developed a version of the model that can be forced with external daily LAI values: the (previously constant) carbon allocation coefficients between plant components are adjusted in order to match the target LAI.

Sub models were tested, modified and finally calibrated on an experimental site in Itatinga, São Paulo, representative of typical regional cultivation practices. Experimental measurements carried out for 5 years after planting date (a typical rotation lasts 6 years) included soil water content, evolution of nitrogen and carbon pools in different plant compartments, leaf area index, soil respiration flux, soil carbon and nitrogen pools, and litter fall. The adjusted model accurately estimated Net Primary Production (NPP), biomass components and litter fall during the first 3 years of growth. An observed very strong drop (-40%) in production during the third year of growth (figure 1) was simulated by the model as a result of the limitation of carbon assimilation by soil water deficit, although its magnitude was underestimated. However, the model was unable to simulate the subsequent very high production rate that was measured during the fourth year, unless critical model parameters were changed (water holding capacity, water use efficiency, litter fall rate).

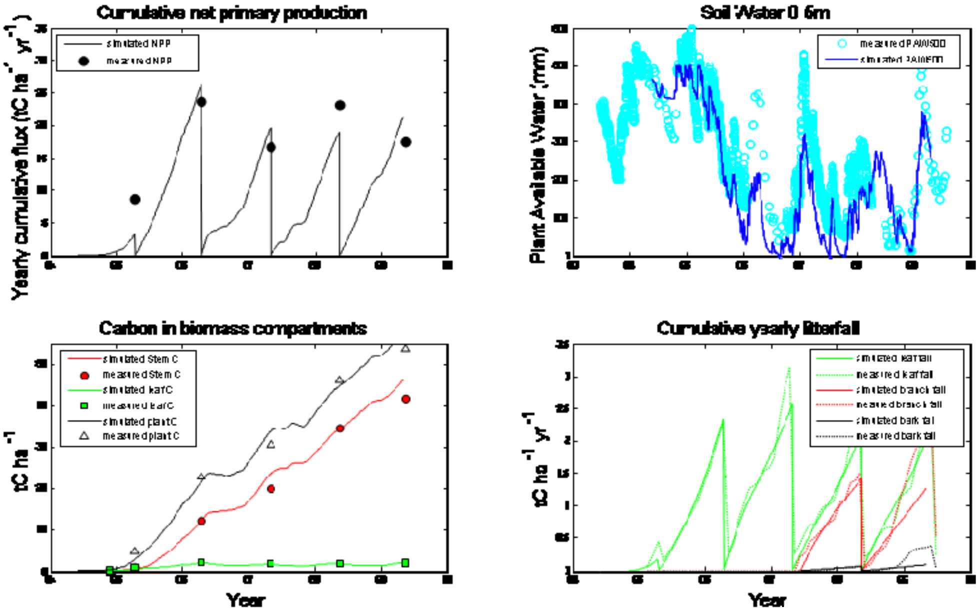

Figure 1. Simulation results at Itatinga experimental site.

2. Application on a network of stands

In a second phase, the model was applied to a network of company-managed clonal plantation stands in order to test whether the model was able to reproduce the strong observed spatial and temporal variations of stand productivity (30 to 55 m^3 ha^{-1} yr^{-1} of dry wood exported). The G'Day model was parameterized with the parameter set obtained at the Itatinga site. Stand-specific maximum plant available water (maxPAW) inferred from soil type and LAI obtained by inversion from MODIS time series (described below) were used in three different simulations: (1) the LAI was simulated by the model, and the maxPAW was fixed to a constant average value, (2) the LAI was simulated by the model and the maxPAW was parameterized to the stand-specific value, and (3) the allocation coefficients were forced to simulate the remotely-sensed LAI and stand-specific maxPAW values were used.

To form the network, 18 stands located in the same region were chosen, representing different ages and contrasted productivity levels (Marsden et al., 2009). Temporal series of biomass production data were available for these stands. Each stand was homogeneous and large enough to include several MODIS pixels. The best single pixel was chosen to represent the reflectance of each stand (Marsden et al., 2009). Field measurements of leaf area index, specific leaf area and cover fraction were carried out on a subset of 9 stands of different ages. Biomass and biomass increments are obtained on the 18 stands from permanent plots followed by the company with a time step of approximately 2 years. Details of these measurements are given in Marsden et al. (2009).

2.1. Leaf area index inversion method

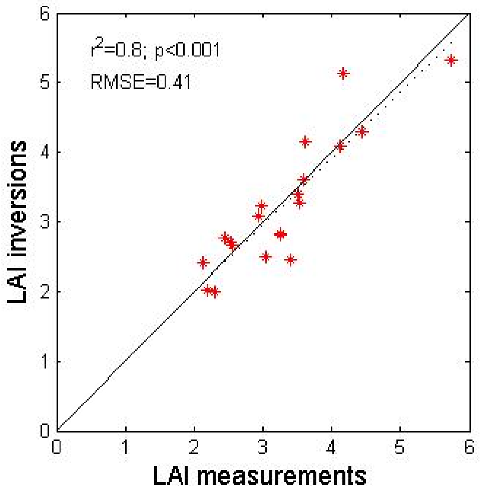

Figure 2. Results of LAI inversion, using a coupled soil-leaf-canopy radiative transfer model. Measurements are estimations from destructive sampling.

We obtained temporal series of red and NIR reflectances from a MODIS Terra Vegetation Index 16-Day 250m resolution V005 series (MOD13Q1) images. Temporal variations of LAI were inferred from the reflectance time series using a reflectance model inversion technique. Canopy reflectance is highly related to LAI, but it also depends on cover fraction, leaf angles, and specific leaf area, which vary with age and season, as well as on solar and viewing geometry, which vary seasonally. It is therefore essential to use a reflectance model that includes all these properties, to be able to separate the effects of different variables. We used a “hybrid-type” canopy radiative transfer model, 4SAIL2 (Verhoef et al., 2007), coupled with a leaf reflectance and transmittance model, PROSPECT4 (Feret et al., 2008), and a soil reflectance model, SOILSPECT (Jacquemoud et al., 1992). These models were parameterized using field measurements for all parameters except LAI. Most of the parameters varied with stand age. Soil parameters were obtained from SOILSPECT inversions on bare ground reflectances, which were available during the short interval between two rotations. After all other parameters were determined, LAI was inverted on the selected pixel reflectance time-series using a Powell minimization algorithm.

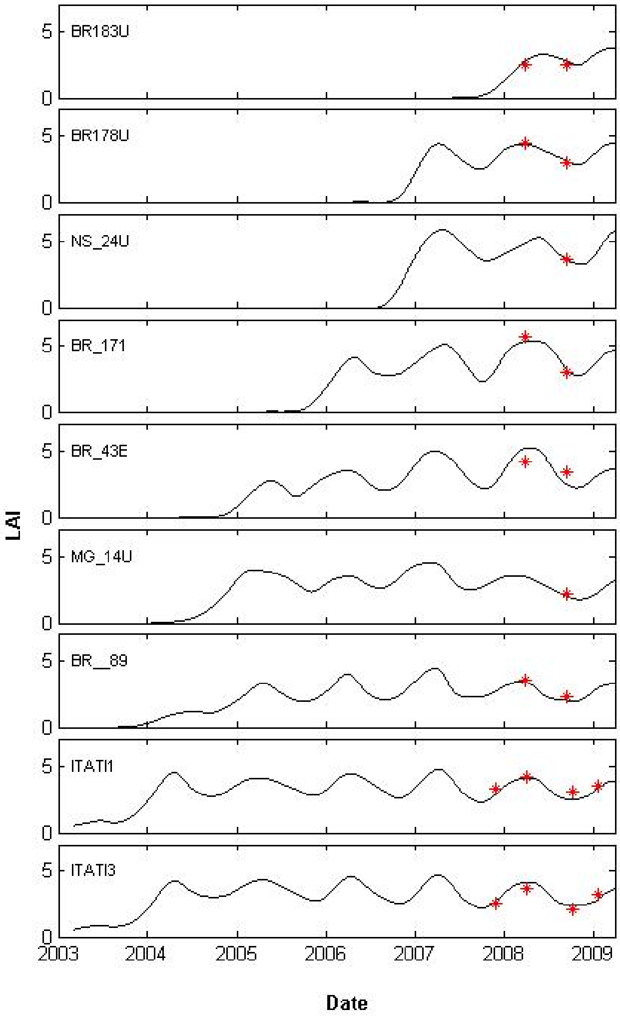

Figure 3. Inverted LAI time series, obtained from MODIS reflectance, on 9 eucalyptus stands. (red stars: destructive LAI estimation).

Inverted LAI was highly correlated with measured LAI, obtained by destructive sampling, with a r^2 of 0.8, a root mean square error of 0.41 and hardly any bias (figure 2). The inter-annual and seasonal variability of LAI was high, and LAI generally showed a slight decline with age after 2-3 years (figure 3).

2.2. Simulation results for stem biomass and stem biomass increment

Figure 4 shows the results of the three different simulations, by comparing simulated and measured stem biomass and stem biomass increment. It is noticeable that without maximum plant available water spatial variability in the simulation, the model is already able to explain 84% of the variability of stem biomass and 67% of the variability of stem biomass increment. This part of biomass variability is simply explained by age and climate, since in this simulation the planting date is the only stand-specific parameter.

When the spatial variability in maxPAW was taken into account, we highly improved the estimation of stem biomass and stem biomass increment: the root mean square error (rmse) is reduced by 48% for stem biomass, the bias is reduced, and the r^2 increased (figure 4). If we also take into account the locally inverted LAI, the estimations are again slightly improved. More importantly, for these last simulations, the biomass increment estimation is substantially improved for young stands, but not the bias (figure 4). These last simulations show that the model tends to underestimate high values of stem biomass increment, which correspond to older stands (2 to 5 years). On the contrary, stem biomass increment is overestimated for young stands, but the spatial variability is well captured.

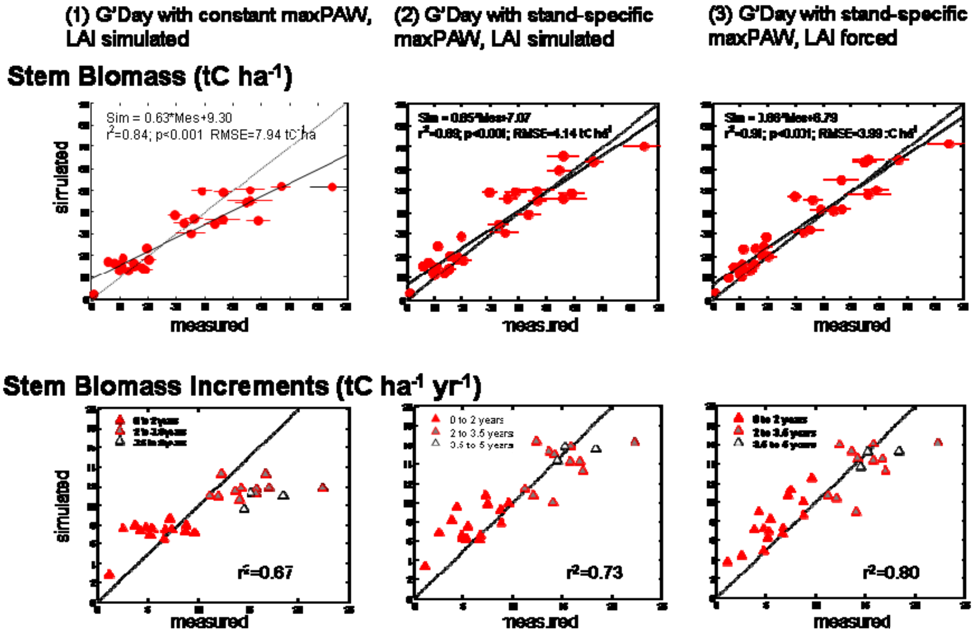

Figure 4. Results of G'Day simulations on 16 stands, for three different simulations

Discussion

The inversion of the coupled radiative transfer model gave good results when compared to destructive measurements, even for the highest LAI values, which are notoriously difficult to retrieve due to the saturation of reflectances for LAI greater than ~4. The inversion methodology is however difficult to implement, due to the number of factors influencing the reflectance signal, and the computation time. For an application to a larger number of stands, the use of a well calibrated vegetation index, tested against these inversions, would be more appropriate.

The results on the stand network confirmed the ability of the model to simulate the temporal and spatial variations in stem biomass and biomass increments. The three different simulations aimed at separating the influence of the stand age and of site conditions. Age alone explains a large part of the variability in wood biomass and productivity, but the additional parameterization of site-specific maxPAW significantly improves estimations. The use of the MODIS data to force the model LAI was overall useful, especially for improving the NPP simulations of young stands (<2 years old). This comes from the high variability in LAI dynamics during the two first years, which is a result of planting date variability within the year and site fertility (Marsden et al., 2009). For older stands, the use of inverted LAI does not bring much improvement, suggesting that the different levels of light interception and allocation coefficients observed on the 18 stands were not sufficient to explain different productivity levels. These results show improvements compared to other studies based on simple ecosystem models, due to the use of remotely-sensed data which mainly enabled to constrain the first years of growth – which are generally difficult to simulate accurately (Almeida et al., in press). Also, it is more suitable to force the model with LAI than with the fraction of absorbed photosynthetically active radiation because of the additional information it holds on biomass allocation.

Conclusion and perspectives

This study confirms the need to use different sources of information for simulating forest plantation growth and yield at the landscape level. In this study, most of the parameters do not vary between sites: only planting date, soil water holding capacities and LAI were assumed to be spatially variable. However, some other parameters may also be site-specific, like the maximum light- or water-use efficiency. Even if not directly measurable at site level, the effect of changes of such parameters will be tested in a modelling exercise. The application of this method at the landscape scale is done with a "stand-mosaic" approach. This approach supposes that there are no spatial interactions between stands, so that each stand has an independent functioning. This is most probably the case for the water balance since soils are very deep and sandy, so there is hardly any runoff or interactions through groundwater. For radiation, carbon and nutrient budgets some interactions may occur at stand borders, but probably do not affect the stand-scale estimations due to the size of the stands (30 ha in average). This method has the advantage that it relies only on external data (satellite images, soil maps, climate) once the model has been calibrated. However, there is still some progress to be made on G'Day simulations, on the use of

MODIS data on small stands, and on the use of G'Day on different Eucalyptus hybrids and on a range of climates.

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