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Mapping short-rotation plantations at regional scale using MODIS time series: Case of eucalypt plantations in Brazil

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ABSTRACT

Short-rotation plantations are extending worldwide due to the increased demand for pulp and wood. Reliable estimations of recent expansion of short-rotation plantation areas and associated land use changes are a prerequisite to assess their environmental impact on regional carbon and water cycles, and on climate. A binary classification methodology using MODerate resolution Imaging Spectroradiometer (MODIS) 16-day 250 m NDVI time series was developed and applied to classify *Eucalyptus* plantations across Brazil. The identification of *Eucalyptus* plantations specific patterns in the time series was based on the calculation of matching functions between the NDVI time series and a ~2 years long reference time series. Among the seven tested matching functions, the bounding envelope was the most successful. This method was robust to residual noise on the NDVI time series, and a threshold coefficient for the binary classification was adjusted using an omission-commission criteria. With this method, it was possible to detect any presence of *Eucalyptus* between 2003 and 2009 at monthly time-steps, including the periods of bare soils between two rotations that are typically 6–7 years long. The dates of first afforestation, of clear-cut at the end of a rotation, and of re-planting at the beginning of a new rotation were retrieved from the NDVI time series with a precision of ~66 days. The final almost continuous tri-dimensional map (space and time) was validated with three different datasets, from local to regional data. All three datasets gave similarly high global accuracy statistics, but a global underestimation of *Eucalyptus* areas compared to large scales census was observed. Discrepancies and way to improve the *Eucalyptus* area estimates were discussed in this study. The developed methodology could be applied to other short-rotation tree plantations.

1. Introduction

Tracking the land uses and land cover changes at a regional scale is of critical importance to analyze the modifications of global biogeochemical cycles and the impacts of environmental policies. Several global land cover maps have been produced from classification of remote sensing data (MODIS land cover product, USGS-IGBP, UMD, GLC2000, GlobCover, etc.). The classification algorithms were an ensemble supervised decision trees, e.g. for MODIS MCD12Q1 product (Friedl, Sulla-Menashe, Tan, Schneider, Ramankutty, Sibley and Huang, 2010), unsupervised classification followed by post-classification refinement, e.g. USGS-IGBP product (Loveland, Reed, Brown, Ohlen, Zhu, Yang and Merchant, 2000), clustered supervised and unsupervised classification, e.g. GlobCover (Bontemps, Defourny, Van Bogaert, Arino, Kalogirou and Ramos Perez, 2011). Such global maps obviously have a small number of classes and have a coarse spatial resolution, and are therefore of limited interest to monitor the area covered by specific crops or plantations. In parallel to the development of these global maps, researchers have used the same satellite image resources to produce maps of crop classes at farm or landscape levels in order to assess regionally and annually the land use changes of the main crops (e.g. Arvor, Jonathan, Meirelles, Dubreuil, & Durieux, 2011; Brown, Kastens, Coutinho, Victoria, & Bishop, 2013; Epiphanio, Formaggio, Rudorff, Maeda, & Luiz, 2010; Galford, Melillo, Mustard, Cerri, & Cerri, 2010; Wardlow, Egbert, & Kastens, 2007). All these studies have shown the potential of satellite image series to classify different crops and cropping systems, and therefore to assess the consequences of agricultural practices on land use changes. Indeed, the knowledge of the crop, forest or grassland phenology, together with their spectral signature, makes it possible to greatly improve the precision of the determination of subclasses. As a consequence, it is difficult to get a unified methodology and many different methods have been used to classify coarse resolution satellite image time series for the production of crop maps, each method depending on the objective of the study and of the crop type under consideration (García-Mora, Mas, & Hinkley, 2011).

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While considerable efforts have been made to follow the deforestation of tropical forests, little has been done to follow the large expansion of forest plantations, while they can represent a significant area compared to deforestation in tropical and subtropical areas (Hansen et al., 2013). For instance, the area of *Eucalyptus* plantations in Brazil was 3.5 million ha in 2006 and now reaches approximately 5 million hectares (ABRAF, 2012). The Ministry of Agriculture of Brazil expects an increase of forest plantations up to a total of 9 million hectares by 2020 (Ministério da Agricultura website), with probably more than three quarters planted with *Eucalyptus* species. However, simulated scenarios show that the forest sector will need to reach 13.5 million hectares in 2020 to meet the expected demand for wood (EMBRAPA-Florestas, 2010). For comparison, perennial and annual croplands covered approximately 60 million hectares and native and cultivated pastures 160 million hectares in Brazil ((IBGE, 2006), compiled in Barretto, Berndes, Sparovek, and Wirsenius (2013)). Recent expansion of *Eucalyptus* plantations is probably the most important agrarian change that have occurred in recent years in some parts of Brazil (Kröger, 2012). Most of commercial *Eucalyptus* plantations in Brazil are managed to produce pulpwood, charcoal for steel industry, biomass for energy, and timber for solid wood items and different types of reconstituted panels (ABRAF, 2012). Selection of productive hybrids and clones, improved silviculture, and ideal soil and climate conditions of Brazil for eucalypt-based forestry have led to mean productivities of 40–45 m^3 ha^{-1} yr^{-1} in commercial plantations across Brazil (Gonçalves et al., 2013).

There is a critical need to monitor the rapid expansion of short-rotation plantations like *Eucalyptus* plantations at regional scales. An accurate estimation of recent changes of *Eucalyptus* areas is a prerequisite to assess, for example, the environmental impact of afforestation or the impact of incentive policies on wood production at a regional scale (Cossalter & Pye-Smith, 2003). *Eucalyptus* plantations are mostly found in the Minas Gerais and São Paulo states (about half of total *Eucalyptus* areas in Brazil), but recent expansions mainly occur in the Mato Grosso do Sul and Para states (ABRAF, 2012). New *Eucalyptus* plantations are mainly established on pastures, or follow the conversion of other forest plantations (mainly pine or low-productive *Eucalyptus* stands), but few statistical data are available on these land use changes. It is likely that future afforestation rates will also be influenced by availability of suitable land (Piketty, Wichert, Fallot, & Aimola, 2009). Use of high resolution satellite images (e.g. Landsat) to monitor *Eucalyptus* expansion would be very difficult at large scales for both technical reasons and lack of data in some areas. Coarse resolution satellite images would be more suitable to follow large areas, and a resolution close to 250 m like the one of MODIS sensor onboard Terra satellite (for Red and Near infrared bands) can be sufficient to monitor commercial *Eucalyptus* plantations (le Maire, Marsden, Verhoef, Ponzoni, Lo Seen, Bégué, Stape and Nouvellon, 2011; Marsden et al., 2010). Another advantage of MODIS sensor is to have more than 12 years of continuous global data, with a high observation frequency.

Eucalyptus plantations have never been mapped across Brazil using remote sensing data, despite their rapid expansion, their economic importance and their large scale environmental impacts. The specific objectives of this study were 1) to develop a MODIS-based methodology to map *Eucalyptus* plantations and 2) to provide information on rotation practices through the detection of planting dates after afforestation and successive clearcuts, 3) to evaluate the potential of the method for regional area estimations.

2. Material and methods

2.1. Theoretical background

Classification of vegetation at coarse spatial resolution and decadal temporal scale is associated with two major issues: the classification method itself and the validation of the classification. Classification methods generally rely on the multispectral signals and their changes along the year, processed through classification algorithms. Classifying MODIS pixels at a 250 m spatial resolution is a challenge because spectral information is low at this sensor spatial resolution, and landscape heterogeneity is likely to lead to large errors. The low radiometric information of 250 m MODIS reflectance products might, however, be counterbalanced by the high temporal frequency of data acquisition (Wardlow et al., 2007). As a consequence, the method chosen in the present study to monitor the area of *Eucalyptus* plantations will focus on the temporal signature of the *Eucalyptus* NDVI.

The phenology of fast-growing *Eucalyptus* plantations across an entire rotation makes the interpretation (and classification) of the satellite images difficult in comparison with annual crops. After the clear-cut of the previous rotation cycle, herbicide application lead to bare soils without vegetation over several weeks. *Eucalyptus* stands are clear-cut all along the year. A very rapid increase in foliage area and therefore a high increment in NDVI occur the first months after planting. Afterwards, the vegetation indices remain high, with a seasonal variation when *Eucalyptus* trees partially shed their leaves during the dry season (le Maire, Marsden, Verhoef, et al., 2011; Marsden et al., 2010; Marsden et al., 2013). Rotation length is usually 6–7 years, but it may range from 3 to 10 years. This time-course of NDVI is characteristic of *Eucalyptus* plantations managed in short rotations.

Methods developed for classifying crops and natural vegetation from NDVI time series are generally not suited in the case of *Eucalyptus* fast-growing plantations as a result of their pluri-annual behavior. Most of the multi-temporal classification methods have been developed for annual crops, because the intra-annual phenology is a good criteria for crop distinction (Arvor et al., 2011; Bagan, Wang, Watanabe, Yang, & Ma, 2005; Brown et al., 2013; Lenney, Woodcock, Collins, & Hamdi, 1996; Wardlow et al., 2007). Classification based only on annual time series may classify the *Eucalyptus* plantations as "evergreen broadleaf forest" or "bare ground/low vegetation cover", "deciduous forest" because of clear-cuts, or even croplands if the NDVI regrowth of the first year match with other cropland NDVI increase. This was the case for MODIS MCD12Q1 product (500 m spatial resolution) and GlobCover product (300 m spatial resolution), which generally classified *Eucalyptus* plantations as "evergreen broadleaf forest" or other classes mentioned before. Classification methods using frequency metrics like wavelet decomposition or Fourier transform could also hardly be used. Such methods are appropriate to detect changes in amplitude and frequencies in NDVI time series, for instance to assess the expansions and intensification of crops in Brazil (Galford et al., 2008). However, in *Eucalyptus* plantations, frequencies do not change between successive *Eucalyptus* rotations or compared to natural forest. A possible solution, used for classifying rubber tree plantations in Southeast Asia, is to separate the plantation class into different classes according to the plantation age (Li & Fox, 2012). Each age class thus has a different spectro-temporal annual signature, and it is possible to merge the different classes together afterwards. However, this method does not take advantage of using the entire rotation time series, which is a much better signature than the annual one in the case of *Eucalyptus* plantations.

In a comparison of eight different time series similarity measurements for classification Lhermitte et al. (2011) stated that the choice of the method requires an understanding of the ecosystem dynamics and the time series characteristics. The "difference" measures showed higher sensitivity to amplitude effects, and are therefore more appropriate for *Eucalyptus* plantations since the main criteria is the NDVI variations as stated above (clear-cut, rapid regrowth, stabilization of NDVI at high values) rather than seasonal variations. Therefore, a method based on the calculation of a distance measurement (matching function) between a pixel NDVI time series signal and a group of "reference" time series was thought to be more suitable for *Eucalyptus* classification. The problem therefore simplifies to a search of the occurrence of a known pattern in the time series. The matching function provides a quantitative estimation of the similarity between a time series