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Relating MODIS vegetation index time-series with structure, light absorption and stem production of fast-growing *Eucalyptus* plantations

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ABSTRACT

By allowing the estimation of forest structural and biophysical characteristics at different temporal and spatial scales, remote sensing may contribute to our understanding and monitoring of planted forests. Here, we studied 9-year time-series of the Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) on a network of 16 stands in fast-growing *Eucalyptus* plantations in São Paulo State, Brazil. We aimed to examine the relationships between NDVI time-series spanning entire rotations and stand structural characteristics (volume, dominant height, mean annual increment) in these simple forest ecosystems. Our second objective was to examine spatial and temporal variations of light use efficiency for wood production, by comparing time-series of Absorbed Photosynthetically Active Radiation (APAR) with inventory data.

Relationships were calibrated between the NDVI and the fractions of intercepted diffuse and direct radiation, using hemispherical photographs taken on the studied stands at two seasons. APAR was calculated from the NDVI time-series using these relationships.

Stem volume and dominant height were strongly correlated with summed NDVI values between planting date and inventory date. Stand productivity was correlated with mean NDVI values. APAR during the first 2 years of growth was variable between stands and was well correlated with stem wood production ($r^2 = 0.78$). In contrast, APAR during the following years was less variable and not significantly correlated with stem biomass increments. Production of wood per unit of absorbed light varied with stand age and with site index. In our study, a better site index was accompanied both by increased APAR during the first 2 years of growth and by higher light use efficiency for stem wood production during the whole rotation. Implications for simple process-based modelling are discussed.

1. Introduction

Fast-growing *Eucalyptus* plantations are extending rapidly in many tropical regions (e.g., close to 300,000 ha planted per year in Brazil since 2004, for a total of about 4 million ha; ABRAF, 2009). Biomass exportation represents the largest carbon sink in these ecosystems and can vary more than tenfold between stands and years: annual wood production varied from 2 to 51 Mg DM (dry matter) ha^{-1} $year^{-1}$ on 40 fertilized and unfertilized stands in south-eastern Brazil (Stape et al., 2004b), for example. As a result there is a high demand for spatialized tools allowing the monitoring and prediction of the dynamics and determinants of wood production in these plantations. Such tools could be used for regional carbon balance accounting and environmental impact assessment studies, as well as for forest management. Plantation ecosystems present unique features in comparison with natural forests, that offer interesting opportunities for monitoring, and in particular, for the use of remote-sensing techniques. Short rotations (5–7 years), terminated by clear-felling and planting of a new crop, cause strong temporal dynamics. Spatial variability

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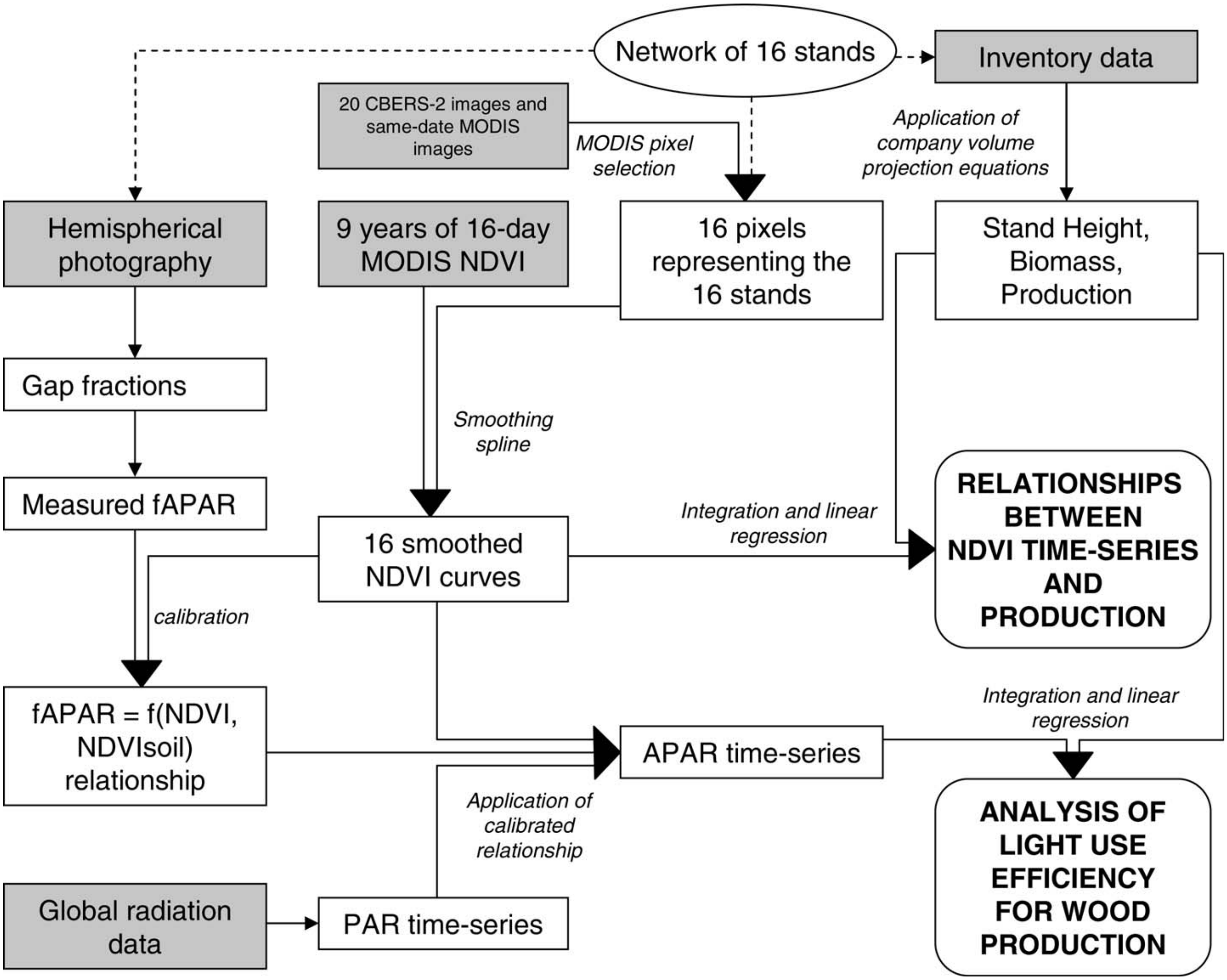

Fig. 1. Flowchart representing the design of our study. The oval represents the study object. Grey boxes depict data input and white boxes represent the results of treatments and calculations. The final results of our study are represented in round-cornered boxes.

inside a plantation is characterised principally by a mosaic of stands with different planting dates and small within-stand variability, due to the use of homogeneous genetic material (clones or mono-progeny seedlings).

The use of a remotely sensed vegetation index gains new interest for the monitoring of these plantations. Vegetation indices, of which the best-known is the Normalized Difference Vegetation Index (NDVI), are built by combining measured surface reflectance in certain spectral bands, in order to be sensitive principally to changes in vegetation properties. The NDVI is defined by NDVI = $(\rho_{NIR} - \rho_R)/(\rho_{NIR} + \rho_R)$, where ρ_{NIR} and ρ_R are reflectances in the near infrared and red spectral bands, respectively (Rouse et al., 1974; Tucker, 1979). This index has been shown to present a non-linear relationship with leaf area index (LAI) and a near-linear relationship with the fraction of photosynthetically active radiation absorbed by a canopy (fAPAR) (Gallo et al., 1985; Goward and Huemmrich, 1992; Law and Waring, 1994; Myneni and Williams, 1994; Myneni et al., 1995; WalterShea et al., 1997). It has been used in many applications, for instance in monitoring of ecosystem fAPAR and crop production (e.g., Asrar et al., 1984; Daughtry et al., 1992; Fensholt et al., 2004), detection of ecosystem phenology (e.g., Soudani et al., 2008), and modelling of local or global primary production (Prince and Goward, 1995; Cramer et al., 1999; Goetz et al., 1999; Coops and Waring, 2001). This success has been mirrored by various studies showing the limitations of the NDVI: the index is affected by varying background reflectance, atmospheric effects and viewing and sun angle configurations (cf., Epiphanio and Huete, 1995; Huete et al., 2002). Different asymptotic behaviours of ρ_{NIR} and ρ_R lead to a loss of sensitivity of the index, or saturation, in the presence of dense vegetation (cf., Tucker, 1979; Baret and Guyot, 1991; Begue, 1993; Huete et al., 2002; Olofsson et al., 2008). Moreover by construction, the use of the NDVI is only sensitive to green biomass, meaning, for example, that it is not possible to use this index (or others built with the same spectral bands) to discriminate zones of different woody (non-green) biomasses. However, in contrast to one-date values, cumulative values of NDVI over a long period can be expected to reflect integrated light absorption and therefore to be related to wood production, according to the light use efficiency concept originally proposed by Monteith (1972). In various studies temporal values of NDVI during a growing season have been related with forest growth achieved over the same period (Goetz and Prince, 1996; Malmstrom et al., 1997; Wang et al., 2004; Olofsson et al., 2007). However, as far as we know, no study of this