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Original Article

Forest Management

Relationship Between Spectral Data and Dendrometric Variables in *Eucalyptus* sp. Stands

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ABSTRACT

The present study aims: (a) to assess the correlations between forest stand characteristics (viz., basal area, dominant height, and volume) and the reflectance values derived from Landsat 5 TM spectral bands as well as from vegetation indices and (b) to understand how *Eucalyptus* sp. stand age influences these correlations. Sampling data comprised a set of 35 permanent plots from a forest inventory conducted annually between 2006 and 2011. Spectral data were derived from Landsat 5 TM images. The results showed that TM4 and TM5 spectral bands, as well as vegetation indices ND54 and TM5/4, were better correlated with basal area and volume, while the TM2 spectral band was better correlated with dominant height. *Eucalyptus* sp. stand age directly influenced the correlations between spectral data and forest stand characteristics, and could not be disregarded in the spectral characterization of the forest variables.

Keywords: vegetation indices, spectral bands, volume, basal area, Landsat 5 TM.

1. INTRODUCTION

Reliable information and knowledge on forest structures is essential to plan sustainable use of forest resources (Mello et al., 2006). This information is obtained through forest inventories (Scolforo & Mello, 2006) that are responsible for a significant amount of forest production costs, due to the time spent allocating and measuring the plots in the field (Silva et al., 2014).

Some studies have demonstrated the potential of geotechnologies to support the traditional forest inventory carried out in the field, since they help with acquisition of information regarding forest growth, mainly through the use of data collected by sensors onboard artificial satellites (Halme & Tomppo, 2001; Mäkelä & Pekkarinen, 2004; Hall et al., 2006; Tomppo et al., 2009; Viana et al., 2012). Consistent, repetitive and systematic observation of forest growth, obtained through remotely sensed images, provides a better characterization of the differences in growth and yield throughout the forest plantation area, since the information can be collected for all pixels in different portions of the electromagnetic spectrum (Ponzoni et al., 2015).

Landsat 5 TM images can be useful in forest management when combined with field measurements (Reis et al., 2015; Silva et al., 2014; Viana et al., 2012; Mäkelä & Pekkarinen, 2004). Spectral information captured by remotely sensed images has a strong relationship with dendrometric variables, both for planted forests (Berra et al., 2012; Canavesi et al., 2010; Watzlawick et al., 2009) and native forests (Reis et al., 2015; Mäkelä & Pekkarinen, 2004; Lu et al., 2004).

However, there is still a need for studies to assess the influence of forest stand age on these relationships, and especially, at what age the images best represent each forest variable and therefore are useful as auxiliary data for the management of planted forest. Thus, the present study aims to contribute to an understanding of the correlations between spectral data and dendrometric variables, regarding the age of *Eucalyptus* sp. stands. In this sense, the specific objectives of this study were: (a) to assess the correlation between forest stand characteristics (viz., basal area, dominant height and volume) and the reflectance values derived from Landsat 5 TM spectral bands as well as from vegetation indices; (b) to understand how stand age influences these correlations.

2. MATERIAL AND METHODS

The *Eucalyptus* clonal stands being studied are located in the Lagoa Grande municipality, northwest of Minas Gerais state, Brazil, situated between the geographic coordinates 17º43’00”S - 46° 32’00”W and 17º44’00”S - 46°33’00”W, at an altitude of 560 meters (Figure 1). According to the Köppen climatic classification,

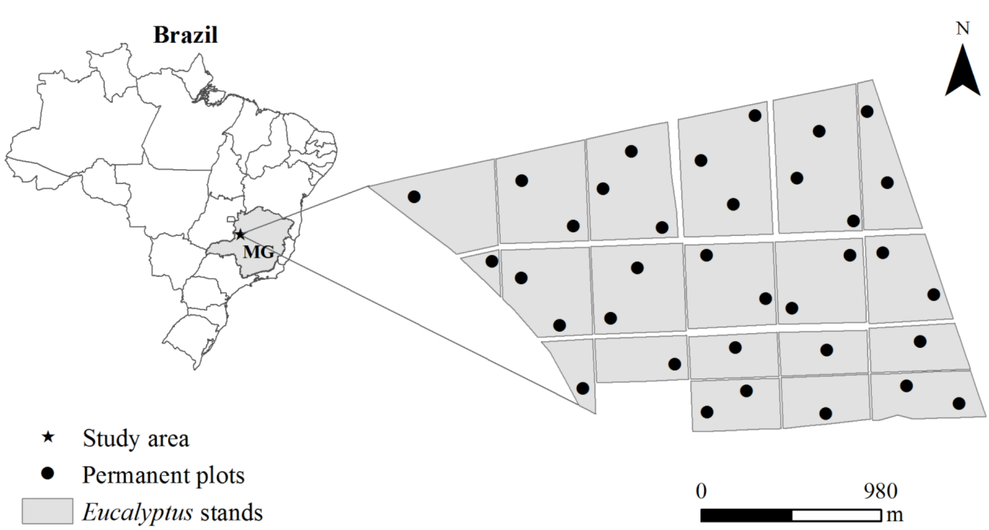

Figure 1. Geographic location of the study area and sampling grid.

the climate in this region is Aw, classified as a tropical savanna climate, with drier months during the winter.

A set of 20 *Eucalyptus* stands planted in the months of April and May 2004, with initial spacing of 3 × 2 m and 3 × 3 m, was selected, totaling an area of 362.2 hectares. The Continuous Forest Inventory (CFI) was carried out on 35 permanent plots of 400 m^2 from 2006 to 2011. CFI consists of a network of permanent plots monitored yearly to verify changes occurring in the forests. Usually, field measurements for *Eucalyptus* stands in Brazil start at two or three years old (Kanegae et al., 2006).

The sampling procedure adopted was the unencumbered systematic sampling design, allocating approximately one circular plot per 10 ha of forest. The plots were georeferenced in the field with GPS Garmin 60CSx. In all plots, the circumference at 1.3 m above the ground (circumference at breast height) of all stems was measured using a metric tape, as well as the total height of the first fifteen trees with normal stems (without bifurcation or any other defect) and dominant tree height according to Assmann's definition (Assmann, 1970), if these trees were not among the fifteen heights already measured in the plot. To estimate the heights of all trees in the plot, a hypsometric model was used. Next, the volume per plot and age was obtained by fitting a volume model based on scaled trees in the field.

Spectral data were obtained from Landsat 5 TM images, with spatial resolution of 30 m, on the dates of 06/17/2006, 07/22/2007, 06/06/2008, 06/25/2009, 06/12/2010 and 03/27/2011, corresponding with field data collection, in orbit 220, point 072, in bands TM1 (0.45-0.52 μm), TM2 (0.52-0.60 μm), TM3 (0.63-0.69 μm), TM4 (0.76-0.90 μm), TM5 (1.55-1.75 μm) and TM7 (2.18-2.35 μm).

The Landsat 5 TM images were obtained from the USGS database (United States Geological Survey), already presenting radiometric calibration, and geometric and atmospheric corrections. The USGS, agency responsible for making the Landsat time series available, uses the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) application, which calculates surface reflectance by compensating atmospheric absorption and scattering effects, thereby generating the correct reflectance of the top of the atmosphere and surface (Feng et al., 2013). In addition, vegetation indices were calculated from the spectral bands of Landsat 5 TM images (Table 1).

We used the pixels located in the centroid of each forest inventory plot to extract the reflectance band values and the vegetation indices for each year of measurement. After that, for each year of measurement

Table 1. Vegetation indices used in this study.

Vegetation indices	Formulation	Reference
TM4/3	TM4/TM3	Jordan (1969)
TM5/3	TM5/TM3	Jordan (1969)
TM5/4	TM5/TM4	Jordan (1969)
TM5/7	TM5/TM7	Jordan (1969)
NDVI	(TM4 - TM3)/(TM4 + TM3)	Rouse et al. (1973)
ND53	(TM5 - TM3)/(TM5 + TM3)	Huete et al. (2002)
ND54	(TM5 - TM4)/(TM5 + TM4)	Huete et al. (2002)
ND57	(TM5 - TM7)/(TM5 + TM7)	Huete et al. (2002)
ND32	(TM3 - TM2)/(TM3 + TM2)	Huete et al. (2002)
SAVI	$\left[(TM4 - TM3)/(TM4 + TM3 + L)\right].(1.5)$	Huete (1988)
MSAVI	$\left[(2TM4+1)-\sqrt{(2TM4+1)^2-8(TM4-2TM3)}\right]/2$	Qi et al. (1994)

Where: TM= Thematic Mapper; ND= Normalized Difference; NDVI= Normalized Difference Vegetation Index; SAVI= Soil-Adjusted Vegetation Index; MSAVI = Modified Soil-Adjusted Vegetation Index.

the Pearson correlation (r) analysis was carried out between basal area (G), dominant height (HD), volume (V), and values of spectral bands and vegetation indices. From these correlations, the relationship between the dendrometric characteristics of *Eucalyptus* stands and their spectral response in Landsat 5 TM images was investigated at different ages. Pearson coefficients, as well as the p-values associated with the test statistics were generated with R software, using the *stats* package and the *cor.test* function (R Core Team, 2015).

3. RESULTS AND DISCUSSIONS

Dendrometric variables presented direct and inverse correlations with Landsat 5 TM reflectance bands and such a relationship varied according to forest age. Table 2 summarizes the correlation coefficients between dendrometric variables and Landsat 5 TM reflectance bands for all measurement ages.

Basal area (G) presented significant correlations with TM4, TM5 and TM7 bands across all ages, with the exception of the TM4 band at age 2 years. At 2 years old, eucalyptus stands are in the initial growth stage, and therefore, there is a greater increase in height in comparison to what is observed for the diameter and crowns. Thus, as canopy closure has not yet occurred, the reflectance values are contaminated by the reflectance of exposed soil, resulting in an absence of significant correlations between basal area and spectral bands in this age. On the other hand, at ages 3, 6 and 7 years, basal area presented significant correlation with the TM3 band. In the case of healthy vegetation, the presence of pigments in the leaves such as chlorophyll, carotenes and xanthophylls are responsible for a greater absorption of electromagnetic radiation in the visible region, mainly in the red region (Ponzoni et al., 2012). Other studies found similar results with high correlations between basal area and TM3, TM4, TM5 and TM7 bands (Berra et al., 2012; Bolfe et al., 2012; Almeida et al., 2014).

The volume (V) presented significant correlation values with TM5 and TM7 bands for all ages, except at age 6 years. These bands were able to efficiently detect the relationship between forest canopy reflectance and the dendrometric variables such as volume and basal area, as also observed by Hall et al. (2006) and Thenkabail et al. (2003). Basal area derives from tree diameter, which is directly related to canopy size, which in turn will determine canopy reflectance. Therefore, this relationship is captured by satellite images that detect the electromagnetic energy reflected by tree crowns that formed the forest canopy. Lu et al. (2004) explored the relationships between forest parameters and

Table 2. Pearson's coefficients (r) between dendrometric variables and Landsat 5 TM spectral bands.

Age (years)	Variables	TM1	TM2	TM3	TM4	TM5	TM7
2	G	0.297^{ns}	0.168^{ns}	-0.166^{ns}	0.236^{ns}	-0.611*	-0.412*
	HD	-0.181^{ns}	-0.444*	-0.090^{ns}	-0.409*	-0.028^{ns}	-0.078^{ns}
	V	0.204^{ns}	-0.057^{ns}	-0.159^{ns}	0.025^{ns}	-0.478*	-0.360*
3	G	-0.129^{ns}	0.158^{ns}	-0.380*	0.570*	-0.515*	-0.461*
	HD	-0.151^{ns}	-0.632*	-0.349*	-0.482*	-0.145^{ns}	-0.133^{ns}
	V	-0.191^{ns}	-0.320^{ns}	-0.484*	0.052^{ns}	-0.432*	-0.380*
4	G	-0.114^{ns}	0.097^{ns}	-0.332^{ns}	0.539*	-0.502*	-0.447*
	HD	-0.325^{ns}	-0.620*	-0.253^{ns}	-0.218^{ns}	0.003^{ns}	-0.027^{ns}
	V	-0.366*	-0.433*	-0.456*	0.231^{ns}	-0.375*	-0.349*
5	G	-0.117^{ns}	0.162^{ns}	-0.186^{ns}	0.799*	-0.666*	-0.684*
	HD	0.256^{ns}	-0.133^{ns}	-0.109^{ns}	-0.241^{ns}	0.038^{ns}	0.013^{ns}
	V	0.095^{ns}	-0.063^{ns}	-0.206^{ns}	0.380*	-0.448*	-0.505*
6	G	-0.112^{ns}	0.138^{ns}	-0.429*	0.646*	-0.608*	-0.647*
	HD	-0.313^{ns}	-0.703*	-0.309^{ns}	-0.537*	0.139^{ns}	0.185^{ns}
	V	-0.288^{ns}	-0.400*	-0.444*	0.001^{ns}	-0.251^{ns}	-0.228^{ns}
7	G	-0.303^{ns}	-0.176^{ns}	-0.602*	0.459*	-0.655*	-0.653*
	HD	-0.291^{ns}	-0.735*	0.032^{ns}	-0.692*	0.316^{ns}	0.298^{ns}
	V	-0.388*	-0.495*	-0.514*	0.060^{ns}	-0.401*	-0.414*

Where: TM1, TM2, TM3, TM4, TM5, and TM7 = reflectance in the bands of blue, green, red, near infrared and mid infrared, respectively; G = basal area ($m^2.ha^{-1}$); HD = dominant height (m); V = volume ($m^3.ha^{-1}$); ^{ns}= not significant at 5% and *significant at 5%.

their spectral responses in Landsat 5 TM images from three areas in the Eastern Amazon basin. The authors observed that the TM5 band is the spectral band that is most strongly correlated with forest variables, corroborating the results found in this study.

Dominant height (HD) presented the best correlations with the TM2 band at all ages, with the exception of the measurement at age 5 years. This fact is due to a severe drought which occurred in that year, according to data recorded in the field, that caused mortality and loss of vigor of the remaining individuals, thereby affecting the correlations with dominant height at this age. Hall et al. (2006) used Landsat 7 ETM+ bands to study a native forest dominated by *Pinus* species in Canada and found negative correlations between tree height and spectral response. These results corroborate the negative correlations found in this study between dominant height and spectral bands. According to Meng et al. (2009) the TM2 band is usually applied for assessments of vegetation vigor, and since more productive sites tend to have more vigorous trees and higher values of dominant height, this explains the higher correlations presented by TM2 band and dominant height.

The low correlations found between dendrometric variables and the TM1 band can be explained by the low contribution of this band to vegetation analysis, since as vegetation cover increases, little change is observed in the reflectance values of TM1 band (Meng et al., 2009).

Correlation coefficients between dendrometric variables and vegetation indices are shown in Tables 3 and 4.

Vegetation indices that include TM4 and TM5 bands in their composition, such as ND54 and TM5/4, had significant correlations with basal area at all forest ages. With the exception of the measurement at age 2 years, the NDVI, TM4/3, SAVI and MSAVI indices also presented significant correlations with basal area.

Dominant height presented closer correlation with vegetation indices in the measurements at ages 4, 6, and 7 years. At ages 4 and 6 years, dominant height was more closely correlated with ND53 and TM5/3 indices. At age 7 years, dominant height presented significant correlations with all vegetation indices, but mainly with SAVI (r = -0.641) and MSAVI (r = -0.610) indices. Since the canopy reflectance of *Eucalyptus* stands at ages 4 and 6 years is mostly composed by the reflectance of green leaves with little participation of soil background and shadows, the dominant height presented high correlations with TM3 and TM5 bands and vegetation indices that include these bands in their composition. According to Ponzoni et al. (2015) the reflectance of eucalyptus stands older than 6 years is influenced by

Table 3. Pearson's coefficients (r) between dendrometric variables and vegetation indices (normalized reasons).

Age (years)	Variable	NDVI	ND53	ND54	ND57	ND32
2	G	0.250^{ns}	-0.398*	-0.656*	-0.026^{ns}	-0.296^{ns}
	HD	-0.069^{ns}	0.094^{ns}	0.188^{ns}	0.047^{ns}	0.375*
	V	0.165^{ns}	-0.271^{ns}	-0.430*	0.026^{ns}	-0.065^{ns}
3	G	0.608*	-0.037^{ns}	-0.720*	0.281^{ns}	-0.572*
	HD	0.113^{ns}	0.346*	0.124^{ns}	0.101^{ns}	0.408*
	V	0.483*	0.210^{ns}	-0.392*	0.233^{ns}	-0.102^{ns}
4	G	0.443*	-0.229^{ns}	-0.538*	0.299^{ns}	-0.485*
	HD	0.115^{ns}	0.584*	0.070^{ns}	0.021^{ns}	0.141^{ns}
	V	0.427*	0.302*	-0.350*	0.219^{ns}	-0.252^{ns}
5	G	0.812*	-0.611*	-0.878*	0.457*	-0.480*
	HD	-0.026^{ns}	0.224^{ns}	0.108^{ns}	-0.019^{ns}	0.053^{ns}
	V	0.543*	-0.280^{ns}	-0.538*	0.373*	-0.178
6	G	0.771*	-0.172^{ns}	-0.733*	0.515*	-0.538*
	HD	-0.083^{ns}	0.542*	0.361*	-0.255^{ns}	0.287^{ns}
	V	0.382*	0.258^{ns}	-0.174^{ns}	0.100^{ns}	-0.102^{ns}
7	G	0.637*	-0.278^{ns}	-0.596*	0.559*	-0.405*
	HD	-0.451*	0.560*	0.550*	-0.383*	0.574*
	V	0.337*	0.058^{ns}	-0.242^{ns}	0.300^{ns}	-0.088^{ns}

Where: ND= Normalized Difference; NDVI= Normalized Difference Vegetation Index; G = basal area ($m^2.ha^{-1}$); HD = dominant height (m); V = volume ($m^3.ha^{-1}$); ^{ns}= not significant at 5% and *significant at 5%.

Table 4. Pearson's coefficients (r) between dendrometric variables and vegetation indices (simple reasons and complex vegetation indices).

Age (years)	Variable	TM4/3	TM5/3	TM5/4	TM5/7	SAVI	MSAVI
2	G	0.199^{ns}	-0.393*	-0.660*	0.010^{ns}	0.316^{ns}	0.318^{ns}
	HD	-0.135^{ns}	0.097^{ns}	0.164^{ns}	0.042^{ns}	-0.355*	-0.296^{ns}
	V	0.098^{ns}	-0.261^{ns}	-0.444*	0.052^{ns}	0.108^{ns}	0.130^{ns}
3	G	0.608*	-0.015^{ns}	-0.712*	0.327^{ns}	0.698*	0.706*
	HD	0.104^{ns}	0.350*	0.114^{ns}	0.116^{ns}	-0.287^{ns}	-0.161^{ns}
	V	0.463*	0.229^{ns}	-0.397*	0.271^{ns}	0.270^{ns}	0.357*
4	G	0.436*	-0.223^{ns}	-0.494*	0.273^{ns}	0.529*	0.528*
	HD	0.126^{ns}	0.594*	0.023^{ns}	0.015^{ns}	-0.088^{ns}	-0.054^{ns}
	V	0.438*	0.317^{ns}	-0.353*	0.188^{ns}	0.328^{ns}	0.355*
5	G	0.763*	-0.625*	-0.872*	0.430*	0.857*	0.858*
	HD	-0.124^{ns}	0.202^{ns}	0.040^{ns}	-0.048^{ns}	-0.176^{ns}	-0.180^{ns}
	V	0.438*	-0.305	-0.583*	0.336*	0.466*	0.463*
6	G	0.675*	-0.145^{ns}	-0.755*	0.506*	0.724*	0.734*
	HD	-0.177^{ns}	0.550*	0.315^{ns}	-0.281^{ns}	-0.434*	-0.387*
	V	0.255^{ns}	0.284^{ns}	-0.218^{ns}	0.082^{ns}	0.115^{ns}	0.150^{ns}
7	G	0.564*	-0.264^{ns}	-0.623*	0.523*	0.525*	0.546*
	HD	-0.493*	0.542*	0.510*	-0.421*	-0.641*	-0.610*
	V	0.250^{ns}	0.066^{ns}	-0.282^{ns}	0.250^{ns}	0.144^{ns}	0.177^{ns}

Where: TM= Thematic Mapper; SAVI= Soil-Adjusted Vegetation Index; MSAVI = Modified Soil-Adjusted Vegetation Index; G = basal area ($m^2.ha^{-1}$); HD = dominant height (m); V = volume ($m^3.ha^{-1}$); ^{ns}= not significant at 5% and *significant at 5%.

green leaf loss and the greater participation of litter (including dry branches deposited on the ground), therefore explaining the highest correlations with the SAVI and MSAVI indices at age 7 years, since these indices are constructed to attenuate soil influence on vegetation reflectance (Bolfe et al., 2012).

Volume presented the best correlations with NDVI, ND54 and TM5/4 indices at age 5 years. However, at ages 6 and 7 years, volume presented significant correlations only with NDVI index, but of low magnitudes (r = 0.382 and r = 0.377, respectively). Berra et al. (2012), studying the correlations between dendrometric variables of *Eucalyptus* sp. stands and vegetation indices obtained from Landsat 5 TM images, found a positive correlation of 0.79 between NDVI and wood volume ($m^3.ha^{-1}$) and of 0.82 between TM4/3 and wood volume ($m^3.ha^{-1}$). In our study, NDVI and TM4/3 indices were also positively related to wood volume ($m^3.ha^{-1}$) but to a lesser degree. Vegetation indices that use the infrared spectral bands suffer less atmospheric dispersion (Jensen, 2009) and this fact can explain the higher correlations presented by these indices and dendrometric variables in comparison with indices that use the visible region bands in their composition. Moreover, these indices present a non-linear relationship with biophysical characteristics such as volume (Ponzoni et al., 2012), which means that these indices reach saturation under medium and high productivity conditions, which is the case of eucalyptus stands at more advanced ages. This fact explains the lower magnitude of correlations found in our study between volume and the NDVI and TM4/3 indices at ages 6 and 7 years.

Berra et al. (2012) and Pacheco et al. (2012) applied correlation analysis between dendrometric variables and spectral data to develop prediction models and concluded that remote sensing data have great potential to explain the forest dendrometric variables. However, these authors only analyzed one occasion of forest stand measurements, therefore not considering the temporal changes that may occur between the correlations during forest stand growth, as observed in our study.

For the estimation of *Eucalyptus* sp. stand variables such as basal area and volume at different ages, we recommend the use of spectral data obtained from TM4 and TM5 bands of Landsat 5 TM images as well as the vegetation indices that are composed by these bands (i.e. ND54 and TM5/4) as auxiliary data for the traditional forest inventory. For dominant height estimation, we recommend the use of spectral data from the TM2 band of Landsat 5 TM images, independent of eucalyptus stand age.

4. CONCLUSIONS

TM4 and TM5 bands of Landsat 5 TM images and vegetation indices that include these bands in their composition, such as ND54 and TM5/4, presented the closest correlations with the dendrometric variables analyzed.

Eucalyptus sp. stand age directly influences the correlations between spectral data and dendrometric variables, and cannot be disregarded in the spectral characterization of the forest variables. Basal area and volume correlated better with spectral data when measured at age 5 years, while dominant height correlated more closely with spectral data when measured at age 7 years.

TM4 and TM5 bands and ND54 and TM5/4 indices have the potential to be used as auxiliary data to manage *Eucalyptus* sp. stands, at all stages of forest stand growth.

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