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ESTIMATES OF THE LEAF AREA INDEX (LAI) USING LAI-2000 AND HEMISPHERICAL PHOTOS IN *Eucalyptus* PLANTATIONS

ESTIMATIVAS DO ÍNDICE DE ÁREA FOLIAR UTILIZANDO O LAI-2000 E FOTOGRAFIAS HEMISFÉRICAS EM PLANTIOS DE EUCALIPTO

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ABSTRACT

The objective of this study was to estimate the Leaf Area Index (LAI) by indirect methods in plantations of *Eucalyptus* clones in two distinct physical-climatic sites, during the dry and rainy periods. The study was performed in four young and adult *Eucalyptus* stands, located in Rio Doce basin, eastern Minas Gerais state (Brazil) situated in areas of lower and higher altitudes. Nine plots were allocated in each stand. Experimental data were collected in months representing the driest and the wettest periods. LAI indirect measurements were performed using the LAI-2000 equipment and cameras with hemispherical lens. To verify the accuracy of estimation, a destructive analysis was also performed. The LAI measurements by the LAI-2000 was the one which best correlated with the observed LAI (R =0.90), although the hemispherical photos had presented good potential use. It is verified that the LAI of stands in the higher altitudes region, surpassed those of lower altitudes, which was also observed by the indirect methods. The destructive analysis indicates lower values of LAI measured in the dry season although this variation is only significant for higher altitudes. This behavior is also observed for estimates with the LAI-2000, different from the hemispherical photographs which did not identify seasonality of LAI.
Keywords: forest canopy; indirect methods; clones; altitude.

RESUMO

O objetivo deste estudo foi estimar o Índice de Área Foliar (IAF) por métodos indiretos em plantios clonais de eucalipto em dois distintos sítios físico-climáticos, durante as estações seca e chuvosa. O estudo foi feito em quatro talhões, dois jovens e dois adultos, localizado na bacia do Rio Doce, leste de Minas Gerais, situados em áreas de baixas e altas altitudes. Nove parcelas foram alocadas em cada talhão. Dados experimentais foram coletados em períodos secos e chuvosos. As medidas indiretas do IAF foram feitas usando o LAI-2000 e câmeras com lentes hemisféricas. Para verificar a precisão da estimativa foi realizada a análise destrutiva. As medias do LAI-2000 foram aquelas que melhores correlacionaram com os dados de IAF observados (R=0,9), embora as fotos hemisféricas apresentem bom potencial de uso. Foi verificado

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que os valores de IAF dos talhões de maiores altitudes foram maiores comparados às regiões baixas, o que também foi observado pelos métodos indiretos. A análise destrutiva indica baixos valores de IAF medidos na época seca, embora esta variação seja significativamente somente nos talhões das regiões mais altas. Este comportamento é também observado nas estimativas do LAI-2000, diferente das fotografias hemisféricas que não identificaram a sazonalidade do LAI.
Palavras-chave: dossel florestal; métodos indiretos; clones; altitude.

INTRODUCTION

The genus *Eucalyptus* occupies the largest planted area in the Brazilian forest sector with an area of 4.754.334 ha (ABRAF, 2011). Forests planted by the pulp and paper sector of Brazil are among the world's most productive ones, responsible for 29% of the consumption of this wood (ABRAF, 2007). This high productivity is the result of studies in diverse areas of importance such as soils and nutrition, genetic improvement, climatology as well as state of the art technology employed in silviculture handling and the favorable climate.

The fixation of carbon by the plants depends on the interception of radiation and its conversion in chemical energy, therefore, LAI can be considered an indicative parameter of the productivity of a forest (FAVARIN et al., 2002). According to Watson (1947), the Leaf Area Index (LAI) is the integrated leaf area of the canopy per unit area projected on the soil (m^2/m^2).

Meteorological variables actuate directly and indirectly on distinct processes which involve plant growth and thus, LAI variation. Radiation is the energy source responsible for excitation of chlorophyll in the visible spectral range (0.40 to 0.70 μm) which initiates carbohydrate production via photosynthesis. Temperature influences various physiological processes, such as respiration, transpiration, cellular division, photosynthesis, possible affecting tree rooting (CUNHA et al., 2009) and phenological phases including senescence, emission of new leafs and floral initiation (MARTINS et al., 2007). Plant transpiration is principally a function of water available in the soil regulating stomatal opening and consequently, the water vapor diffusion process between stomatal cavity and the atmosphere (CARNEIRO et al., 2008).

Direct or "destructive" methods of LAI measurement are important to obtain a real measurement of the leaf canopy from a representative sample as a function of plant size and type. These methods are references for calibration or development of LAI estimation methods (BREDA, 2003).

LAI measurements are normally impractical in destructive processes when performed continually in a large quantity of trees. Indirect methods present an alternative for this estimation. These methods allow the estimation of LAI by means of the fraction of radiation transmitted within the canopy and is based on a statistical probability distribution and arrangement of leaf elements in the canopy (JONES, 1992).

Among the available canopy analyzers, the LAI-2000 model (Licor Inc., Nebraska) has been amply employed for estimations of LAI in forests (URBAN et al. 2009; DAVI et al. 2008), and more specifically in *Eucalyptus* stands (BARCLAY et al., 2000; XAVIER et al., 2002; MONTE et al., 2007). Measurements are obtained from the simultaneous measurements of interception of the diffuse light in five distinct zenithal angles with a "fish eye" lens. The fraction of incident light on the five angles is used to calculate the canopy area based on mathematical equations (LI-COR, 1992). This method involves the relationship between leaf area and the probability of radiation present to be transmitted along the canopy. To simplify estimation of the LAI by the fraction of light coming from the canopy opening, it is assumed that the canopy is horizontally homogeneous (CHASON et al., 1991).

Hemispherical photography is a technique to study leaf canopies via photographs acquired from a hemispherical lens (fisheye) below the canopy (oriented in the zenith direction). The fraction of canopy opening is measured in multiple visualized angles and analytically separate order, and quantified in terms of angle and leaf area. It is a more economic alternative for this estimate due to the lower cost of acquisition equipment, and can be successfully applied in *Eucalyptus* stands (MACFARLANE et al., 2007a; MACFARLANE et al., 2007b).

The determination of the LAI is important in studies of nutrition, competition, soil-water-plant relationships, accumulation of dry material, production, maturation and crop quality, among others. It is also a key parameter for global and regional models of the biosphere for expression of gaseous and energy exchanges of the plant.

Utilization of this variable in models which calculate evapotranspiration (SOARES et al., 1997) and forest productivity (VARGAS et al., 2002; STAPE et al., 2004; RODRÍGUEZ et al., 2009) is essential.

Based on these facts, the objective of this study was to estimate the LAI by indirect methods (canopy analyzer and hemispherical photographs) in stands of *Eucalyptus* clones in two distinct physical-climatic sites in Rio Doce basin, Minas Gerais state, Brazil.

Based on these facts, the objective of this study was to evaluate the efficiency of indirect methods (canopy analyzer and hemispherical photographs) for determining LAI in stands of *Eucalyptus* clones in two distinct physical-climatic sites in Rio Doce basin, Minas Gerais state, Brazil.

MATERIAL AND METHOD

The present study was performed in forest plantations of *Eucalyptus* clones belonging to Celulose Nipo-Brasileira S/A (CENIBRA), located in Rio Doce basin, eastern region of Minas Gerais state, Brazil. Climate in the region is type humid subtropical - Cwa, according to the Köppen classification.

Measurements were performed in four stands: two, located in Belo Oriente (Figure 1- a,b) and two located in Antônio Dias (Figure1-c,d)

The geographical location of the stands, as well as the area and characteristics of the plantations are presented in Table 1. Since the two regions have distinct altitudes and edapho-climatic conditions, it was not possible to standardize the clones. Therefore, it was selected to work with those which presented the greatest productivities according to data of the company, representing the potential of the regions. For each county, the same clone was utilized (hybrids of the *Eucalyptus grandis* x *Eucalyptus urophylla* species), spacing of 3 x 3.33 m and two distinct ages: young (32 months) and adults (58 months).

Nine fixed plots measuring 30 x 30 m were allocated systematically in each stand, totaling 36 plots in the four studied areas. None of the plots were located near the outer limits of the stands to avoid interference of boarder effects for the specified trees.

For evaluation of seasonal behavior of the clones, samples were taken in the months of August (2008), representing the dry season, and January (2009) for the rainy period.

Meteorological data were obtained by means of automatic stations installed near the stands in each region under study. The period of the meteorological data corresponded to the beginning of the plant cycle until the present age at the collection dates.

For climatic characterization of the areas a water balance was performed based on the Thorthwaite and Mather (1955) method. To determine the water balance, average monthly precipitation and reference evapotranspiration (ETP) data estimated by the Penman-Monteith (1965) equation were used, which includes aerodynamic and energy balance components, at given times. An average Available Water Capacity of 150 mm was adapted. Figure 2 presents average values of water balance and temperature to show the climatic differences of the two municipalities studied. A lesser water availability is verified in the Belo Oriente county (Figure 2b) and as expected, it presented a greater average temperature in relation to Antônio Dias county (Figure 2a) due to its lower elevation.

A destructive analysis was performed to express the observed LAI. To select the trees to be cut down, a sampling inventory in each of the 36 plots was made where data of diameter at breast height (cm) and height (m) of each tree were obtained. Despite the small variation in amplitude of the variables in the inventory of a single plot, three trees per plot were selected with average measurements. Thus, a total of 108 trees in the working stands were cut. This process is representative due to the relatively large sample of trees cut in the homogeneous stands.

The observed LAI for each tree was obtained in accordance with the methodology adapted by Dovey and Du Toit (2006). Total fresh weight of the leaf canopy was obtained from cutting the tree. Later, samples of roughly 150 grams were taken for determination of the leaf area in the laboratory utilizing an LI-3000 (LICOR) device. The moist weight and dry leaf mass were obtained using a forced circulation oven at 65°C. The specific leaf

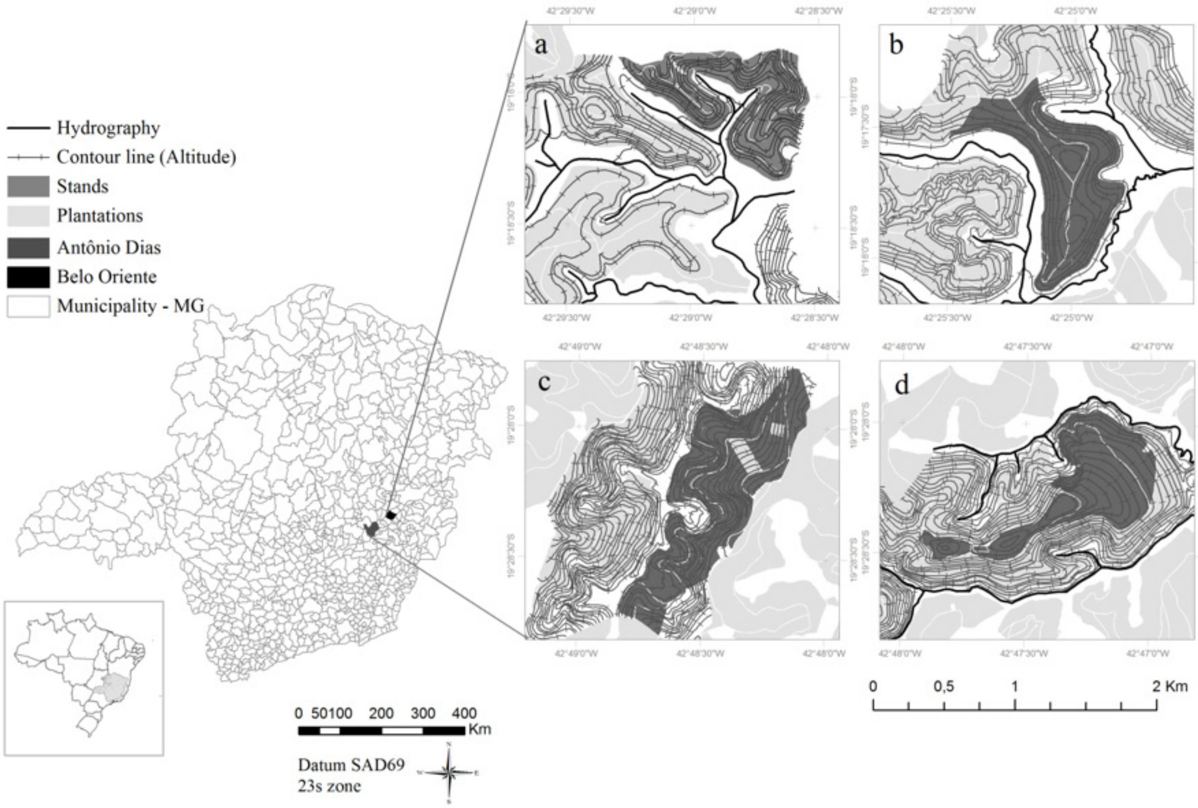

FIGURE 1: Location of the *Eucalyptus* stands: (a, b) Belo Oriente: and (c, d) Antônio Dias.
FIGURA 1: Localização dos Talhões de *Eucalyptus*: (a.b) município de Belo Oriente; (c,d) município de Antônio Dias.

TABLE 1: Description of the stands.
TABELA 1: Descrição dos Talhões.

County	Stand	Age (months)	Clone	Area (ha)	Average slope (°)	Altitude (m)
Antônio Dias	Young	32	372	74	14.7	970
	Adult	58	372	30	19.8	1070
Belo Oriente	Young	32	2719	77	13.4	250
	Adult	58	2719	40	18.6	300

area for each sub-sample was calculated and used to estimate the total leaf area of each sample tree.

LAI-2000 (LI-COR) canopy analyzer was utilized to estimate LAI, operated in remote mode with two optical sensors: one fixed control unit installed in an unobstructed area of open sky and the other mobile unit for measurements below the canopy. Due to the slope of the areas under study, a lens cap of 180° was used to avoid the interference of soil in the measurements. Five measurements were taken per plot, each obtained from five repetitions along each line of the stand (Figure 3), as adopted by Monte et al., (2007).

LAI estimates by means of hemispherical photos involved the use of the following equipment: Nikon camera, FC-E8 (Fish-Eye) Nikon lens with 180° opening, and tripod adjusted to 1.3 m off the ground and leveled. The maximal opening of the objective photography was chosen for conditions of little light as encountered below the forest canopy. The continuous focus mode of the camera was utilized to better capture objects in motion, which is the result of wind in the canopy.

A preliminary test was performed to determine the best position of the camera in relation to the configurations of the stand. Data collected in the row and between rows were analyzed and it was found that the position in the row presented the

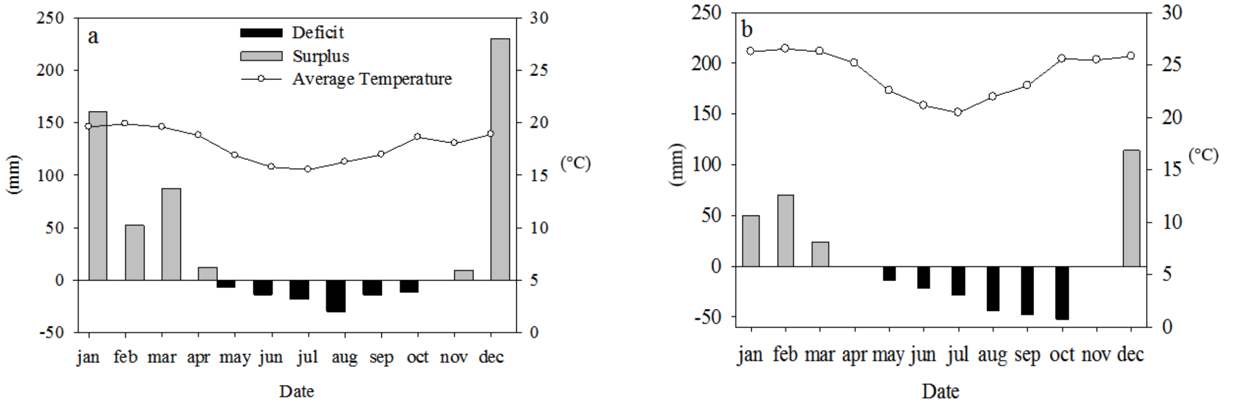

FIGURE 2: Climatic characterization: average monthly water balance and temperature data collected at the meteorological stations of Antônio Dias (a) and Belo Oriente (b).

FIGURA 2: Caracterização climática: Dados médios mensais do balanço hídrico e temperatura coletados nas estações meteorológicas de Antônio Dias (a) e Belo Oriente (b).

greatest correlation (R^2 = 0.8) and lowest coefficient of variation - CV (15%) in relation to the space between rows (R^2 = 0.6; CV=30%) when compared to the LAI obtained by the direct method.

According to the results presented in the preliminary test, four images were obtained in the

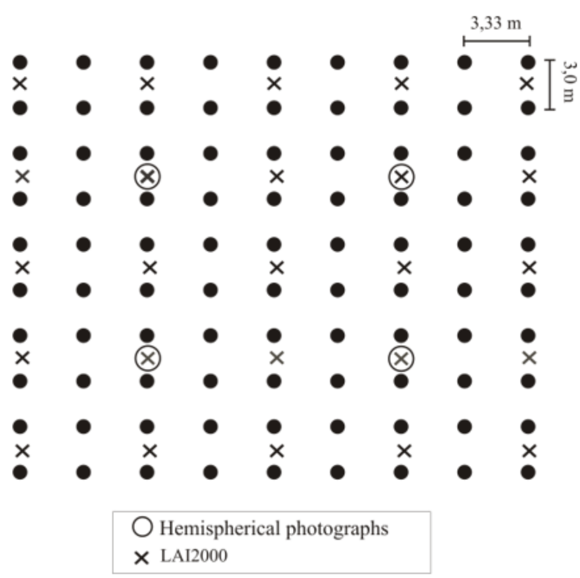

FIGURE 3: Sampling scheme performed by means of the LAI-2000 sensor and hemispherical cameras in the lines and between lines of the *Eucalyptus* stand.

FIGURE 3: Esquema da coleta realizada por meio do sensor LAI-2000 e câmeras hemisféricas nas linhas e entrelinhas dos plantios de eucalipto.

lines of the stand at half the distance of the half-way point along the two diagonals of the plot (Figure 3). Photographs were obtained in resolution of 5 megapixels in the TIFF image format (Tagged Image File Format) in 32-bits. Data utilized for analyses was the average LAI per plot estimated by the hemispherical photographs.

The images were processed using the Hemisfer 1.4.2 (WSL Birmensdorf) software (SCHLEPPI et al., 2007) developed to analyze canopies using hemispherical images. Models developed by Licor (2001) and Lang (1987), models 1 and 2 respectively, were used to estimate the LAI by means of transmission of light in the rings of the lens around the zenith. The Nikon FC-08 lens was adjusted to an angle of 90° and Gamma function of 2.2 as adapted by Macfarlane et al. (2007c) in *Eucalyptus globulus* plantations. The automatic threshold configuration of Nobis and Hunziker (2005) was used to identify the boarders in the image and make separate calculations in five rings (taking into consideration variations in brightness of the sky with the zenith angle).

For both indirect estimate methods, field sampling was preferentially performed under diffuse radiation, in cloudy conditions during the early morning and late afternoon.

Accuracy of the LAI estimates was verified by statistical measurements of dispersion and residuals were utilized to compare results of the indirect methods. The t-test was used to evaluate if the response of the LAI to climatic seasonality is significant at a confidence interval of 95%.

RESULTS AND DISCUSSION

The LAI measurements obtained via the indirect methods showed the same tendency as the destructive analysis, with greater values presented in Antônio Dias at the young age (Table 2). Dovey and Du Toit (2006) encountered average LAI values of 3.80 for LAI-2000 estimates in three year old *Eucalyptus grandis* stands in South Africa at 1260 m above sea level and spacing of 2.44 x 2.44 m. Xavier et al. (2002), working with clones of the same species in the state of Espírito Santo, Brazil, verified a LAI of 1.72 when using the same sensor in stands with an age of 60 months and spacing of 3 x 3 m. These results are near those encountered in this study.

Among the indirect methods, the greatest LAI coefficients of variation are obtained in the oldest stands in Belo Oriente (LAI-2000) and Antônio Dias (hemispherical photos). This can be attributed to the greater volume percentages of trunks and branches not differentiated by the optical sensors, present in the older populations. The presence of hills in these stands may have contributed to the lower homogeneity of data in accordance with the inclination degree of the plot.

When analyzing the dispersion of estimated data in graphical form, a greater variation in LAI-2000 (Figure 3-b) values in relation to the hemispherical photos (Figure 3-c,d) is verified. Although, the lower variability between the measured values appears desirable, it is observed that the deviations encountered in LAI-2000 measurements are closer than those verified by the destructive methods (Figure 3-a), indicating that it is a more precise method in relation to the hemispherical photos. A maximum LAI (LAI-2000) value of 3.14 present in the young stands was encountered in Antônio Dias, while the hemispherical photos presented more homogeneous measurements, and a maximum of 2.09 and 2.08 for the same stand in models 1 and 2, respectively.

Dispersion can also be verified by analyzing the quartiles in each method. A greater variation is

TABLE 2: Average values, standard deviations and coefficients of variation (CV) of the LAI observed by the destructive method, and estimated by LAI-2000 and hemispherical photos (model 1 – HP and model 2 – HP 2) in sampling performed young (Y) and adult (A) stands of *Eucalyptus* clones.

TABELA 2: Valores médios, desvios padrões (SD) e coeficientes de variação (CV) do índice de área foliar observado pelo método destrutivo e estimado pelo LAI-2000 e fotos hemisféricas (modelo 2 – HP e modelo 2 – HP2) em amostragens realizadas em plantios jovens (Y) e adultos (A) de *Eucalyptus* clones.

Stands/Age	Methods	Average	S.D.	C.V. (%)
AD (Y)	Destructive	3.03	0.66	21.7
	LAI-2000	2.48	0.61	24.72
	HP (1)	1.7	0.2	11.85
	HP (2)	1.67	0.17	10.28
AD (A)	Destructive	1.85	0.58	31.52
	LAI-2000	1.98	0.59	29.76
	HP (1)	1.25	0.21	16.82
	HP (2)	1.17	0.19	16.17
BO (Y)	Destructive	1.8	0.47	39.42
	LAI-2000	1.56	0.49	31.27
	HP (1)	1.29	0.15	11.24
	HP (2)	1.24	0.13	10.82
BO (A)	Destructive	1.6	0.3	17.67
	LAI-2000	1.2	0.44	37.19
	HP (1)	1.16	0.16	13.77
	HP (2)	1.13	0.14	12.28

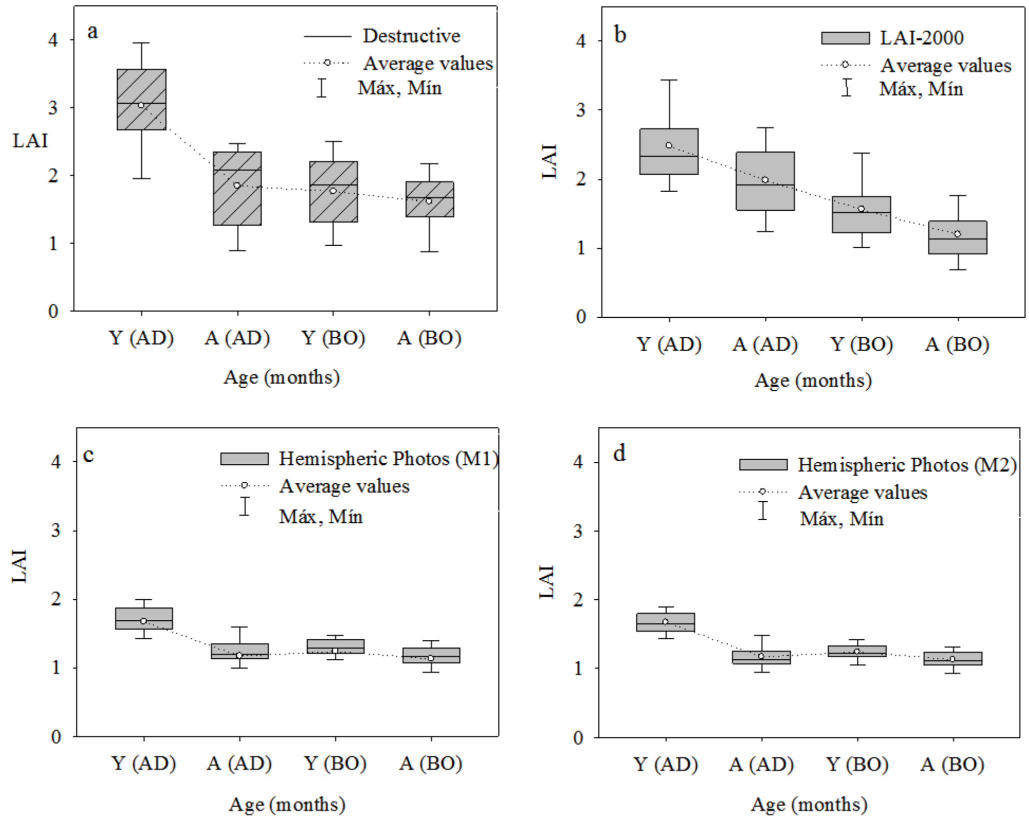

FIGURE 3: Average, maximum and minimum values, and the sampled quartiles for measurements of LAI by destructive (a) and indirect (b, c, d) methods in the stands found in the municipalities of Belo Oriente (BO) and Antônio Dias (AD) at young (Y) and adult (A) stands.

FIGURA 3: Valores Médios, máximos e mínimos e quartis obtidos de medidas de índice de área foliar por métodos destrutivos (a) e indiretos (b,c,d) nos plantios localizados nos municípios de Belo Oriente (BO) e Antônio Dias (AD) em plantios jovens (Y) e adultos (A).

presented by the LAI data from the destructive and LAI-2000 methods. Adult stands in Antônio Dias, for example, showed values that are concentrated in the first to third quartile, where 25% to 75% of all sampled data are encountered, respectively, when compared to the quartiles of the hemispherical photos.

Of the two models used for LAI estimation by hemispherical photos, a non-significant variation was observed between both, where the average value of the first is slightly greater.

At the analyzed ages, greater average estimates of LAI were generally verified for the young stands at both sites. LAI increases exponentially in the younger stands until reaching a maximum point where it stabilizes as the age increases, as presented by Almeida and Soares (2003). These authors encountered a maximum LAI value of 3.5 for *Eucalyptus grandis* between 3 and 4 years old in Espírito Santo, Brazil. Beadle and Turnbull (1992) concluded, from diverse studies by evaluating maximum LAI in *Eucalyptus* plants in Australia, it stabilizes between 4 and 6 years. Battagilia et al., (1998) compiled measurements in a large number of sites in Victoria, Tasmania and Western Australia including areas with irrigation, and verified that the maximum LAI varies between 3 and 6 years for *Eucalyptus nitens* and *Eucalyptus globules*, respectively.

The indirect methods generally present lower values in relation to measured LAI with sub estimates of 2 to 49% per stand. Macfarlane et al. (2007a), working with these optical instruments, encountered a range of LAI estimates lower than 55% in *Eucalyptus globulus* stands. Breda (2003) suggested that the ratio of this sub estimate can be in the non-random distribution of leaf elements within the canopy. Dovey and du Toit (2006) cited that as well as this factor, angular distribution of leaf insertion and homogeneous horizontal distribution of the leaves in the canopy can also contribute for these results. It should be highlighted that in some young plots in Antônio Dias, a complete closure of the canopy was not observed, which causes lower LAI estimates.

In the analysis performed per stand (Table 3), it was found that the LAI-2000 was the best indirect method which correlated with LAI (destructive), with the lowest error (RMSE = 0.23) and angular coefficients near one and linear to zero. From the hemispherical photo models, the model of Lang (1987) (M1) presented the best correlation than the model of Licor (2000) (M2). These results surpass those encountered by Macfarlane et al. (2007a) who observed greater quadratic errors in analysis per stand (RMSE = 1.6) in nine stands of *Eucalyptus globulus*. These same authors also encountered a poor correlation with hemispherical photos.

It was verified that the destructive measurements performed in the dry and rainy periods differed only in Belo Oriente (Figure 4), although in both regions the average during the dry period (2.04 ± 1.05) were lower than those of the rainy period (2.52 ± 0.64). Among the indirect methods, the LAI-2000 also differed in the region of Belo Oriente. Minor variations are evident for the hemispherical photographs in both regions studied, indicating low sensitivity of this method to detect seasonal variations in the LAI.

Analyzing LAI response at the sites, it was found that stands in Antônio Dias showed greater leaf growth compared to those ones in Belo Oriente. The gain in carbon balance of the plantations in Antônio Dias resulted in a greater allocation of assimilates for the plant and lower CO_2 losses via respiration as a consequence of the lower temperatures observed at this site, as indicated in Figure 2.

Souza et al. (2006), studying the same regions, encountered correlations between stomatal conductance and the vapor pressure deficit (VPD) with lower values of conductance in locations where the VPD was greater. The results of Silva (2007) indicate greater evapotranspiration (1177 mm) and VPD (8 mbar) in Belo Oriente compared to Antonio Dias (798 mm and 5 mbar). This result suggests a smaller stomatal opening and, therefore, a decrease

TABLE 3: Precision of LAI estimates by indirect methods in average values per stand in the two sampling periods.

TABELA 3: Precisão das estimativas do índice de área foliar por métodos indiretos em valores médios por talhão nos dois períodos amostrados.

	R	RMSE	Equation
LAI X LAI (LAI-2000)	0.9	0.23	y = 0.868x + 0.004
LAI X LAI (FH/M1)	0.75	0.55	y = 0.220x + 0.940
LAI X LAI (FH/M2)	0.65	0.57	y = 0.243x + 0.841

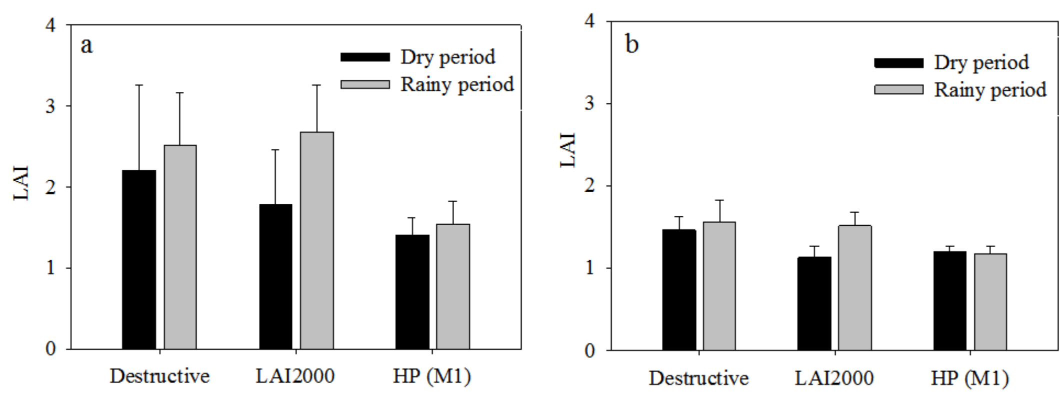

FIGURE 4: Averages of the measured (destructive) and estimated (LAI-2000 and Hemispherical Photos - HP) LAI data in the dry and rainy periods in the regions of Belo Oriente (a) and Antônio Dias (b).

FIGURA 4: Média dos dados medidos (destrutiva) e estimados (LAI-2000 e fotos hemisféricas - HP) nos períodos secos e chuvosos nas regiões de Belo Oriente (a) e Antônio Dias (b) in productivity in Belo Oriente due to reduction of gaseous exchange.

CONCLUSIONS

Of the indirect methods utilized to estimate LAI, the LAI-2000 presented the best correlation with the data obtained from destructive analyses, therefore showing to be more efficient for determination of this eco-physiological variable. Hemispherical photos obtained good results indicating potential use in these estimations.

LAI showed lower values during the dry period in the two ages and sites studied. This response was also verified in the data measured by LAI-2000, indicating a sensibility of the equipment based on seasonal variation present in these stages. It was verified that the LAI of the stands in Antônio Dias, surpassed those of Belo Oriente with lower altitude.

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