DOI: https://doi.org/10.29298/rmcf.v12i63.808

Article

Medición del índice de área foliar y su dinámica estacional en plantaciones de *Eucalyptus urophylla* S. T. Blake

Measurement of the leaf area index and its seasonal dynamics in *Eucalyptus urophylla* S. T. Blake plantations

Adrián Hernández Ramos[1], José René Valdez Lazalde[2*], Gregorio Ángeles Pérez[2], Héctor Manuel de los Santos Posadas[2], Jonathan Hernández Ramos[3], Alicia Peduzzi[4] y Omar Carrero[5]

Resumen

El índice de área foliar (*IAF*, m^2 m^{-2}) es un indicador de productividad en las plantaciones forestales y puede usarse para describir la respuesta de los árboles a la aplicación de prácticas silvícolas. El objetivo del estudio fue identificar un método preciso y eficiente para estimar el *IAF* en plantaciones forestales comerciales de *Eucalyptus urophylla*. Paralelamente, se analizó la dinámica estacional del *IAF* durante un año. Se establecieron 28 unidades de muestreo en las que se realizaron mediciones mensuales de *IAF*, con los métodos de recolección de hojarasca ($IAF_{Hojarasca}$) y óptico ($IAF_{Óptico}$). Además, se implementó un muestreo destructivo de 93 árboles para estimar el *IAF* mediante alométria ($IAF_{Alométrico}$). Los valores promedio estimados de *IAF* fueron 2.7, 2.6 y 1.6 para el método alométrico, recolección de hojarasca y óptico, respectivamente. Esto implicó una subestimación promedio de 39 y 37 % del método óptico, en comparación con los métodos alométrico y de recolección de hojarasca. Un análisis de correlación de las estimaciones de *IAF*, obtenidas con los tres métodos aplicados, permitió identificar una alta asociación (*r*= 0.75, coeficiente de correlación de *Pearson*) entre los valores estimados con los métodos de recolección de hojarasca y óptico. Con base en este resultado (asociación) se ajustó un modelo de regresión, a fin de calibrar las mediciones indirectas ($IAF_{Óptico}$) a un valor más preciso, $IAF_{Calibrado}$. El valor máximo de *IAF* se registró en julio y agosto, meses del mayor crecimiento para *E. urophylla* en condiciones de plantación comercial en México.

Palabras clave: Alometría, área foliar, fotografía hemisférica, fracción de huecos, hojarasca, plantaciones forestales comerciales.

Abstract

Leaf area index (*IAF*, m^2 m^{-2}) is an indicator of productivity in forest plantations and can be used to describe the response of trees to the application of silvicultural practices. The objective of the study was to identify a precise and efficient method to estimate the *IAF* in commercial forest plantations of *Eucalyptus urophylla*. At the same time, the seasonal dynamics of the *IAF* was analyzed for one year. 28 sampling units were established in which monthly *IAF* measurements were made using the litter ($IAF_{Hojarasca}$) and optical ($IAF_{Óptico}$) collection methods. Additionally, a destructive sampling of 93 trees was implemented to estimate the *IAF* through allometry ($IAF_{Alométrico}$). The estimated average values of *IAF* were 2.7, 2.6 and 1.6 for the allometric, litter collection, and optical methods, respectively. This implied an average underestimation of 39 and 37 % of the optical method compared to the allometric and litter collection methods, respectively. A correlation analysis of the *IAF* estimates, obtained through the three methods applied, allowed to identify a high association (*r* = 0.75, Pearson's correlation coefficient) between the values estimated with the litter collection and optical methods. Based on this result (association), a regression model was adjusted to calibrate $IAF_{Óptico}$ values (indirect measurements) to more precise estimates, $IAF_{Calibrado}$. The maximum value of *IAF* was recorded during July and August, months of greatest growth for *E. urophylla* under commercial plantation conditions in Mexico.

Key words: Allometry, leaf area, hemispheric photography, gaps fraction, leaf litter, commercial forest plantations.

Fecha de recepción/Reception date: 26 de junio de 2020
Fecha de Aceptación/Acceptance date: 4 de noviembre de 2020

---

[1]Campo Experimental Saltillo. INIFAP. México.
[2]Posgrado en Ciencias Forestales. Colegio de Postgraduados. Campus Montecillo. México.
[3]Campo Experimental Chetumal, INIFAP. México.
[4]*Woods Hole Research Center*. *Gilman Ordway Campus*. USA.
[5] GRANFLOR. Brasil.
*Autor de correspondencia; correo-e: valdez@colpos.mx

Introduction

Leaf area (*AF*, for its acronym in Spanish) is the surface in which energy and matter are exchanged between a plant and the atmosphere; it is considered a key variable to model the growth of trees and the conditions of a forest (Guangjian *et al.*, 2019). Its dynamics can be analyzed by parameters such as the leaf area index (*IAF*, for its acronym in Spanish), defined as the number of leaves present per unit area (m^2 m^{-2}) (Sun *et al.,* 2019). *IAF* is used as an indicator to assess the productivity of ecosystems and forest plantations (Papamija and García, 2012).

The methods to estimate the *IAF* are direct or indirect. The former require destructive sampling and involve the direct measurement of the tree's foliage or the collection of litter over a period, which makes them costly and slow to apply (Muñoz et al., 2008), which limits their use to large scale. Indirect methods can be based on the measurement of solar radiation that penetrates the forest floor through the canopy of the trees (Hu *et al*., 2014). These methods are an efficient alternative for measuring *IAF* in different types of forest vegetation (Martínez *et al*., 2006; Chen et al., 2018). However, despite their efficiency, indirect methods tend to present bias in the estimates, so it is common to turn to the use of mixed methods that establish precise mathematical relationships between allometric estimates (direct) and optical measurements (indirect) (Aguirre-Salado *et al*., 2011; Guangjian *et al.,* 2019).

The estimation of *IAF* in commercial forest plantations (PFC) is important to determine their productive potential and to establish possible growth responses due to forestry management (Papamija and García, 2012). For this reason, it is justified to determine the most efficient and precise method to estimate this index for each species used in plantations. In Mexico, the *Eucalyptus* genus is the second most frequent in PFC (Conafor, 2014), in particular *E. urophylla* S. T. Blake, a well-adapted and fast-growing species in tropical regions (Wright, 1997).

The main objective of this study was to estimate *IAF* by direct and indirect methods in *E. urophylla* commercial forest plantations, based on the hypothesis that indirect measurements of *IAF* can provide reliable information and with less effort to measure the dynamics of growth and status of forest plantations. At the same time, it was sought to analyze the seasonal dynamics of *IAF* for one year.

Materials and Methods

Study area

The study was carried out in commercial forest plantations of *E. urophylla* established in *Huimanguillo, Tabasco*, Mexico (17°55' N, 94°06' W) (Figure 1), where the average altitude is 30 m. The climate is warm humid (A_m (f)), with rains in summer, 2 500 mm average annual rainfall and average annual temperature around 26 °C (García, 1998). Soils are of the Feozem type (INEGI, 2005). The surrounding vegetation is composed of remnants of high evergreen forest and secondary vegetation (Conafor, 2012). The plantations are between one and seven years old and were established at an average spacing of 2.5 m × 3.5 m between plants and rows, at an average density of 1 367 trees ha^{-1} with *E. urophylla* clonal plants.

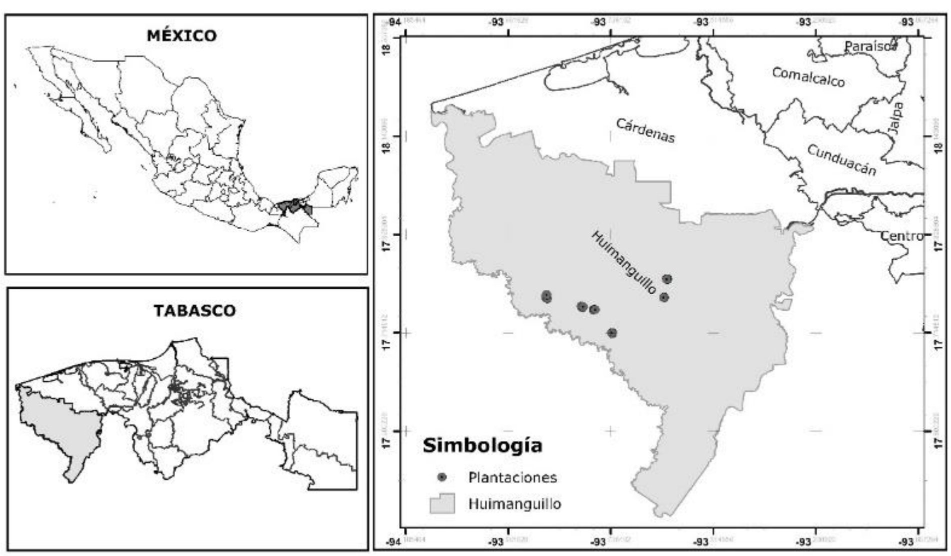


Figure 1. Location of *Eucalyptus urophylla* S. T. Blake comercial forest plantations.

Data collection in the field. Through selective sampling, with special attention to respecting the original plantation density or with the least possible loss of trees, four rectangular sites of 500 m^2 per plantation were demarcated. In total, 28 sampling sites were established distributed in seven plantations, each one with a different age - from one to seven years old. At the beginning and end of the study (July 2014 and August 2015, respectively) the normal diameter (*Dn*, cm) was measured with a 95 cm Mantax Black caliper and the total height (*At*, m) with a SUUNTO clinometer of all trees within the sampling sites.

To estimate the *IAF* by means of the litter collection method, circular capture traps of 1 m^2 of surface were placed, 1 m above the ground. In total, 112 traps were placed (16 per plantation, 4 per sampling site). On a monthly basis, from August 2014 to July 2015, the litter present in the traps was collected and dehydrated until reaching constant weight (about 72 hrs) in a drying SHEL LAB SMO14-2 oven at 70 °C. Subsequently, dry weight (g) was obtained by a 0.01 g precision OHAUS Navigator™ scale.

The optical method involved obtaining five hemispheric photographs (FH, for its acronym in Spanish) at each sampling site by using a Nikon Coolpix D3100 camera (Figure 2), equipped with a 5 mm "fish eye" type lens. The FHs were obtained according to the minimum sample size defined by Whitford *et al*. (1995). Each sampling site was divided into four sections to take one FH per section and one more in the center. The monthly sample was 140 FH, which were analyzed with the Hemisfer© Patrick Schleppi version 2.13 application, an application that integrates a wide variety of methodologies to estimate the *IAF* (Schleppi *et al.,* 2007).

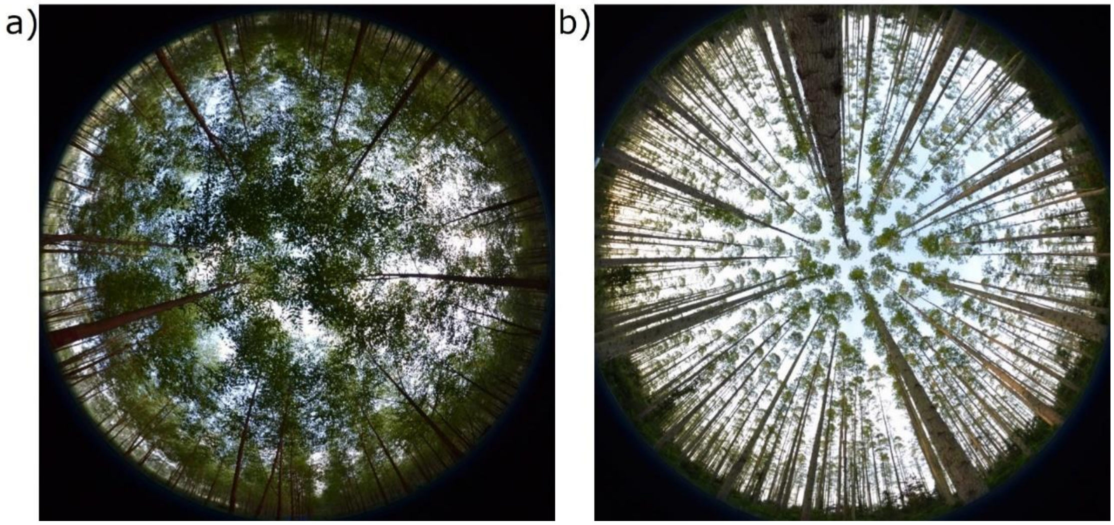


Figure 2. Examples of hemispheric photographs taken in one-year (a) and seven-year (b) old plantations.

The *IAF* allometric estimation involved the destructive sampling of 93 trees selected from seven plantations of different age (15, 13, 12, 12, 12, 15 and 14 individuals in the plantations of one to seven years, respectively), distributed in a 7.8 to 33.2 cm interval of normal diameter and in total height between 8.5 and 33.3 m. According to Jonckheere *et al.* (2004), the sample obtained is representative to estimate the specific leaf area (*AFE*, for its acronym in Spanish, m^2 kg^{-1}) and the projected leaf area (*AFP*, for its acronym in Spanish, m^2). The total weight of the green foliage of each felled tree was recorded and a sample (0.5 kg) of foliage was extracted from different parts of the crown per tree, which was dehydrated at 72 °C to determine its dry weight on a 0.01g OHAUS Navigator^{TM} precision scale. The felled trees were measured for stump diameter (*Dt*, cm) and normal diameter (*Dn*, cm) with a 95 cm Mantax Black^{TM} caliper; in addition to the total height (*At*, m) with a 30 m Truper 12639 measuring tape. With these data, allometric equations were generated to estimate *AFE* and *AFP*.

Estimation of the specific leaf area. The *AFE* was estimated at the tree level ($AFE_{Individual}$, m^2 kg^{-1}) by the arithmetic calculation used by Cano *et al.* (1996) and Muñoz *et al.* (2008). In a subsample of 60 leaves, of the initial sample of foliage collected from each felled tree, the adaxial leaf area of each leaf (AF_{Hoja}) (m^2) was measured with a foliar integrator (Li-COR 3000C). They were then dried and weighed to obtain the dry biomass per leaf (BS_{Hoja}) (kg). Through the quotient of AF_{Hoja} and BS_{Hoja} (Equation 1) the individual *AFE* of each tree was obtained. After that, the values were averaged to obtain a value by plantation age:

$$AFE_{Individual} = \sum_{i=1}^{n} AF_{Hoja} \Big/ \sum_{i=1}^{n} BS_{Hoja} \qquad (1)$$

Estimation of the projected leaf area. The $AFP_{Individual}$ (m^2) per tree was estimated as a result of $AFE_{Individual}$ and the dry leaf biomass (BFS_{Total}) (kg) (Equation 2). BFS_{Total} was calculated by the methodology recommended by Muñoz *et al.* (2008), which comes from multiplying the green leaf weight ($PFV_{individual}$) by the dry weight/green weight quotient ($R_{Muestra}$) of leaves from the foliage simple per felled tree (Equation 3).

$$AFP_{Individual} = (AFE_{Individual})\,(BFS_{Total}) \qquad (2)$$

$$BFS_{Total} = (PFV_{Individual})\,(R_{Muestra}) \qquad (3)$$

Estimation of the leaf area index. The *IAF* was estimated by the allometric, litter collection and optic methods. For the first one, the BFS_{Total} for each tree at the sampling sites was initially calculated with the equations suggested by Hernández-Ramos *et al.* (2017) for the species, using the allometric variables. After that, with the calculated BFS_{Total}, the $AFP_{Individual}$ was estimated for each tree in the site, from the model adjusted in this document and described in the results. These estimations allowed to obtain $IAF_{Alométrico}$ (m^2 m^{-2}) (Equation 4) to the site level for the two measurement dates (Initial: July, 2014 and final: August, 2015).

$$IAF_{Alométrico} = \frac{\sum_{i=1}^{n} AFP_{Individual}}{AS} \qquad (4)$$

Where:

$IAF_{Alométrico}$ = Leaf area index per site calculated through allometric relations

$AFP_{Individual}$ = Projected leaf area estimated per tree (m^2)

AS = Area of the site (m^2)

n = Number of trees at the site

The *IAF* estimation by means of litter collection ($IAF_{Hojarasca}$) for each sampling site resulted from the weight of the dry litter accumulated during a year in a trap and the value of the average $AFE_{Individual}$ for a plantation of the same age; at the end, the four values obtained per trap were averaged to obtain an *IAF* value per site (Liu *et al*., 2015).

The optical *IAF* ($IAF_{Óptico}$) was estimated monthly with the Hemisfer© Patrick Schleppi version 2.13 program, from the individual processing of the FHs taken at each site, with the Thimonier *et al*. (2010) method, which consists of weighting the *IAF* values estimated from the Norman and Campbell Ellipsoidal method with a regression model that integrates the leaf insertion angle and the solar radiation under the canopy as predictive variables (Lang and Yueqin, 1986). The result of the previous process was applied a correction factor for clustering of the canopy and foliage not randomly distributed, to reduce the underestimation of the *IAF* caused by a greater input of solar radiation (Chen and Cihlar, 1995; Liu *et al*., 2015). The $IAF_{Óptico}$ value per site corresponds to the average of the values calculated for the five FHs taken at the site.

In spite of the corrections made to the optical method, the calculated values tend to underestimate the real *IAF* values (Weiss *et al.,* 2004). To reduce this bias, the calibration proposed by Aguirre-Salado *et al.* (2011) was made, which consists of adjusting regression models in which the $IAF_{Alométrico}$ or $IAF_{Hojarasca}$ are dependent variables and the $IAF_{Óptico}$ is the independent variable. The result is a calibrated *IAF* value ($IAF_{Calibrado}$).

Statistical analysis. The values of $AFE_{Individual}$ and $AFP_{Individual}$ obtained from destructive sampling data were analyzed using an ANOVA, defining the planting age as the primary factor. Differences between means were evaluated with the Tukey test. The correlation between the *AFP* and *AFE* variables with the *Dn*, *At* and BFS_{Total} variables was analyzed with the Pearson's correlation coefficient. The variables related to a greater degree with the *AFP* and the *AFE* served as the basis to adjust the non-linear regression models (Table 1) (Cano *et al*., 1996; Aguirre-Salado *et al.*, 2011).

Table 1. Adjusted models to estimate the projected leaf area (*AFP*) and the calibrated leaf area index in *Eucalyptus urophylla* S. T. Blake.plantations.

Model	Type of model	Structure
1	Chapman-Richards	$y = \beta_0\left(1 - e^{(-\beta_1 X_1)}\right)^{\beta_2}$
2	Monserud y Sterba	$y = X_1 e^{\left(\beta_0 X_1^{\beta_1} X_2\right)}$
3	Power	$y = \beta_0 X_1^{\beta_1}$
4	Schumacher Cobb-Webb	$y = \beta_0 X_1^{\beta_1} X_2^{\beta_2}$
5	Schumacher´s exponential	$y = \beta_0 e^{\left(-\beta_1/X_1\right)}$

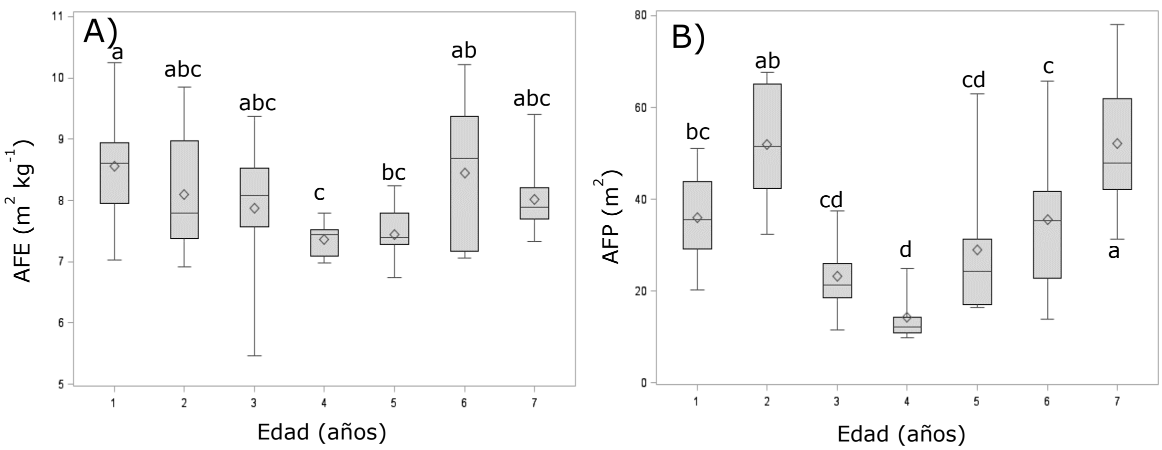
y = Dependient variable; χ_n = Normal diameter (*Dn*); *At* = Total height; *Ab* = Basimetric area; *Vt* = Total volume; BFS_{Total} = Dry leaf biomass; B_n= Parameters of the model.

For *IAF*, the estimated values by the three methods used were plotted and compared by means of a Pearson correlation analysis. It should be noted that for the comparison of the allometric and optical *IAF*, the values and FH corresponding to the same measurement date were used to avoid a temporality error. The direct and indirect methods mostly related were used to generate a calibrated $IAF_{Calibrado}$ from a non-linear regression model, with the models in Table 1. The selection of the models with the best fit was made considering the highest adjusted R^2 value and the lowest value of the root mean square error (*RECM*), in addition to the significance of its parameters. The selected models were analyzed to corroborate compliance with the regression assumptions using the Shapiro-Wilk test for normality and the White test to detect heteroskedasticity ($p \geq 0.05$). Given that the data presented this last problem, specifically the *IAF*, a residual correction was applied using the *AFP/ROOT* variable (BFS^2). Finally, the Durbin-Watson test was applied to detect collinearity between variables. The analysis was carried out using the PROC MODEL procedure of SAS 9.4 Institute Inc. (SAS, 2014).

Results and Discussion

Specific leaf area and projected leaf area. The average value of $AFE_{Individual}$ and *AFP* was 8.024 m^2 kg^{-1} and 35.995 m^2, respectively, for the sample. Both variables showed significant differences (P = 0.0001) between the averages of the trees with different ages (Figure 3). The comparison of means showed a higher value of *AFE* (8.56 m^2 kg^{-1}) in the one-year-old plantation. In contrast, the four-year plantation yielded the lowest value (7.36 m^2 kg^{-1}). The highest value of individual *AFP* was presented by the seven-year plantation (52.23 m^2) and the lowest value (14.18 m^2) was calculated for four-year plantations, coinciding with the lowest value of *AFE*. The *AFE* is lower at the age of four and five years of planting (Figure 3A). This tendency can be explained by the adaptation of the leaves to competition for light, water stress and management practices at intermediate ages of growth (Vega *et al*., 2010). Other species show a similar trend. For example, *Pinus patula* Schiede ex Schltdl. *et* Cham.

showed a 6 % reduction when going from one to two years of age, which was attributed to the increase in structural components and substances in the older foliage, making it heavier (Cano *et al*., 1996). On the other hand, the *AFE* values obtained in this study that vary between 7.36 and 8.56 m^2 kg^{-1} are high, which may be related to the high density of the plantations (1 367 trees ha^{-1}), as demonstrated by Muñoz *et al*. (2008) for *Eucalyptus nitens* H. Deane & Maiden, who calculated the highest *AFE* values in plantations with higher densities.



Different letters indicate statistical difference (Tukey, p≤0.05) in their mean.

Figure 3. Trend of (A) specific leaf area (*AFE*, m^2 kg^{-1}) and (B) projected leaf area (*AFP*, m^2) in regard to the age of the plantation.

In the *AFP* an irregular behavior was observed, since it increased in the first years of growth, later it decreased and then increased again (Figure 3B). This variation is due to the mortality that is registered in the plantations, in which, by losing individuals, the *AFP* decreases in the short term and then increases due to the increase in the availability of nutrients, water and light, which allows generating more foliage per unit area (Rodríguez-Ortiz *et al.,* 2011), which favors capturing more solar radiation to increase the photosynthetic rate.

Relationship of the *AFE* and *AFP* with structural variables of the plantation. In the case of *AFE*, this relationship is negative and not significant, so no regression models were adjusted. For *AFP*, the correlation is positive (BFS_{Total} [0.97] and *Dn* [0.50]), which indicates a greater amount of leaves as the dimensions of the tree increase, especially the width of the normal diameter and, consequently, the crown diameter (Rodríguez-Ortiz *et al.,* 2011).

Model 3 exhibited $R^2_{ajustada}$ high values, low for *RCME*, highly significant parameters, normality (Shapiro-Wilk with a 0.95 value), inexistence of collinearity (Durbin-Watson test (1.67) and logical estimations of *AFP* for the low study sites (Table 2). However heterocedasticity problems occurred, which were solved by correction for weighting residuals with the *AFP/RAÍZ* (BFS^2) variable. The correction of the model improved the fit statistics ($R^2_{ajustada}$ = 0.9526, RECM= 0.9077 and its structure: $AFP_{Individual} = 7.952315(BFS_{Total})^{1.006678}$) making it statistically stable and reliable to estimate *AFP* in *E. urophylla* plantations.

Table 2. Statistics and values of the statistical parameters of the adjusted models to estimate the projected leaf area.

Mo	*RECM*	$R^2_{ajustada}$	Parameter	Estimator	*EE*	*t* value	Pr > |*t*|
1	4.2141	0.943	B_0	163.6677	78.6830	2.08	0.0410
			B_1	0.072823	0.0512	1.42	0.1591
			B_2	1.169669	0.1657	7.06	<0.0001
2	8.1996	0.784	B_0	3.972913	0.8064	4.93	<0.0001
			B_1	-1.14553	0.0731	-15.67	<0.0001
3	4.2394	0.942	B_0	8.508989	0.4954	17.18	<0.0001
			B_1	0.964571	0.0320	30.19	<0.0001
4	4.2404	0.942	B_0	9.244596	0.9333	9.91	<0.0001
			B_1	-0.03867	0.0389	-0.99	0.3238
			B_2	0.982786	0.0367	26.76	<0.0001
5	5.2332	0.912	B_0	103.333	4.1930	24.64	<0.0001
			B_1	4.322394	0.2083	20.75	<0.0001

RECM = Root of the mean square error; $R^2_{ajustada}$ = Adjusted coefficient of determination; *EE* = Standard error; B_n = Parameters of the model; Valor *t* = Value of the Student t distribution; Pr>|*t*| = Significance.

Leaf area index. The estimated values of average *IAF* that include the seven plantations are 2.7, 2.6 and 1.6 m^2 m^{-2}, within the ranges 1.8 to 3.7, 1.3 to 4.2 and 1.0 to 2.6 m^2 m^{-2}, for $IAF_{Alométrico}$, $IAF_{Hojarasca}$ e $IAF_{Óptico}$, respectively. The allometric method estimated the highest value of *IAF* in the one-year plantation and the lowest was recorded for the three-year old (Figure 4). The highest $IAF_{Hojarasca}$ value was recorded in the seven-year-old plantation and the lowest in the four-year-old. The $IAF_{Óptico}$ value was higher in the seven- and one-year-old plantations and the rest presented homogeneous values of less than 1.7 m^2 m^{-2}.

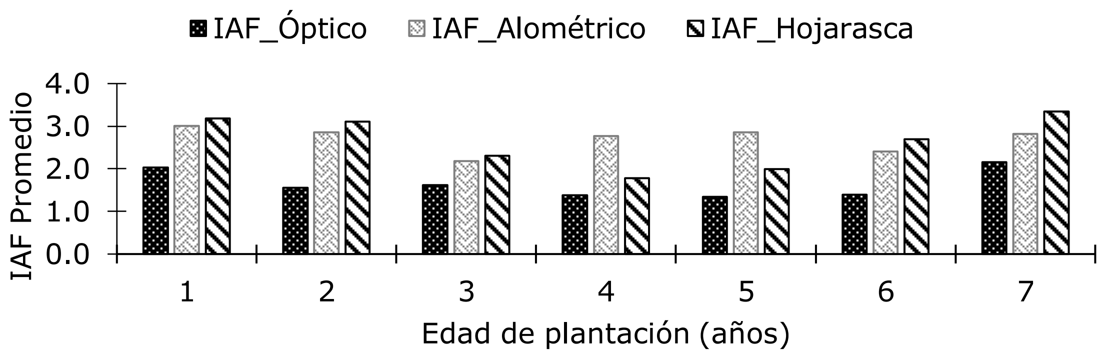


Figure 4. Leaf area index (*IAF*) estimated by direct and indirect methods for *Eucalyptus urophylla* S.T. Blake plantations.

If the direct methods are considered as a reference, the $IAF_{Óptico}$ presented an average underestimation of -39 and -37 % in the evaluated plantations, with the $IAF_{Alométrico}$ and the $IAF_{Hojarasca}$, respectively. Although an average percentage difference of 8 % was verified between the direct methods, for all plantations, the $IAF_{Hojarasca}$ value was taken as a reference parameter since, in addition to estimating the *IAF* with precision; it allows describing its dynamics during a growth cycle. In addition, its measurement is not destructive of the trees, as demonstrated by Castellanos and León (2010) when modeling the monthly foliar production of *Acacia mangium* Willd. In other words, the $IAF_{Hojarasca}$ value was considered the basis for the comparisons between methods and for the calibration of the values obtained using the indirect method ($IAF_{Óptico}$), since this method predicts the mean and spatial variability of *IAF* with greater precision (Iwamoto and Hiura, 2011).

The correlation of the $IAF_{Alométrico}$ values with the $IAF_{Óptico}$ and the $IAF_{Hojarasca}$ is 0.30 and 0.33 respectively, which are inadequate to fit a regression model. However, the correlation between the $IAF_{Óptico}$ and $IAF_{Hojarasca}$ is 0.75. Therefore, the models presented in Table 1 were adjusted to calibrate the $IAF_{Óptico}$ using the $IAF_{Hojarasca}$. The time of measurement of the allometric method corresponded to the beginning of leaf production, which surely influenced the low values of the $IAF_{Alométrico}$ compared to the $IAF_{Hojarasca}$.

Except for the power type model (Table 1, model 3), the models tested to calibrate the *IAF* presented low adjustments. Model 3 had a reasonable adjustment in the calibration of the $IAF_{Óptico}$ in regard to the $IAF_{Hojarasca}$ (Table 3). These two techniques can be compared at the site level since the litter collection and hemispheric photographs were made without spatial difference (Figure 5). The selected model showed normality with a statistic of W = 0.94, the White test indicated homoscedasticity and the Durbin-Watson statistic was 1.78, which means there is non-collinearity between variables.

Table 3. Adjustment statistics of the power model (model 3) to calibrate the estimates of the leaf area index of *Eucalyptus urophylla* S.T. Blake.

IAF	**Mo**	B_0	B_1	B_2	***RECM***	$R^2_{ajustada}$
Litter *vs* Optical	3	1.650636	0.956617	-	0.428	0.55

RECM = Root of the mean square error; $R^2_{ajustada}$ = Adjusted coefficient of determination; B_n = Parameters of the model.

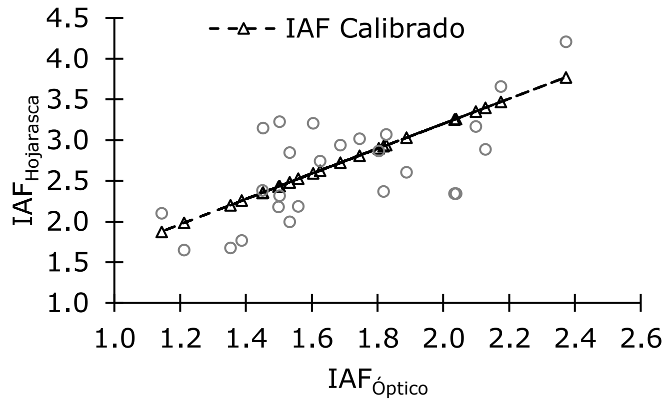


Figure 5. Scatter diagram of the leaf area index, real data (litter collection) and estimates ($IAF_{Calibrado}$) ($IAF_{Calibrado} = 1.650636 * IAF_{Óptico}{}^{0.956617}$) for *Eucalyptus urophylla* S. T. Blake.

The estimated *IAF* values are similar to those of *E. nitens* plantations in the Central Zone of Chile, with + values between 1.63 and 2.55 m^2 m^{-2} for densities of 1 100 trees ha^{-1}. At the same time, these values are low compared to lower density plantations due to the competition for space among the trees for the development of the crown (Muñoz *et al.,* 2008). Papamija and García (2012) recorded $IAF_{Alométrico}$ values of 2.30 to 3.20 m^2 m^{-2} for *Eucalyptus grandis* W. Hill ex Maiden plantations established in Colombia and even higher with the optical method, from 2.42 to 3.64 m^2 m^{-2}, which differs from that calculated in this study, in which the $IAF_{Óptico}$ underestimates the value obtained by allometry, in addition to obtaining a correlation coefficient between the two methods equal to 0.011.

Macfarlane *et al*. (2007) determined an *IAF* of 3.0 m^2 m^{-2} for *Eucalyptus marginata* Donn ex Sm. plantations of 12-years old using the allometric method and 1.77 m^2 m^{-2} using the optical method with correction for FH agglutination, which represents a 41 % underestimation. In a similar way, Chen and Cihlar (1995) determined underestimations of the *IAF* in a range of 15 to 25 % by means of the optical method due to the agglutination of the foliage, for which they recommended applying a correction to reduce the error by integrating a parameter of branch area index. This variation in the low estimates of the $IAF_{Óptico}$ is due to factors such as the automatic exposure of the lens towards the light (Thimonier *et al*., 2010); the clumping effect of the tree canopies (Weiss *et al*., 2004) and the subjective choice of threshold when analyzing images with any program (Coops *et al*., 2004).

Monthly dynamics of the leaf area index. With the adjusted model ($IAF_{Calibrado}$) and the $IAF_{Óptico}$ measurements, the monthly *IAF* values were calculated (Figure 6). As expected, these values presented a negative relationship with the fall of litter, that is, the maximum peaks of leaf collection agree with low values of *IAF* in the plantations. During the months of February to May, there was an increase in the fall of litter and consequently a decrease in the *IAF* in *E. urophylla* (Figure 6), the values varied between 2.14 and 2.20 m^2 m^{-2} in the season of lower production. In June and July an increase in the *IAF* was observed, corresponding to the time of maximum leaf production and the beginning of the growth stage, when they reached maximum values from July to September of 2.65 to 2.71 m^2 m^{-2}.

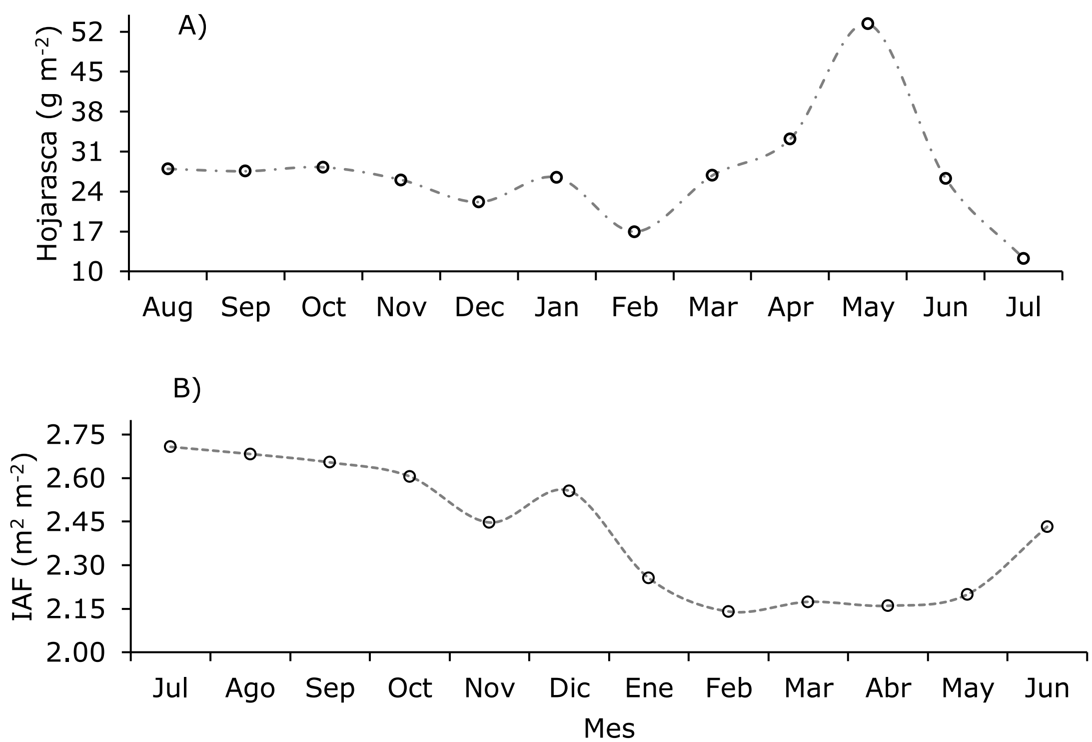


Figure 6. Monthly dynamics of litter fall (A) and leaf area index (B) for *Eucalyptus urophylla* S. T. Blake plantations.

In November took place a steep decline in the *IAF* value from an increment in litter fall in October; however, the following month a foliar recovery was observed, indicating that during the rainy or growing season *E. urophylla* presents a continuous replacement of foliage according to water availability. This behavior is similar to that described by Castellanos and León (2010) for *Acacia mangium* forest plantations, in which the highest peak of foliar production occurred at the beginning and during the rainy season (July to October).

Theoretically, older plantations should have a high *IAF*, however, for the case studied, the highest *IAF* value was presented in younger plantations, with a decreasing trend as age increases. If the mentioned by Peduzzi *et al.* (2010) regarding that the *IAF* is an indicator of the productivity of the land, the values found indicate that the evaluated plantations of four and five years are the ones with the lowest production by registering the lowest values of *IAF* in comparison with the plantations of other ages. Greater efficiency in activities such as fertilization, weed control and thinning is expected when carried out in young plantations due to the greater amount of foliage they have.

Conclusions

The litter collection method ($IAF_{Hojarasca}$) was considered the most accurate for the purpose because it involved the monthly collection of litter during an annual growth cycle of the species, which also allowed a detailed description of the dynamics of the index of leaf area. Based on the results obtained by this method, and in order to recommend an alternative to estimate the *IAF* efficiently and accurately, a regression model was generated that calibrates initial measurements of *IAF* obtained through an indirect method ($IAF_{Óptico}$), easy to obtain but with low precision, to make a more adequate and efficient estimation of the leaf area index ($IAF_{Calibrado}$).

In regard to the dynamics of *IAF*, the analysis carried out allows to conclude that the highest production of leaves occurs in the rainy season (from June to October), which corresponds to the season of greatest growth of *E. urophylla*. Therefore, it is reasonable to assume that the application of forestry management practices such as fertilization and weeding would be more effective if applied at this time.

Acknowledgements

This research was supported in part by the US Department of Agriculture, Office of International Programs, Forest Service, through the Northern Research Station and the Sustainable Landscapes Program of the US Agency for International Development, and by PROTEAK company, owner of the studied plantations.

Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Adrián Hernández Ramos, José René Valdez Lazalde, Gregorio Ángeles Pérez, Héctor Manuel de los Santos Posadas and Jonathan Hernández Ramos: design and delimitation of the experiment, field data collection, data analysis and obtaining of results; Alicia Peduzzi and Omar Carrero: relations and organization of field work in the study area; Adrián Hernández Ramos and José René Valdez Lazalde: drafting of the document; all authors reviewed and edited the final document.

References

Aguirre-Salado, C. A., J. R. Valdez-Lazalde, G. Ángeles-Pérez, H. M. Santos-Posadas and A. l. Aguirre-Salado. 2011. Mapping leaf area index and canopy cover using hemispherical photography and spot 5 HRG data: regression and k-nn. Agrociencia 45(1): 105-119. https://agrociencia-colpos.mx/index.php/agrociencia/article/view/863 (10 de julio de 2020).

Cano M., E. E., A. Velázquez M., J. J. Vargas H., C. Rodríguez F. y A. M. Fierros G. 1996. Área foliar específica en *Pinus patula*: efecto del tamaño del árbol, edad del follaje y posición de la copa. Agrociencia 30(1): 117-122. https://agrociencia-colpos.mx/index.php/agrociencia/article/view/1350 (10 de julio de 2020).

Castellanos B., J. y J. D. León P. 2010. Caída de hojarasca y dinámica de nutrientes en plantaciones de *Acacia mangium* (Mimosaceae) de Antioquia, Colombia. Acta Biológica Colombiana 15(2): 8 p. https://www.redalyc.org/pdf/3190/319027885020.pdf (17 de septiembre de 2020).

Chen, Y., W. Zhang, R. Hu, J. Qi, J. Shao, D. Li, P. Wan, C. Qiao, A. Shen and G. Yan. 2018. Estimation of forest leaf area index using terrestrial laser scanning data and path length distribution model in open-canopy forests. Agricultural and Forest Meteorology 263: 323-333. Doi: 10.1016/j.agrformet.2018.09.006.

Chen, J. M. and J. Cihlar. 1995. Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size analysis methods. Transactions on Geoscience and Remote Sensing 33: 777-787. Doi: 10.1109/36.387593.

Comisión Nacional Forestal (Conafor). 2012. Situación actual y perspectivas de las plantaciones forestales comerciales en México. http://www.conafor.gob.mx:8080/biblioteca/ver.aspx?articulo=434 (10 de julio de 2020).

Comisión Nacional Forestal (Conafor). 2014. Superficies de plantaciones forestales comerciales establecidas por año con apoyos de la Conafor. http://www.conafor.gob.mx/web/temas-forestales/plantaciones-forestales/ (17 de marzo de 2019).

Coops, N. C., M. L. Smith, K. L. Jacobsen, M. Martin and S. Ollinger. 2004. Estimation of plant and leaf area index using three techniques in a mature native eucalypt canopy. Austral Ecology 29: 332-341. Doi: 10.1111/j.1442-9993.2004.01370.x.

García, E. 1998. Climas (clasificación de Köppen, modificado por García). Escala 1:1000000. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad México. http://www.conabio.gob.mx/informacion/gis/ (15de septiembre de 2020).

Guangjian, Y., H. Ronghail, L. Jinghuil, W. Marie, J. Hailan, M. Xihan, X. Donghui and Z. Wuming. 2019. Review of indirect optical measurements of leaf area index: Recent advances, challenges, and perspectives. Agricultural and Forest Meteorology 265: 390-411. Doi: 10.1016/j.agrformet.2018.11.033.

Hernández-Ramos, J., H. M. Santos-Posadas, J. R. Valdez-Lazalde, J. C. Tamarit-Urias, G. Ángeles-Pérez, A. Hernández-Ramos, A. Peduzzi and O. Carrero. 2017. Aboveground biomass and expansion factors in commercial forest plantations of *Eucalyptus urophylla* S. T. Blake. Agrociencia 51(8): 921-938. https://agrociencia-colpos.mx/index.php/agrociencia/article/view/1336 (10 de julio de 2020).

Hu, R., G. Yan, X. Mu and J. Lou. 2014. Indirect measurement of leaf area index on the basis of path length distribution. Remote Sensing of Environment 155: 239-247. Doi: 10.1016/j.rse.2014.08.032.

Instituto Nacional de Estadística, Geografía e Informática (INEGI). 2005. Marco Geoestadístico Municipal 2005, versión 3.1. https://www.inegi.org.mx/temas/mg/ (10 de julio de 2020).

Iwamoto I., M. and T. Hiura. 2011. Modeling leaf area index from litter collection and tree data in a deciduous broadleaf forest. Agricultural and Forest Meteorology 151: 1016-1022. Doi: 10.1016/j.agrformet.2011.02.007.

Jonckheere, I., S. Fleck, K. Nackaerts, B. Muys, P. Coppin, M. Weiss and F. Baret. 2004. Review of methods for in situ leaf area index determination, Part I. Theories, sensors and hemispherical photography. Agricultural and Forest Meteorology 121: 19-35. Doi: 10.1016/j.agrformet.2003.08.027.

Lang, A. R. G. and X. Yueqin. 1986. Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies. Agricultural and Forest Meteorology 37: 229-243. Doi: 10.1016/0168-1923(86)90033-X.

Liu, Z., G. Jin and M. Zhou. 2015. Evaluation and correction of optically derived leaf area index in different temperate forests. iForest: Biogeosciences and Forestry 9: 55-62. Doi: 10.3832/ifor1350-008.

Macfarlane, C., M. Hoffman, D. Eamus, N. Kerp, S. Higginson, R. McMurtrie and M. Adams. 2007. Estimation of leaf area index in eucalypt forest using digital photography. Agricultural and Forest Meteorology 143: 176-188. Doi: 10.1016/j.agrformet.2006.10.013.

Martínez, B., F. Camacho C. y F. J. García H. 2006. Estimación de parámetros biofísicos de vegetación utilizando el método de la cámara hemisférica. Revista de Teledetección 26: 5-17. http://www.aet.org.es/revistas/revista26/AET26-01.pdf (10 de julio de 2020).

Muñoz, F., M. Espinosa, J. Cancino, R. Rubilar y M. Herrera. 2008. Efecto de la poda y raleo en el área foliar de *Eucalyptus nitens*. Bosques 29: 44-51. Doi: 10.4067/S0717-92002008000100005.

Papamija, M. D. y S. C. García. 2012. Estimación del índice de área foliar en plantaciones de *Eucalyptus grandis* W. Hill. Colombia Forestal 15: 261-271. Doi: 10.14483/udistrital.jour.colomb.for.2012.2.a09.

Peduzzi, A., A. H. Lee and R. H. Wynne. 2010. Leaf area of overstory and understory in pine plantations in the flatwoods. Southern Journal of Applied Forestry 34: 154-160. Doi: 10.1093/sjaf/34.4.154.

Rodríguez-Ortíz, G., V. A. González-Hernández, A. Aldrete, H. M. De Los Santos-Posadas, A. Gómez-Guerrero y A. M. Fierros-González. 2011. Modelos para estimar crecimiento y eficiencia de crecimiento en plantaciones de *Pinus patula* en respuesta al aclareo. Revista Fitotecnica Mexicana 34(3): 105-212.

http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0187-7380201100030001 2 (17 de septiembre de 2020).

Schleppi, P., M. Conedera, I. Sedivy and A. Thimonier. 2007. Correcting non-linearity and slope effects in the estimation of the leas area index of forests from hemispherical photographs. Agricultural and Forest Meteorology 144: 236-242. Doi: 10.1016/j.agrformet.2007.02.004.

Statistical Analysis System (SAS). 2014. SAS/ETS® 13.2 User's Guide The MODEL Procedure. SAS Institute Inc. Cary, NC, USA. 1783 p.

Sun, Q., X. Gu, L. Sun, G. Yang, L. Zhou and W. Gou. 2019. Dynamic change in rice leaf area index and spectral response under flooding stress. Paddy and Water Environment. Doi: 10.1007/s10333-019-00776-5.

Thimonier, A., I. Sedivy and P. Schleppi. 2010. Estimating leaf area index in different types of mature forest stands in Switzerland: a comparison of methods. European Journal of Forest Research 129: 543-562. Doi: 10.1007/s10342-009-0353-8.

Vega, M., M. Pizano y S. Barth. 2010. Variación del área foliar específica en *Pinus elliottii* var. elliottii Engelm. X *Pinus caribaea* var hondurensis Morelet. y su extrapolación al cálculo del área foliar proyectada. 14as Jornadas Técnias Forestales y Ambientales. Facultad de Ciencias Forestales, UNaM - EEA Montecarlo, INTA. Eldorado, Misiones, Argentina. 8 p. https://inta.gob.ar/sites/default/files/script-tmp-variacion_area_foliar_pinus.pdf (17 septiembre de 2020).

Weiss, M., F. Baret, G. J. Smith, I. Jonckheere and P. Coppin. 2004. Review of methods for in situ leaf area index (LAI) determination Part II. Estimation of LAI, errors and sampling. Agricultural and Forest Meteorology 121: 37-53. Doi: 10.1016/j.agrformet.2003.08.001.

Whitford, K. R., I. J. Colquhoun, A. R. G. Lang and B. M. Harper. 1995. Measuring leaf area index in a sparse eucalypt forest: a comparison of estimates from direct measurement, hemispherical photography, sunlight transmittance and allometric regression. Agricultural and Forest Meteorology 74: 237-249. Doi: 10.1016/0168-1923(94)02189-Q.

Wright, J. A. 1997. A review of the worldwide activities in tree improvement for *Eucalyptus grandis*, *Eucalyptus urophylla* and hybrid *urograndis*. *In*: White, T., Huber, D., & Powell, G. (comps.). Proceedings of the 24th Biennial Southern Forest Tree Improvement Conference. Orlando, FL, USA. pp. 96-102.