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Updating of Dominant Height Growth Modeling and site Index of *Pinus taeda* L. in southern Brazil

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ABSTRACT

Background: Classification of forest site provide benefits that assists to establish management regimes since the forest yield capacity is strong related to site index. **Objective:** This research had two goals: a) classify forest sites basing on dominant height of Pinus taeda, in southern Brazil; b) compare our results with site curves of P. taeda L. obtained at 26 years ago, in a research carried out by Scolforo and Machado (1988). **Methodology:** Curve-guide method was adopted to compose the site classes using 20 years as reference age. The reliability of curves was verified by the tendency of plots remain into the same site class, besides the anamorphic curve test. Dominant height growth was fitted by six models: Schumacher-modified, Chapman-Richards, Clutter-Jones, Prodan, Bailey-4P and Mitscherlich. The best model was selected by statistical criteria, including standard error of estimate (SEE), coefficient of determination (R^2) and residual analysis. Five site classes with amplitude of 4.5 m between them were established. Results: The models presented SEE between 13% and 14% and R^2 larger than 80% and Chapman-Richards' model was selected to estimate the site curves. The statistical tests revealed great reliability and anamorphism of site curves, as well as estimatives without tendency along the years. It was verified statistical differences between the curves generated in this study and those presented in Scolforo and Machado (1988). **Conclusions:** We recommend the use of site index of this research due to the goodness of fit of model. Comparing our results with Scolforo and Machado (1988), we recommend our site curves because a more expressive database was utilized to develop it and the length of time between both surveys.

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INTRODUCTION

In Brazilian agrarian sector, the cultivation of forest species began to be stimulated after the tax incentives granted by the federal government between the 60s and 80s. At that time, there was a deadlock: high timber demand for various purposes and a low supply of forests from sustainable origin. Due to this situation, the incentives were released to rural producers, and plantations started to appear mainly with the species of genera

Pinus* and *Eucalyptus:

Specifically in southern Brazil, historical data show that the species of pine were preferred for the cultivation and nowadays this still remains. Information from 2012 reveals that the region accounts for approximately 85% of total area of pine forests in the country (ABRAF 2013). Large portion of this achievement is due to regional characteristics conducive to pine cultivation, as the edaphoclimatic conditions, which are closely related to the site index (Clutter *et al*. 1983).

Husch *et al*. (1982) explain that the site quality is a decisive factor for evaluating the viability of deployment of a certain species. The authors also have mentioned that the concept of site is restricted for a particular species, because it may propitiate variation of yield for different forest species. Regarding to the pine species, this fact was confirmed by Tonini *et al*. (2002) when they compared forest sites for *Pinus elliottii* Engelm. and *Pinus taeda* L. in some states of southern Brazil.

Clutter *et al*. (1983) explain that the site quality can be quantified by direct and indirect methods. The efficiency and practicality of the direct method based on dominant heights make this method one of the most widely used. This occur because this variable is strongly correlated to the forest yield and also little affected by

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other factors, such as density and thinnings (Adame *et al*. 2006; Bergès *et al*. 2005; Bravo-Oviedo and Montero 2005; Diéguez-Aranda *et al*. 2005; González *et al*. 2005; Calama *et al*. 2003; Niinemets and Lukjanova 2003; Clutter *et al*. 1983).

In practice, classification of sites is advantageous because it allows the adjustment of mathematical models that includes site index as a variable. It allows the stratification of the forest by units equally productive, which contributes for cost reduction in forest inventories, due to the decrease of sample size within strata.

David (2014) affirmed that site quality is an important parameter to establish management regimes. The author showed that regardless of management regimes, sites highly productive always provide the larger income before of those lower productive. Moreover, the author observed that the thinning weights should be determined taking into account the site quality, in which a wrong decision-making can make the forest project economically not viable.

Given the importance of site quality in forest yield, this research had two goals: the first was to classify forest sites basing on dominant height of *Pinus taeda* in Parana and Santa Catarina states, Brazil. The second was to compare the results with those obtained in a research made by Scolforo and Machado (1988), also for *P. taeda* in both states.

MATERIAL AND METHODS

Study area and data base:

The study area encompasses thirty municipalities and seven mesoregions of Parana and Santa Catarina states. The mesoregions of Parana are Center-south, Central-eastern, metropolitan region of Curitiba, Northwest and the Southeast and the mesoregions of Santa Catarina are North and Itajai valley.

According to Köppen classification, the study area corresponds to Cfa climate. It is characterized as sub-tropical without dry season and temperature of the hottest month above 22 ºC. Beyond that, occur the Cfb climate, which presents the same conditions but with temperature of the hottest month less than 22 ºC. Eight kinds of soil are predominant in the region, including Ultisols, Cambisols, Gleysols, Oxisols and Entisols (David 2014).

Databases of *Pinus taeda* L. from forest companies in Parana and Santa Catarina states were compiled. A total of 7,344 data pairs of dominant height (h_{dom}) and age (A) was used, of which 6,032 are from temporary plots and 1,312 are from permanent plots, distributed in both states. All data were collected in even-aged stands planted with seminal or clonal seedlings. Majority of the plots was sampled in a systematic grid with 100 m between them.

The forest sites were classified by direct method based on dominant height. To define the site classes, the curves were drawn up with employment of the guide-curve method, which consists in tracing anamorphic curves equally sloped (Clutter *et al*. 1983). Dominant heights were measured according to Assmann (1961). The average dominant height of the plots ranged from 2.2 to 36.8 m and the ages from 2 to 35 years. Only plots aged of 19, 21, 30 and 32 years did not happen.

Dominant height modeling:

Six non-linear models (Table 1) were adjusted adopting dominant height and age as dependent and independent variables, respectively. Guide-models were generated when the dominant height is equal to the site index (S) and the age (A) is equal to the reference age. The site class curves were drawn up by means of a guide-model obtained using the model selected by statistical criteria.

Table 1: Dominant height models adjusted for *Pinus taeda L.* in Parana and Santa Catarina states.

Author	Original model	Guide-model	Nº
Schumacher-modified	$h_{dom} = K_0.e^{\beta_1 I^{-\beta_2}} + \varepsilon$	Solved by K_0:	
		$h_{dom} = S.e^{\beta_1\left[\left(\frac{1}{I}\right)^{\beta_2} - \left(\frac{1}{I_i}\right)^{\beta_2}\right]} + \varepsilon$	(1)
Chapman-Richards	$h_{dom} = \theta_1.(1 - e^{-K.I})^{\left[(1 - m)^{-1}\right]} + \varepsilon$	Solved by θ_1:	
		$h_{dom} = S.\left[\frac{1-e^{(-K.I)}}{1-e^{(-K.I_i)}}\right]^{\left[(1 - m)^{-1}\right]} + \varepsilon$	(2)
Clutter-Jones	$h_{dom} = K_0.\left(1 + \beta_1.I^{\beta_2}\right)^{\beta_3} + \varepsilon$	Solved by K_0:	
		$h_{dom} = S.\left(\frac{1 + \beta_1.I^{\beta_2}}{1 + \beta_1.I_i^{\beta_2}}\right)^{\beta_3} + \varepsilon$	(3)
Prodan	I^2	Solved by β_0:	

		$h_{dom} = \dfrac{I^2}{\dfrac{Ii^2}{S} + \beta_1.(I - I_i) + \beta_2.(I^2 - I_i^2)} + \varepsilon$	(4)
Bailey of 4 parameters	$h_{dom} = \theta_1.\left(1 - e^{-\theta_2.I^{\theta_3}}\right)^{\theta_4} + \varepsilon$	Solved by θ_1:	
		$h_{dom} = S.\left(\dfrac{1 - e^{-\theta_2.I^{\theta_3}}}{1 - e^{-\theta_2.I_i^{\theta_3}}}\right)^{\theta_4} + \varepsilon$	(5)
Mitscherlich	$h_{dom} = \theta_1.\left(1 - \theta_2.e^{-\theta_3.I}\right) + \varepsilon$	Solved by θ_1:	
		$h_{dom} = S.\left(\dfrac{1 - \theta_2.e^{-\theta_3.I}}{1 - \theta_2.e^{-\theta_3.I_i}}\right) + \varepsilon$	(6)

h_{dom}: plot dominant height, in m; A: age, in years; S: site index, in m; A_R: reference age, 20 years; K, K_0, θ_i, β_i and m: model parameters; e: base of the natural logarithm; ε: random error. Obs.: Parameters were estimated by Marquardt's method.

Three statistics were tested as criterion for selecting the best model: a) the smallest standard error of estimate, in percentage [SEE(%)], b) the higher coefficient of determination adjusted ($R^2_{adj.}$) and c) the best scatterplot of residuals, in percentage [(R(%)], whose formulas are presented as following in (7), (8) and (9):

$$SEE(\%) = 100\ \overline{Y}^{-1}\left[(n - p)^{-1}\Sigma(Y_i - \hat{y}_i)^2\right]^{\frac{1}{2}} \quad (7)$$

$$R^2_{adj.} = 1 - (n - 1)(n - p)^{-1}\Sigma\left[(Y_i - \hat{y}_i)^2\left(Y_i - \overline{Y}\right)^{-2}\right] \quad (8)$$

$$R(\%) = 100\ Y_i^{-1}(Y_i - \hat{y}_i) \quad (9)$$

Where: Y_i and $\hat{y}_i$ = observed and estimated variables, respectively; $\overline{Y}$ = average of observed variable; n = number of observations; p = number of parameters.

After selection the best dominant height model, a number of site classes was drawn up such that all plots could be encompassed inside their limits. It was established 4.5 m as interval between site classes at a reference age, in this case 20 years was arbitrarily chosen. However, site classes can be drawn up for any reference age using the guide-model selection with their respective estimated coefficients.

Reliability of site curves:

The reliability of site curves was checked by its anamorphic stability in time. The procedure consisted to analyze the linear correlation between site indexes and average dominant heights. The purpose of this was to confirm that the site index depends only on the productive capacity and not of age.

The procedure was repeated for ages 5, 10, 15, 20, 25 and 35, of which graphs relating the site index and the dominant height were made for each age and subsequently, their linear correlations were assessed. The site index used is that one estimated by the guide-model selected by the statistical criteria.

A graphical analysis was also performed to verify if the average dominant heights tend to remain in the same site class over the years. The analysis was repeated twice, one for all plots and other for some permanent plots selected randomly. In both cases it was desirable observe the sampled plots stability over the years.

Comparison between site curves:

The site curves developed in this research were compared with those obtained by Scolforo and Machado (1988). The comparison was appropriated because in both researches five site classes were produced with an interval of 4.5 m between them, as well as the adoption of 20 years as reference age.

As these authors used data from plots of *Pinus taeda*, also in Parana and Santa Catarina states, initially we assume the null hypothesis (H_0) of equality of site curves. Three statistics were applied as a criterion for rejection or acceptance of H_0.

In the first of them, the lower and upper limits of the classes of each site were plotted on graphs where on the y-axis was assigned the results obtained in this research work and on the x-axis were assigned the research results from Scolforo and Machado (1988).

Thus, the curves are equal if the relationship between them behaves as simple linear equation with parameters of intersection equal to "0" and of slope equal to "1". The statistical t test was applied to evaluate the equality of the coefficients, at 95% probability level. So, it was assumed the following hypotheses:
H_0: $\alpha = 0$ and $\beta = 1$ (Equality between curves);
H_1: $\alpha \neq 0$ and $\beta = 1$, $\alpha = 0$ e $\beta \neq 1$, $\alpha \neq 0$ e $\beta \neq 1$ (Non-equality between curves).

Test for α and β parameters can be described as (9) and (10):

$$t_{\alpha} = (\alpha - 0)\left[(\Sigma y^2 - \alpha\Sigma y - \beta\Sigma xy)(n - p)^{-1}\right]^{-\frac{1}{2}} \left[\Sigma x^2 (n\Sigma x^2 - n^2\,\bar{x}^2)^{-1}\right]^{-\frac{1}{2}} \quad (9)$$

$$t_{\beta} = (\beta - 1)\left[(\Sigma y^2 - \alpha\Sigma y - \beta\Sigma xy)(n - p)^{-1}\right]^{-\frac{1}{2}} (\Sigma x^2 - n\bar{x}^2)^{-\frac{1}{2}} \quad (10)$$

Where: α and β = parameters of intersection and slope, respectively; x = independent variable; y = dependent variable; n = number of observations and p = number of parameters.

The second statistical test was used to compare the limits of the curves of siege by the chi-square (χ^2), at 95% probability. The test was done with the curve values ranging from 1 to 35 years of age. The curves of this research and those from Scolforo and Machado (1988) were considered as observed and expected variables, respectively. The statistics is presented in (11):

$$\chi^2 = \Sigma\left[e_i^{-1}(o_i - e_i)^2\right] \quad (11)$$

Where: o_i = observed variable; e_i = expected variable; n = number of observations.

The third evaluation was made based on confidence intervals for the coefficients. The model for dominant height selected by Scolforo and Machado (1988) was fitted to the data of this study and thus generated a confidence interval for the coefficients, at 95% probability for the student's t test.

The initial hypothesis of equality of the coefficients is accepted if they are included in the confidence interval, against the alternative hypothesis of no equality, i.e., when the coefficients are outside of the interval bounds.

RESULTS AND DISCUSSIONS

Dominant height modeling:

Coefficients significant at 95 % of probability level were obtained with the adjustments of dominant height models. The standard errors of estimate (SEE) ranged from 13.5% to 13,8% and the adjusted coefficients of determination ($R^2_{aj.}$) were greater than 0.8 (Table 2).

Table 2: Parameters and fitting statistics of dominant height models for *Pinus taeda L.*, Parana and Santa Catarina states.

Model	Coefficients				SEE(%)	$R^2_{aj.}$	Nº
Schumacher-modified	K_0 = 38.21760*	β_1 = -5.64391*	β_2 = -0.81186*		13.77	0.8069	(1)
Chapman-Richards	θ_1 = 27.39820*	K = 0.11534*	m = 0.30211*		13.54	0.8133	(2)
Clutter-Jones	K_0 = 39.17490*	β_1 = -0.36379*	β_2 = -0.76099*	β_3 = 13.73070*	13.78	0.8065	(3)
Prodan	β_0 = 1.29945*	β_1 = 0.19901*	β_2 = 0.029622*		13.70	0.8089	(4)
Bailey-4P	θ_1 = 25.25550*	θ_2 = 0.00001*	θ_3 = 4.03717*	θ_4 = 0.21054*	13.57	0.8124	(5)
Mitscherlich	θ_1 = 28.22810*	θ_2 = 1.12744*	θ_3 = 0.09514*		13.66	0.8100	(6)

* significant at 95% probability level; K, K_0, θ_i, βi and m: parameters of the model.

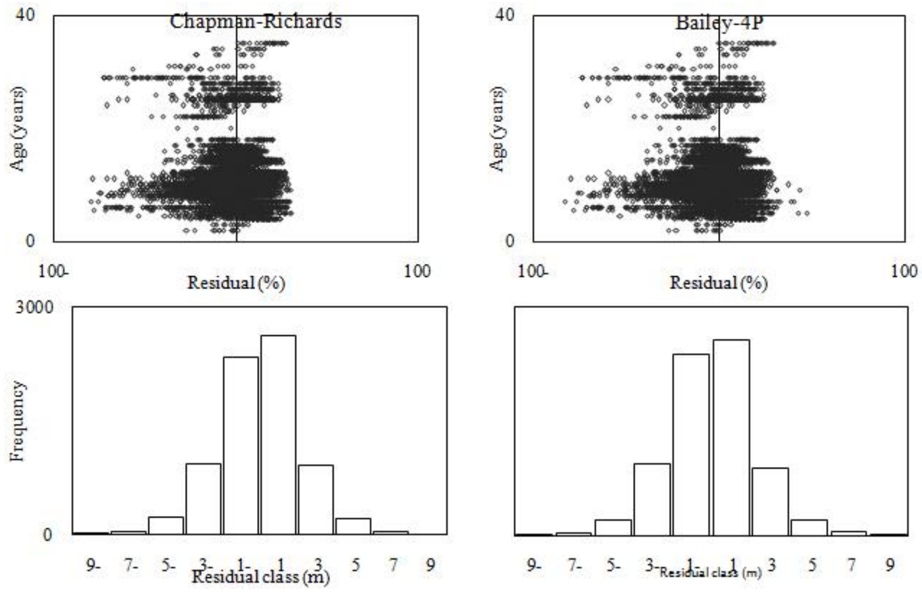


Fig. 1: Residuals generated by the best dominant height models in *Pinus taeda L.*, in Parana and Santa Catarina states.

According to Table 2, Chapman-Richards' model presented the best results regarding the accuracy statistics. Similar results were obtained by Bila *et al*. (2012) for *Pinus caribaea* var. *hondurensis* and by Scolforo and Machado (1988) for *Pinus taeda*. Some better accuracy statistics were presented by Diéguez-Aranda *et al*. (2005) for *Pinus sylvestris* L., by Adame *et al*. (2006) for *Quercus pyrenaica* Willd. and by Calama *et al*. (2003) for *Pinus pinea* L.

After the Chapman-Richards' model, stand out Bailey-4P's and Mitscherlich's models, in which presented the second and the third best performances, respectively. The Clutter-Jones' model presented the highest SEE(%) in estimating the dominant height in function of age.

Considering that the selected model to drawn up the site curves must generate unbiased estimates for dominant heights over the ages, it was made a comparison among the models of Chapman Richards and Bailey 4P. So, bias could be detected by means of scattering the residuals (Figure 1) of the best two models.

The scatter plots were similar for both models. The number of plots with ages greater than 18 years old was very low, in comparison to the ages less than 18, what hampered detecting the trends for very advance ages. However, residuals remained relatively well distributed.

Although both models were similar in relation to dispersion of the residuals and the frequency of distributions, curves well-drawn can be observed in the guide-curve model of Chapman-Richards (Figure 2). Bailey-4P's guide-model presented estimates of dominant heights practically equal to those with ages greater than 24 years, probably due to the lower number of plots at these ages.

Thus, Chapman-Richards' model was selected for drawing up site curves. Five site classes were necessary to cover all plots and setting an interval of 4.5 m between site classes at reference age (Figure 2).

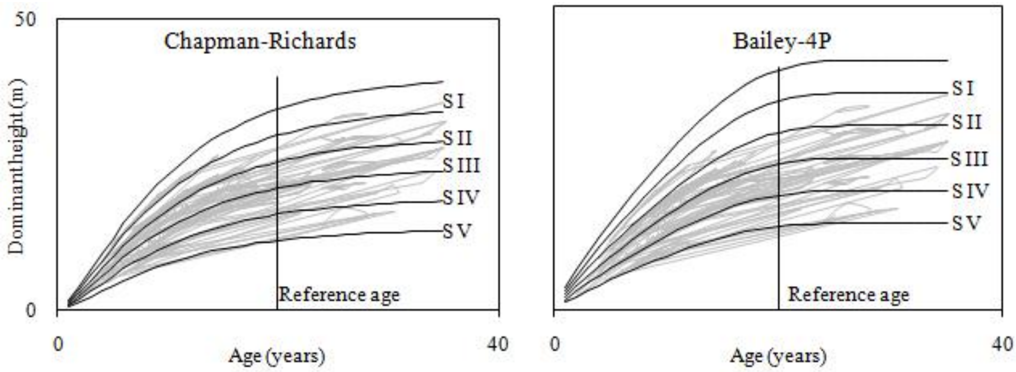


Fig. 2: Site curves for *Pinus taeda* in Parana and Santa Catarina states.

From Figure 2, also was observed that the site classes I and II were overestimated by Bailey-4P's model and a better distribution of plots by all classes was observed by the Chapman-Richards' model (Figure 2), confirming the best performance of this model. Table 3 presents values of lower and upper limits of five site classes obtained by the Chapman-Richards' guide-model.

Table 3: Limits of site classes for *Pinus taeda* in Parana and Santa Catarina states.

Idade	Site V	Site IV	Site III	Site II	Site I
(anos)	14.25 m	18.75 m	23.25 m	27.75 m	32.25 m
1	0.6–0.8	0.8–1.0	1.0–1.2	1.2–1.5	1.5–1.7
2	1.4–2.0	2.0–2.5	2.5–3.1	3.1–3.6	3.6–4.2
3	2.4–3.3	3.3–4.2	4.2–5.1	5.1–6.0	6.0–6.9
4	3.3–4.6	4.6–5.9	5.9–7.1	7.1–8.4	8.4–9.6
5	4.3–5.9	5.9–7.5	7.5–9.1	9.1–10.7	10.7–12.3
6	5.2–7.1	7.1–9.0	9.0–11.0	11.0–12.9	12.9–14.8
7	6.0–8.2	8.2–10.5	10.5–12.7	12.7–15.0	15.0–17.2
8	6.7–9.3	9.3–11.8	11.8–14.3	14.3–16.9	16.9–19.4
9	7.5–10.2	10.2–13.0	13.0–15.8	15.8–18.6	18.6–21.4
10	8.1–11.1	11.1–14.2	14.2–17.2	17.2–20.3	20.3–23.3
11	8.7–11.9	11.9–15.2	15.2–18.5	18.5–21.7	21.7–25.0
12	9.2–12.7	12.7–16.1	16.1–19.6	19.6–23.1	23.1–26.5
13	9.7–13.4	13.4–17.0	17.0–20.6	20.6–24.3	24.3–27.9
14	10.1–14.0	14.0–17.8	17.8–21.6	21.6–25.4	25.4–29.2
15	10.5–14.5	14.5–18.5	18.5–22.4	22.4–26.4	26.4–30.3
16	10.9–15.0	15.0–19.1	19.1–23.2	23.2–27.3	27.3–31.3
17	11.2–15.4	15.4–19.6	19.6–23.8	23.8–28.1	28.1–32.3
18	11.5–15.8	15.8–20.1	20.1–24.5	24.5–28.8	28.8–33.1
19	11.8–16.2	16.2–20.6	20.6–25.0	25.0–29.4	29.4–33.8
20	*12.0–16.5*	*16.5–21.0*	*21.0–25.5*	*25.5–30.0*	*30.0–34.5*

21	12.2–16.8	16.8–21.4	21.4–25.9	25.9–30.5	30.5–35.1
22	12.4–17.0	17.0–21.7	21.7–26.3	26.3–31.0	31.0–35.6
23	12.6–17.3	17.3–22.0	22.0–26.7	26.7–31.4	31.4–36.1
24	12.7–17.5	17.5–22.2	22.2–27.0	27.0–31.8	31.8–36.5
25	12.8–17.7	17.7–22.5	22.5–27.3	27.3–32.1	32.1–36.9
26	13.0–17.8	17.8–22.7	22.7–27.5	27.5–32.4	32.4–37.3
27	13.1–18.0	18.0–22.9	22.9–27.8	27.8–32.7	32.7–37.6
28	13.2–18.1	18.1–23.0	23.0–28.0	28.0–32.9	32.9–37.8
29	13.2–18.2	18.2–23.2	23.2–28.1	28.1–33.1	33.1–38.1
30	13.3–18.3	18.3–23.3	23.3–28.3	28.3–33.3	33.3–38.3
31	13.4–18.4	18.4–23.4	23.4–28.5	28.5–33.5	33.5–38.5
32	13.5–18.5	18.5–23.5	23.5–28.6	28.6–33.6	33.6–38.7
33	13.5–18.6	18.6–23.6	23.6–28.7	28.7–33.8	33.8–38.8
34	13.6–18.6	18.6–23.7	23.7–28.8	28.8–33.9	33.9–39.0
35	13.6–18.7	18.7–23.8	23.8–28.9	28.9–34.0	34.0–39.1

The amplitude of dominant height at 20 years was 4.5 m, being this the interval pre-established to drawn up the site curves. At this age, the minimum and maximum dominant heights were 12.0 m and 34.5 m. The maximum dominant height was 39.1 m, value observed at 35 years in the site I.

A lower variation of dominant heights was observed by Scolforo (1992) to classify site index for *Pinus caribaea* var. *hondurensis* in Sao Paulo state, where only three site classes were established. The author observed dominant heights higher than those shown in Table 3, indicating that such species present a better dominant height growth in that region of study.

Bila *et al*. (2012) evaluated sites for *Pinus caribaea* var. *hondurensis* in Minas Gerais state and they also observed lower amplitude of sites in comparison to the present research, being necessary the use of only three site classes. Comparing the results of Bila *et al*. (2012) with those shown in Table 4, it was verified that the sites of center (II, III and IV) were equivalent to the three sites established by these authors, indicating greater variation in dominant heights in this research.

In Rio Grande do Sul state, Selle *et al*. (1994) classified forest sites for *Pinus taeda* and they observed that the dominant heights were considerably lower than those presented in Table 3, showing that the species in question reaches better growth in Parana and Santa Catarina states.

Reliability of site curves:

The reliability of site classes generate by the Chapman-Richards' guide-model was verified by means of stability of dominant heights in maintain in same site class over the ages. Figure 3a illustrates the trend of the dominant heights averages of all plots when age advances. Figure 3b illustrates this behavior but for dominant heights of permanent plots randomly selected.

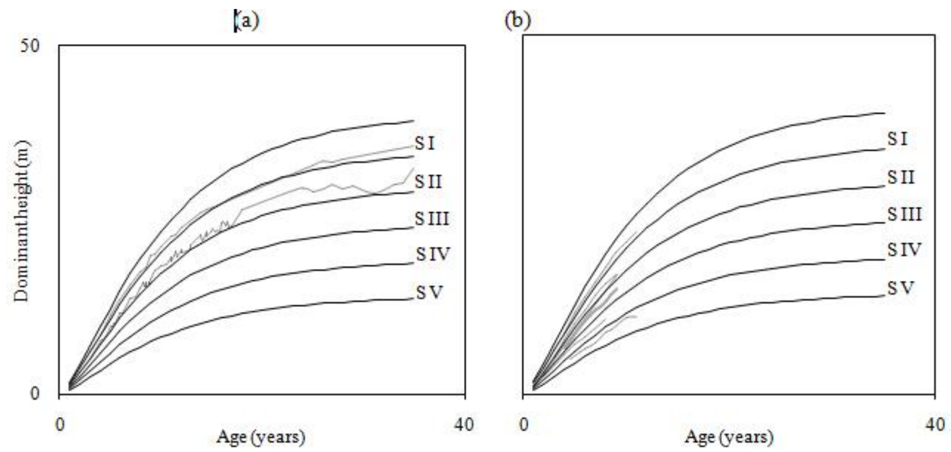


Fig. 3: Stability of average dominant heights of all plots (a) and permanent plots (b) of *Pinus taeda L.*, in Parana and Santa Catarina state.

A desirable characteristic in site curves is their stability in maintain in the same class over the ages (Clutter *et al*. 1983). This was evidenced in the case of dominant heights averages (Figure 3a) and for the five permanent plots randomly selected (Figure 3b). Although in initial ages this behavior is difficult to be seen, after the age of 5 years it became clear that there was stability in both cases.

The sites classification for ages less than 5 years is often not recommended because the interval between classes is reduced in these ages. In addition, the plots tend to be more susceptible to migration between adjacent sites, because plants at younger ages are more influenced by external factors (David 2014).

To confirm the reliability and anamorphism of the site classes in relation to the ages, the model of Chapman-Richards was readjusted by isolating as the dependent variable the site index initially estimated. The adjustment was made basing on the observed variables dominant height and age. Considering the original model of Chapman-Richards, the algebraic solution for the isolation of the dependent variable is:

$$h_{dom} = \theta_1\left(1 - e^{-KA}\right)^{\left[(1-\theta_2)^{-1}\right]} + \varepsilon(2)$$

Isolating q_1 we have:

$$\theta_1 = \frac{h_{dom}}{\left(1 - e^{-KA}\right)^{\left[(1-\theta_2)^{-1}\right]}} + \varepsilon \quad (11)$$

Considering that the site index is obtained on reference age, we have:

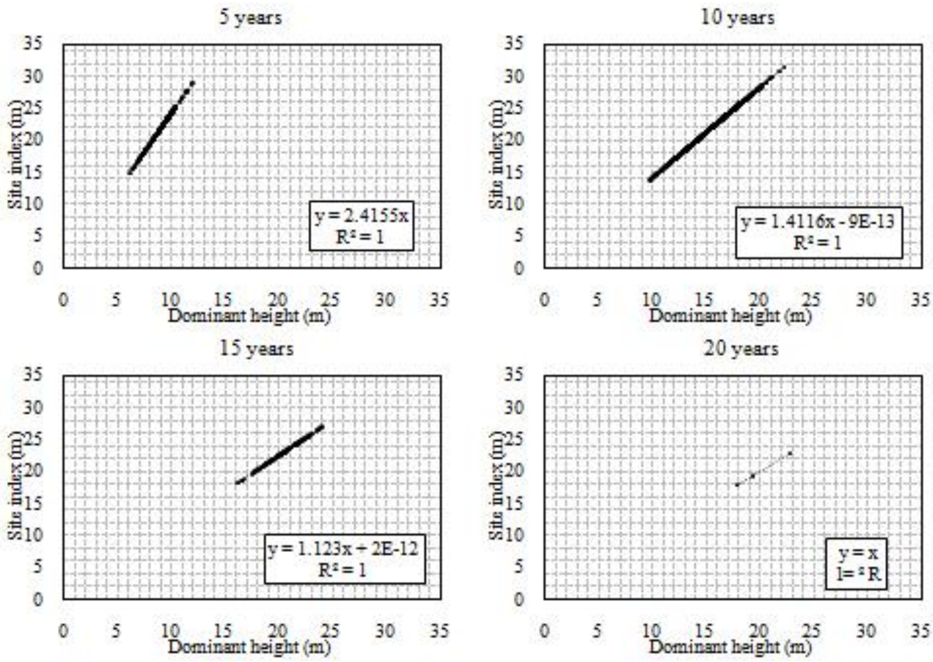
$$S = \theta_1\left(1 - e^{-KA_R}\right)^{\left[(1-\theta_2)^{-1}\right]} + \varepsilon \quad (12)$$

Replacing (11) in (12), the final model is:

$$S = h_{dom}\,\frac{\left(1 - e^{-KA_R}\right)^{\left[(1-\theta_2)^{-1}\right]}}{\left(1 - e^{-KA}\right)^{\left[(1-\theta_2)^{-1}\right]}} + \varepsilon \quad (13)$$

Where: h_{dom} = dominant height, in m; S = site index, in m; A and A_R = age and reference age, in years, respectively; θ_i and K = parameters of the model; *e* = base of the natural logarithm and ε = random error.

The adjustment of the model (13) resulted in $S = h_{dom}\,\frac{\left(1 - e^{-0.10631.20}\right)^{\left[(1-0.13941)^{-1}\right]}}{\left(1 - e^{-0.10631.A}\right)^{\left[(1-0.13941)^{-1}\right]}} + \varepsilon$. This equation was used to estimate the site index in function dominant height and a fixed age. Thus, the procedure was repeated six times, i.e., for the ages of 5, 10, 15, 20 and 25 years. Interpreting the relationship between site index and dominant height as maximum, this is solely dependent of the dominant height, and not of age. Figure 4 shows the relationship between site index and dominant height and their respective linear equations.



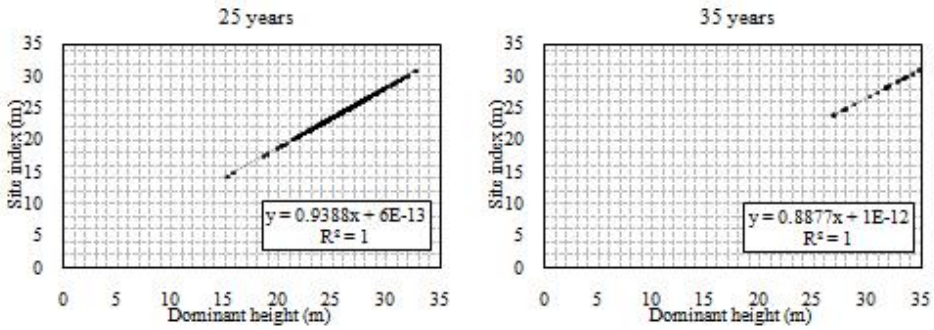


Fig. 4: Relation between site index and dominant height of *Pinus taeda L.* in Parana and Santa Catarina states.

As shown in Figure 4, in all the six ages used to evaluate the curve anamorphism, the maximum correlation between site index and dominant height was observed. This indicates good structuration of curves made by the Chapman-Richards' guide-model and confirms the stability of the plots in maintain themselves in same site classes. The results demonstrate that the site index does not depend on age and vary only according to the dominant height.

Regarding to the coefficients of linear equations, the results were the best possible, in which it was desirable that the slope coefficient would decrease with increasing age and that the intersection coefficient would be close to zero. For the age of 20 years (reference age) a perfect linear correlation was observed.

Comparison between site curves:

The site curves generated in this study were statistically compared with those obtained by Machado and Scolforo (1988). These authors evaluated the behavior of dominant heights of *Pinus taeda* in the same geographical area of this research and the Chapman-Richards' model also was selected, whose obtained equation was: $h_{dom} = 30.1750\left(1 - e^{-0.0720\,I}\right)^{\left[(1 - 0.1003148)^{-1}\right]} + \varepsilon$, where h_{dom} = dominant height in m; A = age in years; e = base of natural logarithm and ε = random error.

The comparison of classes limits was possible due to the equivalence between site indexes found in both surveys, being corresponding to dominant height of 14.25 m, 18.75 m, 23.25 m, 27.75 m and 32.25 m for the site indexes (S) V, IV, III, II and I, respectively.

Although there are ten limits of classes (5 classes x 2 limits, upper and lower), the procedure was repeated six times, since the upper and lower limits are common to the adjacent site classes. Table 4 presents the student's t test to verify whether the intersection and slope parameters are statistically equal to "0" and "1", respectively. The coefficients (α) and (β) are those obtained in the linear equation generate by the relation of site curves of both researches.

Table 4: Student's t test for coefficients between site curves of *Pinus taeda* obtained in two different generations, in Parana and Santa Catarina states.

Limit (Site index)	Coefficient	T test	P-value
Upper (S I)	α = 1.28988	2.350*	0.025
	β = 0.93658	-3.622*	0.001
Upper (S II)	α = 1.12164	2.350*	0.025
	β = 0.93658	-3.622*	0.001
Upper (S III)	α = 0.95339	2.350*	0.025
	β = 0.93658	-3.622*	0.001
Upper (S IV)	α = 0.78514	2.350*	0.025
	β = 0.93658	-3.622*	0.001
Upper (S V)	α = 0.61690	2.350*	0.025
	β = 0.93658	-3.622*	0.001
Lower (S V)	α = 0.44865	2.350*	0.025
	β = 0.93658	-3.622*	0.001

* = significant at 95% probability level.

According Table 4, the slope parameters of the linear equations did not change for the site classes, because the curves are parallel and anamorphic. It was observed changes only in the intersection parameters, which presented reduction proportional to site quality, indicating that the curves of lower quality sites were more similar than those of highest quality.

The intersection parameters (α) were statistically different from "0" and the slope parameters (β) were statistically different from "1", which indicates, a priori, rejection of the null hypothesis of equality between site curves. However, the conclusion about the hypothesis took also into account the results of the second and the third statistical criteria, being the χ^2 test and the confidence interval, which are presented in Table 5 and Table 6.

Table 5: Chi-square test for site curves of *Pinus taeda* obtained in two different generations, in Parana and Santa Catarina states.

Limit (Site index)	χ^2 test	P-value
Upper (S I)	2.469*	5.477E-14
Upper (S II)	2.147*	6.411E-15
Upper (S III)	1.825*	5.155E-16
Upper (S IV)	1.503*	2.460E-17
Upper (S V)	1.181*	5.403E-19
Lower (S V)	0.859*	3.316E-21

* = significant at 95% probability level.

Table 6: Comparison of coefficients of models adjusted for dominant heights of *Pinus taeda* obtained in two different generations, in Parana and Santa Catarina states.

Parameter	Confidence interval by David *et al*. (2014)	Coefficient by Scolforo and Machado (1988)	Conclusion
$\hat{\theta}_1$	$[27.05960 \leq \hat{\theta}_1 \leq 27.71540] = 95\%$	30.17500*	Rejected
K	$[0.11063 \leq \hat{K} \leq 0.12081] = 95\%$	0.07201*	Rejected
m	$[0.27537 \leq \hat{m} \leq 0.33255] = 95\%$	0.10031*	Rejected

* = significant at 95% probability level.

The χ^2 values were significant at 95% probability level, confirming the inequality between the site curves, already noted by the student's t test for the coefficients of the linear equation (Table 4). In addition, the confidence intervals shown in Table 6 indicated the inequality between the coefficients of the Chapman-Richards' model proposed by David *et al*. (2014) and by Scolforo and Machado (1988).

Thus, these three statistics evaluated together is a strong indication that the curves are really distinct. Figure 5 illustrates the curves generate by the Chapman-Richards' model obtained in both studies, with emphasis on ranges of ages 0 to 10 years, 10 to 20 years and 20 to 40 years.

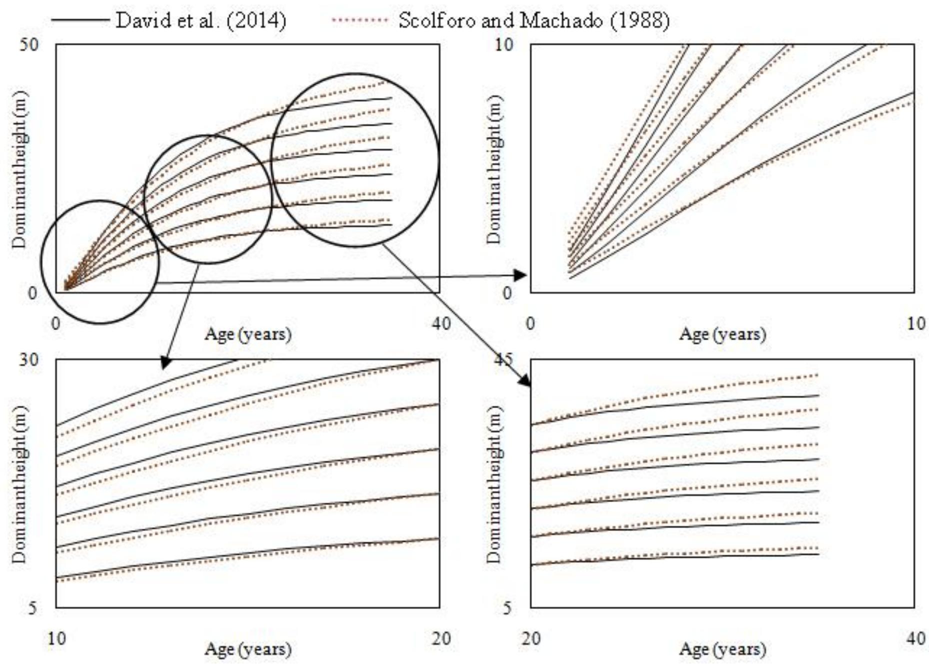


Fig. 5: Comparison of site curves for *Pinus taeda* obtained in two different times, in Parana and Santa Catarina states.

In addition to the statistical tests performed, as shown in Figure 5, was also found that on average, the growth of dominant heights differed in function of age. Figure 5 indicates also that the site curves of this research reached the asymptotic value before of curves proposed by Scolforo and Machado (1988). Consequently, the dominant heights of both curve families reached stagnation at different ages.

For the ages close to 20 years, it was noted that the dominant heights estimated by Scolforo and Machado (1988) were exceed those estimated in the present study, reaching differences larger how better the site quality. For the lower quality sites, although the t test indicated difference between the curves, they were similar even in more advanced ages.

The behavior between the curves shown in Figure 5 correspond to the values of the parameters of the model of Chapman-Richards estimated in both surveys, because Scolforo and Machado (1988) found that, for the asymptote parameter (q_1), a value greater than 30, while in the current research this value was close to 28 (Table 2).

The ages of the plots used by Scolforo and Machado (1988) varied from 1 to 27 years and a low number of plots aged greater than 17 years old was observed. In present study, the largest observed age was 35 years, which can to explain those differences between curves aged greater than 20 years old.

In relation to the slope parameter (K), in the present study this coefficient was greater than 0.11 (Table 2), against a value of 0.07 for the search of Scolforo and Machado (1988), which confirms a faster growth of dominant heights of this research.

The third parameter (m) corresponds to the inflection point of the curve. The coefficients indicated that this point occurred before in the experiment of Scolforo and Machado (1988), whose value was 0.10031, against a value equal to 0.30211 observed in this research.

In this kind of comparison, also is valid noting that the database used in the two researches is entirely different. Scolforo and Machado (1988) used 1,522 data pairs of dominant height and age. Data were obtained of complete stem analysis of 92 dominant trees besides 324 plots.

In the present study, the number of data pairs from plots (7,344) was considerably higher, which gives in theory, a greater representation of the behavior of dominant heights in the region. In addition, more than 1,000 data pairs were obtained in permanent plots distributed throughout the study area.

Recommendations:

Chapman-Richards' model is the best to estimate dominant heights in function of age of *Pinus taeda* in Parana and Santa Catarina states. The site classes drawn up are reliable and stable for dominant height of *Pinus taeda* in stands of young to old ages. The site classes of this research when compared to those obtained by Scolforo and Machado (1988) are different in growth rate of dominant height; this is faster in the current research and it reaches lower asymptotic values at older ages.

We recommend the use of site index of this research because it was generated with a more expressive database and because of the length of time between this research and the one from Scolforo and Machado (1988).

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