Research Article

Effect of Climate Variables on Monthly Growth in Modeling Biological Yield of *Araucaria angustifolia* and *Pinus taeda* in the Juvenile Phase

Naiara Teodoro Zamin, Sebastião do Amaral Machado, Afonso Figueiredo Filho, and Henrique Soares Koehler

Federal University of Paraná (UFPR), Department of Forest Sciences (DECIF), Avenue Pref. Lothário Meissner, 900-Jardim Botânico-Campus III, 80210-170 Curitiba, PR, Brazil

Correspondence should be addressed to Naiara Teodoro Zamin; narazamin@hotmail.com

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The aim of this study was to investigate the effect of climate variables on monthly growth in diameter and height of *Araucaria angustifolia* (Bert.) O. Kuntze and of *Pinus taeda* L., over a six-year period, as well as verifying the contribution of these variables in the composition of the Chapman-Richards model. To this end, we selected 30 trees of each species and measured monthly the diameter and height, between June 2006 and August 2012. The climate variables were obtained from two SIMEPAR meteorological stations near the plantings. A correlation matrix was constructed to determine the effect of climate variables on the monthly growth. Next a principal component analysis (PCA) was conducted to determine the climate variables to be included in the fit of the Chapman-Richards model. The results indicated that the climate variables with the highest correlation (about 0.6) with monthly growth in diameter and height of the species were temperature, photoperiod and atmospheric pressure, and precipitation for some years of the study. The fitted model that included climate variables showed reduced $Sy\%$ of about 0.8% compared to the traditional biological model. However, ANOVA showed no statistical difference between the production estimates obtained by both models.

1. Introduction

In forestry planning knowledge of the present and future growth and yield of trees and forest stands is important as it aids in the implementation of appropriate management regimes, when the quality of the final product is the goal for an increasingly demanding consumer timber market.

In this context, biological modeling becomes a useful tool in planning forest production. Moreover, Maestri [1] pointed out that modeling growth is possible only if a perfect match between the measurements of stands in forest inventory and environmental variables is carefully aligned in spatial and temporal terms. However, environmental characteristics are not reflected in traditional biological growth models, which only consider tree growth as a function of the size and age of the individuals.

In this sense, statistical methodologies have evolved in recent years, enabling a breakthrough in forest data modeling,

and thereby allowing researchers to arrive at estimates that represent reality with increasing accuracy, a fact that has motivated numerous attempts to model the environmental factors in association with biological growth and yield. This fact suggests that establishing a link using modeling between environmental variables and the productive capacity of the forest stand seems to contribute to the improvement of volumetric estimates [1].

However, to determine whether the growth equations must contain a term responsible for the environmental changes, one must investigate this effect on tree growth [2].

Thus, the objective of this study was to assess the effect of climate variables on monthly growth in diameter and height of the species *Araucaria angustifolia* (Bert.) O. Kuntze and *Pinus taeda* L., during a six-year period, as well as verifying the contribution of these variables in the composition of the Chapman-Richards biological model of growth and yield.

2. Materials and Methods

2.1. Study Area. Data came from an *A. angustifolia* planting in Campina Grande do Sul and from a *P. taeda* planting located in Curitiba, PR. The cities of Curitiba and Campina Grande do Sul are located on the Paraná plateau, at an altitude of 934 meters and 918 meters a.s.l., respectively.

The climate of the region is of type Cfb, according to the Köppen classification, or temperate subtropical with mild summers and evenly distributed rainfall throughout the year. According to the SIMEPAR meteorological stations, from June 2006 to July 2012, the average annual rainfall of the place was about 1600 mm, with a mean maximum temperature near 23°C and minimum of 13°C.

2.2. Data Collection. Thirty *P. taeda* trees spaced at 3 × 3 m and 30 *A. angustifolia* trees spaced at 4 × 4 m were selected for this study. Each tree received a metal tag with a unique number, to help distinguishing between individuals. These individuals were measured monthly, from June 2006 to August 2012, when *P. taeda* was 2–7 years old and when *A. angustifolia* was 1–6 years old.

During the analysis the diameter was measured at 10 cm from the ground (D10) in the *A. angustifolia* planting and at 1.3 m from the ground (DBH) in the *P. taeda* planting using pachymeter until the diameter reached 6 cm, and afterwards using a metric tape measure with millimeter graduations. The measurement point on tree was flagged and spray painted, so that all measurements could be performed consistently. The diameter of *A. angustifolia* was measured at 10 cm of soil because the height of the stand was less than 1.3 m at the start of measurement (2006). To measure the height variable an altimetric ruler was used with precision of 1 cm in both plantings.

2.3. Climate Variables. Monthly climate data were provided by the Meteorological System of Paraná (SIMEPAR), at the meteorological stations in Curitiba and Pinhais, which were selected for their proximity to the plantings. The Pinhais weather station was located an average of 10 km from the *A. angustifolia* planting, while the Curitiba was located in the same location as the *P. taeda* planting, that is, UFPR Campus III.

The monthly climate variables analyzed in this study were total precipitation (mm), average minimum, average and maximum temperature (°C), average atmospheric pressure (hPa), mean radiation incident on the surface (W/m²), and relative humidity (%). Additionally, the average monthly photoperiod (h/day) for the latitude of each planting was calculated.

From these data correlation matrices were constructed between the current monthly increment (CMI) in height and diameter in response to climatic variables in order to identify which were the most related to the growth of *P. taeda* and *A. angustifolia* during the six years of the study. For variables that showed the highest correlation, charts were prepared relating the variables diameter and height (*x*-axis) to the correlated climate variables (*y*-axis). These charts were constructed

to represent the monthly increment trend and to discover whether the growth oscillations were well represented by the correlated climate variables.

2.4. Biological Modeling Using Climate Variables. To complement the analysis of the effect of climate variables on growth and monthly yield in diameter and height for these two species the Chapman-Richards biological yield model was fit with and without the inclusion of these variables.

Before fitting these growth models the set of monthly climate variables were subjected to multivariate analysis, or principal component analysis (PCA). This allows the selection of just a few variables that express most of the variability in data collected in the analysis [3].

PCA was performed with the Statgraphics Centurion XVI program, and the Kaiser criterion was used for the selection of principal components. This criterion selects all components that have eigenvalue greater than one. Therefore, only the climatic variables selected by PCA were used in biological yield models.

To include climate variables in the biological model without unduly decharacterizing it, that is preserving the sigmoidal shape characteristic of biological growth, these variables were included as modifying factors to the parameter representing the asymptote (α), as shown in (1). The productive capacity of trees is related to the asymptotic value that the function can reach; that is, it is closely related to the parameter α of the Chapman-Richards model [1], and thus a modifying factor for the parameter as a function of environmental variables was inserted in the monthly yield models:

$$\text{Mod}_\alpha = \frac{\alpha}{1 - [(c_1 * \nu c_1) + (c_2 * \nu c_2) + \dots + (c_n * \nu c_n)]} + \varepsilon_i, \quad (1)$$

where Mod_α = modifying factor of the asymptotic parameter; α = asymptotic parameter of the Chapman-Richards model; $c_1, c_2, \dots, c_n$ = parameters of regression; $\nu c_1, \nu c_2, \dots, \nu c_n$ = climatic variables selected by PCA; ε_i = random error.

Using the asymptote modifier and the values of the parameters ($c_1, c_2, \dots, c_n$) one can verify by how much each climate variable in the equation contributes to improvement of fit, since these coefficients equal zero, the asymptote remains unchanged and the biological yield equation remains the same. Thus, the formulation of the Chapman-Richards model took the following form:

$$Y = \text{Mod}_\alpha * (1 - e^{-\beta_1 t})^{1/(1-\beta_2)} + \varepsilon_i, \quad (2)$$

where Y = monthly production in diameter and height of the species under investigation; β_1, β_2 = parameters of the Chapman-Richards model; t = month of measurement (1 to 12).

After fitting, an analysis of variance (ANOVA) was conducted to identify whether there was a statistical difference between the estimates of monthly production in diameter and height and the Chapman-Richards biological model with and without the inclusion of climate variables.

The Index of Schlaegel [4] was estimated by the formula

$$IA = 1 - \left(\frac{n-1}{n-p} \right) \cdot \left(\frac{SQ_{res}}{SQ_{tot}} \right), \quad (3)$$

where IA = Schlaegel Index; n = number of observed data; p = number of parameters in the model; SQ_{res} = sum of squared of residuals; SQ_{tot} = sum of squared total.

3. Results and Discussion

3.1. Effect of Climate Variables on Monthly Growth. In Table 1, one can observe the correlation in current monthly increment in diameter and in height of *A. angustifolia* and *P. taeda* with the climate variables derived from weather station records near the plantings. The degree of correlation of climatic variables with tree growth can be seen in this table, with r -value ranging from approximately 0.4 to 0.8. These results indicate that there is a moderate to strong relationship and a tendency for the growth in height and diameter to occur almost simultaneously, falling in and out of sync according to the influence of different environmental factors on each of the increments [5].

Different tree growth patterns are related to seasonal conditions to which they are exposed, since individuals adapt their growth to withstand the seasonal stress to which they are subject [6]. Assmann [7] also stated that the growth rates fluctuate throughout the year according to weather conditions. However, he stressed that the growth rate depends not only on climate conditions in the year of assessment, but also on the conditions of previous years, especially in months where apical buds form.

In the UFMT experimental farm growth variables were related to the bioclimatic variables for several savanna (*cerrado*) species and low correlation between the growth and climatic variables was observed [8]. Those authors added that this result usually occurs in tropical conditions where variations in temperature, precipitation, solar radiation, and other climatic factors are considered of lesser ecological significance than in temperate regions. However such was not the case of the present study, since climate variations throughout the year are significant, considering that the regions where plantings are located are characterized by the climate class Cfb.

The climate variables that showed the highest correlation with the monthly production and growth in diameter and height of *A. angustifolia* and *P. taeda* were average, maximum, and minimum temperature and photoperiod. Correlations with the variable height were generally stronger than those with the variable diameter, averaging 0.8 and 0.5, respectively (Table 1). The independent growth in diameter may be related to the fact that the cambium is protected by a thick bark layer that reduces the effects of weather on cell division [5]. This is not the case for height since the apical meristems are very exposed to climate variations, affecting them even during the yearly dormant period.

Light is one of the constituents of the environment most greatly influences tree development, since the growth and shape of the tree are directly affected by the intensity,

duration, and quality of light [9]. This author also affirms that the temperature is also an important factor for the growth, as it influences many physiological activities that affect the metabolic rates of the plant.

Furthermore, according to Lüttge and Hertel [10], the environmental stimuli that affect the cyclic activity of annual growth are primarily temperature and photoperiod. For these authors the most important factor that initiates hardiness and dormancy of the cambium is the occurrence of short days. Meanwhile breaking dormancy in the apical meristem involves primarily temperature, since plants need be exposed to low temperatures an extended time period before elevated temperatures arrive and cause buds to open.

Souza [11] conducted a study on growth of *Ipê-felpudo* in response to climate variable in Linhares, state of Espírito Santo, concluding that the temperature did not greatly affect the growth of this species. According to this author, this could be attributed to the lack of variation in the climate variable throughout the year in the study region, being close to the tropics. Said region is determined mainly by the seasonal variation in rainfall, unlike in the present study, where the high altitude of the planting results in significant temperature variation over the course of the year.

Table 1 also shows high correlation between precipitation (ca. 0.6) and *A. angustifolia* growth in measurement years 4 and 5. Those years refer the period between August 2009 and July 2011 and were characterized by high rainfall during summer months, with reduced rainfall in winter, with annual rainfall greater than 2000 mm. As for *P. taeda*, a correlation of 0.45 was found between the rainfall variable and the current monthly increment in diameter and height for measurement years 3 and 5. During this period, high rates of rainfall were evident from December to February in year 5, with rainfall peaks in August and October of year 3, and which were accompanied by higher growth rates during these months (Figure 1). This figure graphically displays the CMI variation of both species with the highest correlated climate variables.

According to Souza [11] of all substances that plants absorb, water is required in the largest quantities and sometimes corresponds to up to 95% of the total weight of the plant. Thus, the requirement of adequate water for proper growth and development of plants stems from the multiple functions it plays in plant physiology, since virtually all metabolic processes are affected by water.

Bognola [12] indicated temperature and precipitation as the climate variables that most greatly affect *P. taeda* growth, a claim verified by Zanon [13] in a study of the growth of adult *A. angustifolia* individuals and by Sette Jr. et al. [14] in the diameter growth of *Eucalyptus grandis*, findings which corroborate those presented in this study.

In estimating productivity of monoclonal stands of the hybrid *Eucalyptus grandis* and *E. urophylla*, Stape et al. [15] concluded that productivity is highly dependent on the precipitation coincident during the process of plant growth. Souza [11] also noted that a large variation in precipitation present several problems to plants, since the water is of great importance in their development.

Using the correlation matrix (Table 1), one can observe that in the first measurement year when the *A. angustifolia*

TABLE 1: Correlation matrix between the current monthly increment in diameter and height of the species *Araucaria angustifolia* and *Pinus taeda* over the six-year evaluation period with climatic variables.

Species	Variables	Year 1		Year 2		Year 3		Year 4		Year 5		Year 6	
		CMI D	CMI H	CMI D	CMI H	CMI D	CMI H	CMI D	CMI H	CMI D	CMI H	CMI D	CMI H
<i>Araucaria angustifolia</i>	CMI D	1	—	1	—	1	—	1	—	1	—	1	—
	CMI H	0.1150	1	0.0672	1	0.7531	1	0.5607	1	0.5228	1	0.4950	1
	P_p	0.2031	0.2171	0.3437	0.5635	−0.0063	−0.1714	0.7090	0.5204	0.3873	0.5259	−0.1757	−0.0631
	Pressure	0.1454	−0.6527	−0.2193	−0.8529	−0.5052	−0.8189	−0.6167	−0.9387	−0.5324	−0.8183	−0.5820	−0.7602
	$T_{\max}$	−0.1328	0.8313	0.4327	0.6185	0.7604	0.8976	0.6609	0.8564	0.5972	0.8748	0.5337	0.8411
	T_{avg}	−0.0793	0.8882	0.3899	0.8208	0.7857	0.9087	0.6954	0.8703	0.6056	0.8480	0.5334	0.8800
	$T_{\min}$	−0.0100	0.9138	0.3888	0.8762	0.7869	0.9055	0.7302	0.8802	0.6260	0.8093	0.5578	0.9001
	UR	0.3386	0.7236	0.5903	0.6330	0.1249	0.1930	0.2721	0.2299	0.4139	0.3805	−0.3104	−0.0505
	Rad	−0.3020	0.6537	0.3375	0.4895	0.5000	0.8341	0.4315	0.7371	−0.1420	0.2947	0.4974	0.5098
	Photo	−0.1184	0.5976	0.5067	0.6712	0.7631	0.8394	0.7952	0.9164	0.6173	0.8520	0.7516	0.8127
<i>Pinus taeda</i>	ICM D	1	—	1	—	1	—	1	—	1	—	1	—
	CMI H	0.9177	1	0.6618	1	0.4156	1	0.4266	1	0.5029	1	0.2410	1
	P_p	0.4367	0.2669	0.1971	0.4307	0.5352	0.4620	−0.0067	0.3746	0.3689	0.5446	0.0155	−0.2702
	Pressure	−0.8830	−0.8778	−0.3971	−0.6719	−0.1855	−0.7848	−0.6042	−0.8976	−0.3207	−0.8449	0.1402	−0.6805
	$T_{\max}$	0.6711	0.5967	0.8023	0.8430	0.3132	0.5794	0.5003	0.6798	0.5104	0.7966	−0.1710	0.5963
	T_{avg}	0.7076	0.6138	0.7872	0.8375	0.3616	0.6635	0.4973	0.7151	0.4895	0.7587	−0.2657	0.5498
	$T_{\min}$	0.7230	0.6076	0.7669	0.8321	0.3664	0.7298	0.4562	0.7591	0.4529	0.7270	−0.3102	0.5213
	UR	0.4543	0.4208	0.2510	0.4860	0.1912	0.5922	−0.5023	0.0171	0.1532	0.2949	−0.3199	−0.6204
	Rad	0.0635	−0.1482	0.7061	0.8192	−0.0611	0.6078	0.4975	0.7589	0.1314	0.6997	0.0104	0.6333
	Photo	0.8975	0.9448	0.7664	0.9515	0.4089	0.9521	0.4574	0.8564	0.3294	0.8980	−0.0193	0.8467

Where CMI D: current monthly increment in diameter (cm); ICM H: current monthly increment in height (m); P_p : monthly precipitation (mm); Pressure: atmospheric pressure (hPa); $T_{\max}$: maximum temperature (°C); T_{avg} : average temperature (°C); $T_{\min}$: minimum temperature (°C); RH: relative humidity (%); Rad: solar radiation (W/m²); Photo: photoperiod (hours/day).

stand was one-year old and in the sixth measurement year, when the *P. taeda* was seven-year old, monthly increment in diameter was only weakly correlated with climatic variables, indicating that growth in this period occurs almost independently.

Analyzing the increment curves during these periods (Figure 2), one can perceive a pattern of atypical growth, with almost constant development rates for *A. angustifolia* and decreasing rates for *P. taeda* during the year. This result suggests that the increment is not particularly sensitive to climate variations, and somewhat more influenced by energy reserves and metabolic activities intrinsic to the tree, either in adaptation to the specific location as in *A. angustifolia*, or in the level of competition for the *P. taeda* stand, whose growth rates began to decline beginning at age six. Thus, the growth and development phases are being directed by endogenous growth rates inherent to each species [16], since climate variations would not be sufficiently pronounced or regular enough to induce alterations in cambium activity [17].

Table 1 shows a strong inverse correlation between height increments and atmospheric pressure in both species. Whereas the atmospheric pressure varies throughout the year in a manner contrary to other climatic variables, being higher in winter and low in summer, one can perceive an inverse correlation values reaching −0.9.

Additionally, Ferreira and Couto [18] concluded that atmospheric pressure was a variable strongly correlated with altitude and determined that the altitude of the planting was as a factor greatly influencing the occurrence of height growth in *Eucalyptus* spp. stands located in Minas Gerais and Espírito Santo, and for all species increased altitude resulted in shorter trees.

Plantings located in higher altitudes tend to begin growing later in the vegetative year and have longer growth periods throughout the year, as was observed by this author where growth in diameter at 500 m began about 2 to 4 weeks after growth at 300 m [7]. This observation supports the conclusion that altitude, and consequently the atmospheric pressure, greatly influences the growth in diameter and height of trees, as expressed in the correlation matrix of the present study (Table 1).

3.2. Biological Modeling of Monthly Production Using Climate Variables. The monthly climate variables for the six-year study period, derived from the Curitiba and Pinhais meteorological stations were subjected to principal component analysis (PCA). The PCA began with eight climate variables, from among which two principal components were selected using the Kaiser criterion (eigenvalue > 1). In all years evaluated for both stands, these two selected climate variables

FIGURE 1: Correlation between the current monthly increments (CMI) in diameter (cm) and height (m) with the climate precipitation variable (P_p) in plantings of *Araucaria angustifolia* and *Pinus taeda*.

explained about 90% of the variability in all variables. Variables obtained by means of PCA have low correlation with each other, and thus avoiding the effects of multicollinearity in the model [1]. This means that eight explanatory variables studied can be replaced by two principal components and suffer on a 10% loss of information.

Table 2, for example, shows the PCA analysis for the fourth year from the Pinhais meteorological station representing variables to be inserted in the Chapman-Richards biological model of production in diameter and height for *A. angustifolia*. The same procedure was performed for *P. taeda*, with data from the Curitiba meteorological station.

In Table 2, we can see that the two principal components (PC) selected represent 89.36% of the total variability of the climate variables for the period between August 2009 and July 2010. Furthermore, the climatic variables that showed the highest loading on CP1 and CP2 were photoperiod and relative humidity, respectively, and were therefore the variables to be included in the modeling of monthly production of diameter and height of *A. angustifolia* for the vegetative period referring to the four-year-old planting. In selecting a variable from each of the first components, each having the

largest absolute coefficient, one will in effect be selecting those variables that best explain the total variability and which are least related to each other [1].

The PCA analysis for the remaining years of the study enabled the selection of the climate variables shown in Table 3, which were included in the modeling of monthly production of diameter and height of both species. One will note that much of principal component 1 (PC1) is most greatly loaded with the climate variables temperature and photoperiod. Meanwhile in PC2 rainfall and relative humidity predominate, both variables representing water availability for tree development. Thus, one can see that the PCA analysis corroborated the findings presented in the correlation matrix, since they were climate variables that had the greatest effect on monthly growth.

Solar radiation was selected in PC2 for the first and second measurement years for *P. taeda* and for the second year of *A. angustifolia*. This variable also has an important effect on growth, since photosynthesis is initiated by photosynthetically active radiation, and the absorbed radiation is dependent on the leaf area index (LAI) trees [19].

TABLE 2: Principal components analysis of Pinhais meteorological data for *Araucaria angustifolia*, for the fourth measurement year (July 2010 to August 2009).

Component number	Eigenvalue	% Variance	Cumulative %	Climate var.	Principal component 1	Principal component 2
1	5.618	70.223	70.223	Photo	0.4135	0.0703
2	1.531	19.139	89.362	P_p (mm)	0.2695	0.4697
3	0.463	5.794	95.156	Pressure	-0.3802	-0.0751
4	0.295	3.691	98.846	Solar rad.	0.3321	-0.3955
5	0.063	0.791	99.638	T_{max}	0.4040	-0.1555
6	0.026	0.324	99.961	T_{avg}	0.4086	-0.0847
7	0.003	0.036	99.998	T_{min}	0.4101	0.0039
8	$1.67E - 04$	0.002	100	UR	0.0563	0.7623

The bold item means first the number of principal components that were selected by the analysis and after it represents the climatic variables that were selected by composing the model.

TABLE 3: Climate variables selected by principal component analysis for the six-year study from the Curitiba and Pinhais meteorological stations.

Evaluation period	Curitiba meteorological station		Pinhais meteorological station	
	<i>Pinus taeda</i>		<i>Araucaria angustifolia</i>	
Year 1	T_{min}	Solar rad.	T_{min}	UR
Year 2	T_{min}	Solar rad.	Photo	Solar rad.
Year 3	T_{min}	P_p	T_{avg}	UR
Year 4	T_{avg}	P_p	Photo	UR
Year 5	Photo	UR	T_{avg}	UR
Year 6	T_{max}	P_p	Photo	UR

FIGURE 2: Current monthly increment in diameter in the first year of measurement for *Araucaria angustifolia* and in the sixth year of measurement for *Pinus taeda*.

Once climate variables were selected for inclusion in the modeling of monthly production for the six-year study, Table 4 could be compiled showing the coefficients, fit parameters, and precision of the Chapman-Richards equation with and without the inclusion of climate variables.

Analyzing the coefficients, c_1 and c_2 , components of the asymptote modifying factor (Mod_α) in the equations when climate variables were included, one can see that coefficient c_1 was generally larger than c_2 and therefore had a greater effect on the asymptote. This behavior confirms in essence the

high representativeness of the variable climate in CPI on tree growth, which as shown before, are the variables temperature and photoperiod.

In order to illustrate how the formulation of the asymptote modifier was included in the Chapman-Richards model, (4) describes Mod_α for the fitted model of monthly production in diameter during the first year of measurement (June 2006 to July 2007) for *P. taeda*:

$$Mod_\alpha = \frac{6.2914}{1 - [(0.0132 * T_{min}) + (-0.0002 * UR)]}. \quad (4)$$

The models where climate variables were included showed goodness of fit (Table 4), with high IA [4] values, a little beat inferior to those obtained for the traditional equations. These equations also presented smaller values of standard error of the estimate (in average 0.5% for *A. angustifolia* and 0.8% for *P. taeda*) indicating that the effect of the climatic variables on the growth of this species collaborated in the monthly production fit.

In Linhares, ES, models were developed for six *Ipê-felpudo* experiments with different planting spacings, showing that the inverse accumulated water deficit, accumulated rainfall, and the natural logarithm of accumulated rainfall were the most frequent climate variables, and coefficients of determination of equations were greater than 0.93 [11]. This result corroborates the high IA presented by the yield equations in this paper when climate variables from Table 4 were included, which are very close to those present in traditional biological models.

TABLE 4: Coefficients and statistics of the Chapman-Richards equation for monthly production in diameter (D) and height (H) of *Araucaria angustifolia* and *Pinus taeda*, with (CV) and without (NCV) the inclusion of climate variables.

Period	Var.	Type	<i>Araucaria angustifolia</i>							<i>Pinus taeda</i>						
			Equation coefficients					IA	Syx%	Equation coefficients					IA	Syx%
			α	β_1	β_2	c_1	c_2			α	β_1	β_2	c_1	c_2		
Year 1	D	NCV	1.4270	0.1277	0.3903	—	—	0.7388	37.84	6.2914	0.1931	0.5888	—	—	0.9659	12.99
		CV	1.5800	0.0826	0.2401	-0.0101	0.0028	0.6918	36.35	8.4300	0.0946	0.4121	0.0132	-0.0002	0.9602	12.29
	H	NCV	1.0018	0.1292	0.0000	—	—	0.6412	35.66	2.1729	0.3392	0.7704	—	—	0.9312	18.80
		CV	0.9424	0.1449	0.0000	-0.0061	0.0009	0.5218	37.44	2.4700	0.1633	0.5473	0.0219	-0.0006	0.9230	17.83
Year 2	D	NCV	4.3122	0.0767	0.0929	—	—	0.8852	20.87	7.3312	0.1515	0.4863	—	—	0.9615	13.46
		CV	4.1258	0.0951	0.1221	-0.0030	-0.0002	0.8486	20.27	9.9380	0.0772	0.3407	0.0103	-2.2E-05	0.9531	12.95
	H	NCV	1.7444	0.3260	0.8309	—	—	0.9475	18.83	2.0521	0.4236	0.8678	—	—	0.9519	16.91
		CV	1.8600	0.3408	0.8361	0.0001	-0.0004	0.9391	18.22	1.8737	0.3193	0.8057	0.0067	0.0004	0.9445	16.18
Year 3	D	NCV	4.1678	0.1729	0.3941	—	—	0.9621	11.85	6.1763	0.1204	0.2201	—	—	0.8968	19.52
		CV	3.6582	0.1531	0.3720	0.0045	0.0014	0.9496	11.55	10.009	0.0427	0.0115	0.0079	0.0001	0.8657	18.81
	H	NCV	2.0871	0.2560	0.6651	—	—	0.9367	17.74	2.0801	0.3654	0.8267	—	—	0.9606	14.88
		CV	2.0300	0.2295	0.6405	0.0053	0.0001	0.9218	17.27	2.0001	0.2756	0.7514	0.0088	0.0003	0.9545	14.16
Year 4	D	NCV	4.3914	0.1518	0.4343	—	—	0.8858	22.87	5.8306	0.1460	0.3665	—	—	0.8723	23.35
		CV	3.6196	0.1126	0.3752	0.0129	0.0019	0.8571	22.22	6.6597	0.0892	0.2384	0.0079	-0.0001	0.8389	22.59
	H	NCV	1.6234	0.3489	0.7655	—	—	0.9552	14.91	1.9455	0.4129	0.8526	—	—	0.9681	13.29
		CV	1.5002	0.3805	0.7868	-0.0138	0.0024	0.9449	14.48	1.8104	0.3548	0.8153	0.0061	3.4E-05	0.9621	12.83
Year 5	D	NCV	3.9219	0.1641	0.4436	—	—	0.9174	18.93	6.3711	0.0755	0.1949	—	—	0.7791	31.66
		CV	3.6229	0.1549	0.4270	0.0008	0.0010	0.8959	18.33	6.7998	0.0689	0.1814	0.0041	-0.0006	0.7238	30.71
	H	NCV	1.5641	0.4103	0.8491	—	—	0.9509	16.46	1.8148	0.3410	0.8028	—	—	0.9191	21.18
		CV	2.2466	0.3639	0.8232	0.0138	-0.0068	0.9413	15.89	1.0102	0.1774	0.6259	0.0200	0.0043	0.9066	20.15
Year 6	D	NCV	4.3932	0.1688	0.4272	—	—	0.8365	27.11	3.0697	0.0972	0.1446	—	—	0.6992	37.29
		CV	4.1163	0.2233	0.5007	-0.0253	0.0025	0.7984	26.09	2.9608	0.1405	0.2554	-0.0062	-4.0E-05	0.6313	35.91
	H	NCV	1.6546	0.3776	0.8708	—	—	0.9467	18.65	1.6395	0.3862	0.8155	—	—	0.9296	18.87
		CV	1.1100	0.3439	0.8547	0.0143	0.0022	0.9393	17.94	1.4015	0.2735	0.7095	0.0102	-2.0E-05	0.9181	17.87

Ferreira [19] performed a fit for the production for the variables, site location, basal area, and volume of *Eucalyptus* spp. with and without the inclusion of climate variables, as selected by PCA. This author obtained an Syx% of 6.9 for the fit equation from the traditional model and 6.1 from the equation when climate variables were included. Meanwhile for volume Syx% values were 5.7 and 5.2. For basal area, both models gave values of Syx% equal to 5%. The results obtained by Ferreira [19] were similar to those obtained in this study, since they possess a very similar percentage improvement in the precision of equations after inclusion of climate variables to model, or less than 1%.

Maestri [1], comparing the traditional height model often used for *Eucalyptus grandis* with a model including environmental variables observed improved accuracy of 0.2 m in absolute terms in the equation when variables were selected using PCA, whereas the traditional equation resulted in Syx of 1.43 m and the mechanistic equation resulted in an Syx of 1.23 m. Meanwhile other authors [20] found that in the inclusion of climate variables in growth and yield of *P. taeda*, the fitted equation showed a significant gain in the forecasted

height, achieving a reduction in the absolute standard error of estimate from 0.53 m to 0.49 m.

We conducted an analysis of variance (ANOVA) to verify statistical difference between the equations with and without the inclusion of climate variables. The results showed that for each year of the study VC and NVC equations had F values near zero and P values near 1 in the ANOVA, at 0.05 significance level, from which we concluded that there was no statistical difference between the estimates obtained by the Chapman-Richards equation when climate variables were included and those obtained from the traditional model.

4. Conclusion

The variables with the highest correlation with the monthly increment in diameter and height for *A. angustifolia* and *P. taeda* were temperature and photoperiod. Monthly increment in diameter and height for the species were inversely correlated with atmospheric pressure.

Precipitation was correlated with the monthly growth during years of heavy and more regular rainfall, with more precipitation during the summer and less in winter.

The diameter variable for both species was less correlated with climatic variables than height was.

PCA analysis enabled the selection of two climatic variables for inclusion in yield models, with only a 10% loss in explanatory power. Moreover, the variables selected by this method best represented those environmental variables most highly correlated with monthly growth.

The equation with climate variables presented less precision than the traditional equation, with slightly smaller IA values. Despite a reduction in the error of the estimates (Syx%) when climate variables were included in the Chapman-Richards model, the ANOVA showed that there was no statistical difference between the estimates obtained by the Chapman-Richards equation when climate variables were included and those obtained from the traditional model.

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