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Original Article

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Diameter Increment Modeling in an Araucaria Forest Fragment Using Cluster Analysis

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ABSTRACT

The aims of the present study were to test the hypothesis that data stratification by cluster analysis and the use of other variables, in addition to DBH, can improve the precision of the estimates in diametric increment modeling for Mixed Ombrophilous Forest species. The study was carried out in the Irati National Forest. Data from 25 permanent sample plots of 1 ha each were used with all individuals presenting DBH equal to or greater than 10 cm being identified and measured. The increment modeling was performed for the whole forest (non-stratified data), ecological groups and species subgroups (stratified data) defined by cluster analysis. DBH presented a low correlation with the diametric increment and the use of other independent variables had a positive effect on the fitting, reducing the standard error of estimate and increasing the coefficient of determination. The data stratification did not make the models suitable to estimate the diametric increment; however, it provided improvements by reducing the standard error of estimate, suggesting that this technique can be better applied in the search for improvements to diametric modeling in natural forests.

Keywords: data stratification, growth, Mixed Ombrophilous Forest, multivariate analysis.

1. INTRODUCTION

Management of even-aged populations, mainly composed of a single species, has been widely studied for a long time, and significant understanding regarding characteristics, techniques and tools to manage these populations has been obtained.

Although many Brazilian native forest species present high potential for use, they have received little attention in terms of understanding their growth rate (Della-Flora et al., 2004). However, in recent decades, increasing attention has been paid to studying native forests, due to concerns with the decay rate of these ecosystems, and interest in secondary forest products and the sustainable use of noble wood products.

One of the fundamental requirements for wood production is sustainable management. This requires knowledge of current stock and growth rates of the species that comprise the forest or, at least, those considered relevant for the activity. The stock can be obtained through inventories of the relevant areas. However, forest growth, determined via successive inventories, can only be predicted based on growth or increment models of the relevant species contained in a forest (Della-Flora et al., 2004). A predictive function for the tree diameter increment is fundamental for growth models, as well as for other functional models based on the individual tree or on size classes (Alder, 1995).

Tree growth modeling is always related to diameter (DBH), due to the ease of measuring this variable, its sensitiveness to environmental changes and population density and the fact that it is strongly related to the crown, tree mass and stem volume. According to Alder (1995), in tropical forests, diametric increment can be predicted empirically from tree DBH or basal area, tree competition situation or population and continuous or categorical variables of the site.

Several studies have been developed aiming to model diametric increment or the basal area, based on the dimensional and sociological tree variables, site index and competition (Vanclay, 1991; Chai & Lemay, 1993; Palahí et al., 2003; Palahí & Grau, 2003; Della-Flora et al., 2004; Phillips et al., 2004; Nebel & Meilby, 2005; Rossi, 2007; Stepka et al., 2012). However, the results obtained were not particularly satisfactory due to the low performance of these models' fit. This is frequently a result of the existing variation between different tree increments or due to diverse factors that may interfere with the dynamics of each individual, such as genetic variability, age difference, environmental conditions and even competition with other individuals.

In this regard, we can affirm that modeling of the diameter increment of tropical species or even of individual trees has a long way to go. However, even with this being the case, such modeling is important because it allows us to understand the effects of environmental factors on tree growth rates.

Considering the difficulties involved in modeling the diametric increment of native forest species, this study sought to test the hypothesis that data stratification by cluster analysis and the use of other dimensional, qualitative, site and competition variables, in addition to the DBH, can improve the precision of diametric increment modeling estimates of Mixed Ombrophilous Forest species.

2. MATERIAL AND METHODS

2.1. Data origin and study area location

This study was carried out in a fragment of Mixed Ombrophilous Forest at the National Forest of Irati, which is on the Paraná second plateau, within the limits of Fernandes Pinheiro and Teixeira Soares counties, including the Irati Colonial micro region. The area is located between the right margin of the river das Antas and the left margin of the river Imbituva, both belonging to the river Tibagi watershed, with an average altitude of 820 meters.

According to the Köppen classification, the climate in the region is type Cfb – Mesothermal Humid Subtropical, characterized by mild summers, severe and frequent frost in winter and no dry season. It presents well defined climatic seasons, with rainfall throughout the year. The average monthly rainfall is 194 mm and the monthly average for relative air humidity is 79.5%. The average annual temperature is 18 °C, with -2 °C annual minimum and 32 °C maximum temperatures. The average temperatures in Irati are between 13 and 23.5 °C (SIMEPAR, 2012).

Three soil types are predominant in the area: Rhodic Hapludox (Oxisol), Humic Dystrudept and Humic Pachic Dystrudept (Inceptisols), classified according to the Soil Taxonomy classification systems (USDA, 1999).

The data used in this study was collected from the Continuous Forestry Inventory carried out between 2002 and 2011 in 25 permanent plots of 1ha (100 × 100 m) each, in which all the individuals whose diameter at breast height was equal to or greater than 10 cm (DBH ≥ 10 cm) were identified and measured.

2.2. Diameter increment

The diameter increment was obtained based on the diameter growth of trees measured in the first measurement and that remained alive throughout the whole period of fragment monitoring. Therefore, the diametric increment observed between 2002 and 2011 was recorded. The periodic diameter increment (IP) and periodic annual increment (IPA) were calculated using Equations 1 and 2:

$$IP_d = d_f - d_i \tag{1}$$

$$IPA_d = \frac{IP_d}{P} \tag{2}$$

where: IP_d = periodic diameter increment (cm); IPA_d = periodic annual increment in diameter (cm.year^{-1}); d_f = DBH at the end of the growth period evaluated (cm); d_i = DBH at the beginning of the growth period evaluated (cm); P = measurement interval (years).

2.3. Data stratification

To reduce data variation when seeking more efficient modeling, groups of species with similar growth characteristics were defined. To this end, species were firstly classified into ecological groups (pioneer, early secondary, late secondary and climactic) based on classifications by: Lorenzi (2002), Carvalho (2006, 2008) and Sawczuk et al. (2012).

For each ecological group, a data matrix was structured with the i-TH species and the DBH class j-TH, considering the mean diametric increment values, that is, the species were grouped based on their size and growth rate. Each data matrix was submitted to cluster analysis through the Hierarchical agglomerative method using the Euclidian Distance as a similarity measure, and a dendrogram was generated for each ecological group, obtained through the complete linkage clustering method (farthest neighbor), which served as a basis to define species subgroups with similar growth characteristics.

The determination of the number of species subgroups obtained for each ecological group was carried out through the graphic analysis of the dendrogram. Different subgroup compositions were defined for each ecological group (different threshold levels in the dendrogram) and regression fittings were realized to evaluate the estimates generated for the different possibilities as well as to determine which composition presented the best results.

In this way, it was possible to compare the results of the diameter increment modeling at whole stand level (data without stratification), by ecological group, and their respective species subgroups (stratified data).

Rare species, that is, those with density lower than one individual per hectare (Kageyama & Gandara, 1994), were not considered in the cluster analysis, since they generally formed isolated groups and, in such cases, the number of appearances was not sufficient to allow modeling.

2.4. Diameter increment modeling

The diametric increment modeling was carried out using two methods. In one, eight models were tested (Table 1), of which three were linear and five were non-linear, with the independent variable being the DBH at the beginning of the evaluation period for estimation of the diametric increment.

The annual periodic increment was calculated, based on the 2002-2011 period, using the diameter in 2002 as an independent variable. Model fitting was performed also considering smaller intervals (3 and 6 years), but the results obtained were inferior in comparison to the period of nine years. Thus, only the modeling for the period 2002-2011 is presented.

Aiming to evaluate the effect of using other variables, besides diameter, in the diametric increment estimate, equations were generated by Stepwise procedure, for both ecological groups, subgroups obtained by cluster analysis and for the forest as a whole. The dimensional and qualitative characteristics, competition indexes and site were used as independent variables. In this sense the following variables were defined:

Table 1. Diametric increment models tested.

N°	Author	Models
1	Alemdag (1978)	$I_d = \beta_0 + \beta_1 DBH + \beta_2 DBH^2$
2	Von Bertalanffy (1957)	$I_d = \beta_0 DBH^{\beta_1} - DBH^{\beta_2}$
3	Rossi (2007)	$I_d = \beta_0 DBH^{\beta_1} e^{\beta_2 DBH}$
4	Rossi (2007)	$I_d = DBH(\beta_0 - (\beta_1 \ln DBH))$
5	Rossi (2007)	$I_d = e^{\beta_0 + \beta_1 (1/DBH)}$
6	Rossi (2007)	$I_d = \beta_0 + \beta_1 DBH$
7	Rossi (2007)	$I_d = \beta_0 + \beta_1 DBH^2$
8	Rossi (2007)	$I_d = e^{\beta_0 + \beta_1 DBH}$

I_d = periodic annual diameter increment (cm.year^{-1}); DBH = diameter at 1.3m (cm) at the beginning of the growth period; ln = naperian logarithm; e = base of the naperian logarithm; β_0, β_1, β_2 = coefficients to be estimated.

a) *Dimensional variables:* diameter at breast height, diameter added to a standard deviation; diameter added twice to a standard deviation; diameter raised to the square; naperian logarithm of the diameter; inverse of the diameter; cross-sectional area; diameter class center (15 to 105 cm, and the class amplitude used was 10 cm);

b) *Site variables:* plot basal area (10 × 50 m); species basal area per hectare;

c) *Competition variables:* Glover and Hool index (defined by the ratio between the tree diameter square of the tree considered by the forest mean diameter square) and BAL index (Basal Area Larger), defined by the ratio between the mean basal area per sample unit and the tree basal area considered;

d) *Qualitative Variables:* Stem form (SF); straight stem (3); slightly tortuous stem (2) and tortuous stem (1); sociological position (SP); upper extract (3); medium extract (2) and lower extract (1); Plant health (HE): good health (3), medium health (2) and poor health or pest attack, rotten stem, etc (1). Two other variables used that should be mentioned were, crown position (CP) and crown shape (CS), evaluated according to Dawkins (1958).

Dawkins (1958) pointed out that the crown position is determined as a function of the incidence of sunlight. Therefore, a cone with a 90° angle is considered from the crown base. The method divides the crown position into five classes (Figure 1). In class 5 (emerging), the crown surface is completely exposed to sunlight in a vertical position and is free from lateral competition, with total incidence of light on the cone. In class 4 (complete upper lighting), the upper part of the crown is completely exposed to sunlight, but there is some lateral shading from other crowns of the same height or taller, within the cone. In class 3 (partial upper lighting), the crown surface is not totally exposed to sunlight in the vertical position, since it is partially shaded by other crowns. In class 2 (some natural light), the crown surface is completely shaded in the vertical direction, but is still exposed to some direct sunlight from an opening or the end of an upper canopy. In class 1 (no direct sunlight), the crown surface is completely shaded, in both the vertical and lateral directions.

The crown shape, according to Dawkins (1958), is also divided into five classes (Figure 1). Class 5 (perfect shape): no irregularities, both in the upper and lateral directions. Class 4 (good shape): there is slight irregularity in the crown format. Class 3 (tolerable shape): more irregularities, but lower than 50% of the crown. Class 2 (poor shape): irregularities are found in over 50% of the crown; Class 1 (intolerable shape): significant irregularities that can affect the whole crown.

2.5. Evaluation of models

The selection of models was carried out based on the highest adjusted coefficient of determination (R^2 adj) and lowest standard error of the relative estimate (Syx%). Additionally, the significance of coefficient (p-valor $\alpha \leq 0.05$) was verified for each adjustment carried out. When no significant coefficients were found, these were disregarded and a new adjustment was performed with the significant coefficients (or variables).

The graphic distribution of residuals was also evaluated. However due to space limitation and to the great number of equations tested in this research, these graphics were not presented even though no trend toward underestimation or overestimation was observed.

3. RESULTS AND DISCUSSION

The definition of the species subgroups for each ecological group was performed by graphic analysis of the dendrogram resulting from the cluster analysis based on the increment mean values per species and DBH class. Figure 2 presents the dendrograms obtained by the Euclidian distance as a similarity measure, using the complete linkage clustering method with the furthest neighbor, for each ecological cluster.

Based on the dendrograms, four distinct subgroups were defined for the pioneer and secondary species main groups and two subgroups for the climax species, as follows:

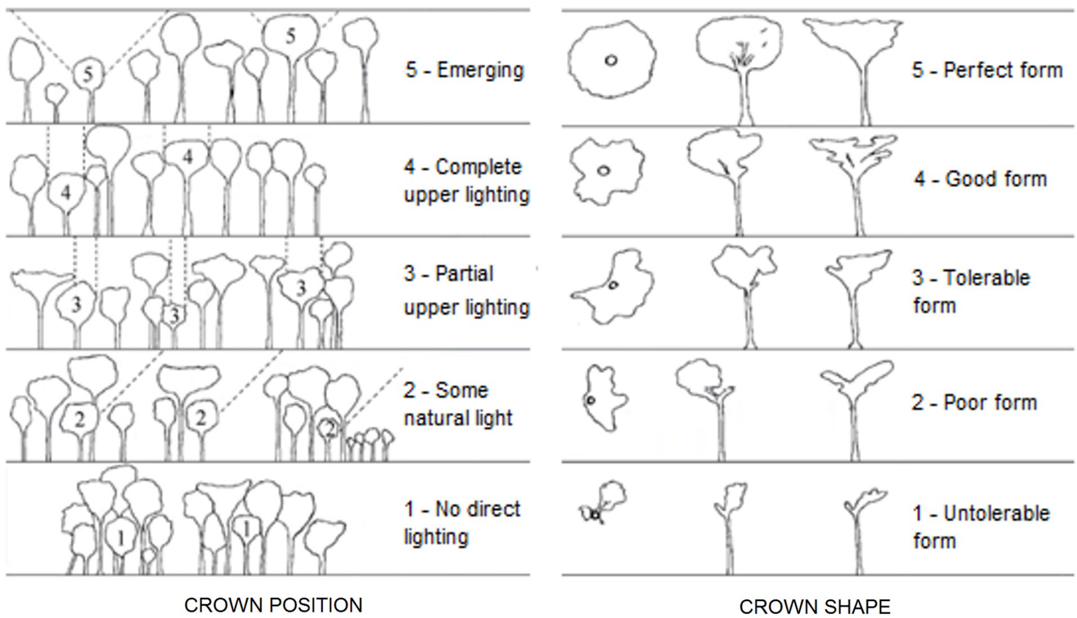

Figure 1. Classification of crown position and crown shape as proposed by Dawkins (adapted from Dawkins, 1958).

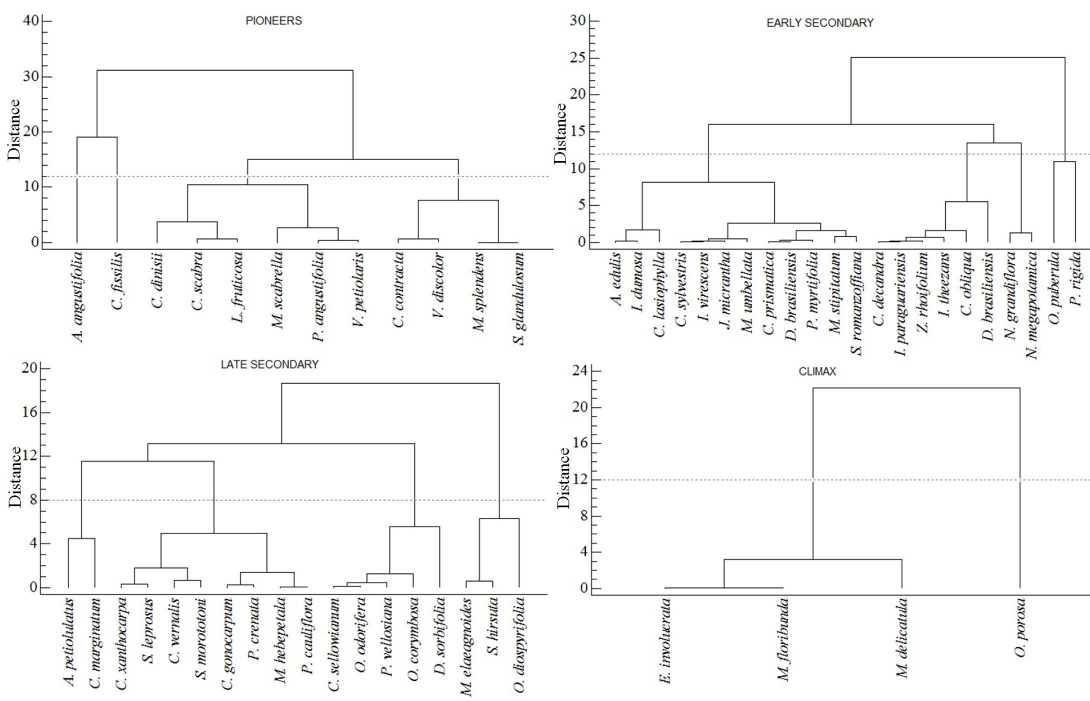

Figure 2. Clustering according to the square Euclidian distance, by the furthest neighbor method of pioneer, early secondary, late secondary and climax species from a Mixed Ombrophilous Forest fragment.

PIONEERS - Subgroup 1: *Araucaria angustifolia* (Bertol.) Kuntze; Subgroup 2: *Cedrela fissilis* Vell.; Subgroup 3: *Cinnamodendron dinisii* Schwacke, *Clethra scabra* Pers., *Laplacea fructicosa* (Schrad.) Kobuski, *Mimosa scabrella* Benth., *Piptocarpha angustifolia* Dusén ex Malme and *Vernonanthura petiolaris* (DC.) H.Rob.; Subgroup 4: *Coussarea contracta* (Walp.) Müll.Arg., *Myrcia splendens* (Sw.) DC., *Sapium glandulosum* (L.) Morong and *Vernonanthura discolor* (Spreng.) H.Rob.

EARLY SECONDARY - Subgroup 1: *Allophylus edulis* (A.St.-Hil. et al.) Hieron. ex Niederl., *Ilex dumosa* Reissek, *Casearia lasiophylla* Eichler, *Casearia sylvestris* Sw., *Inga irescens* Benth., *Jacaranda micrantha* Cham., *Myrsine umbellata* Mart., *Curitiba prismatica* (D.Legrand) Salywon & Landrum, *Dalbergia brasiliensis* Vogel, *Prunus myrtifolia* (L.) Urb., *Machaerium stipitatum* Vogel and *Syagrus romanzoffiana* (Cham.) Glassman; Subgroup 2: *Casearia decandra* Jacq., *Ilex paraguariensis* A.St.-Hil., *Zanthoxylum rhoifolium* Lam., *Ilex theezans* Mart. ex Reissek, *Casearia obliqua* Spreng. and *Drimys brasiliensis* Miers; Subgroup 3: *Nectandra grandiflora* Nees and *Nectandra megapotamica* (Spreng.) Mez; Subgroup 4: *Ocotea puberula* (Rich.) Nees and *Parapiptadenia rigida* (Benth.) Brenan.

LATE SECONDARY - Subgroup 1: *Allophylus petiolulatus* Radlk. and *Chrysophyllum marginatum* (Hook. & Arn.) Radlk.; Subgroup 2: *Campomanesia xanthocarpa* (Mart.) O.Berg, *Styrax leprosus* Hook. & Arn., *Cupania vernalis* Cambess., *Schefflera morototoni* (Aubl.) Maguire et al., *Chrysophyllum gonocarpum* (Mart. & Eichler ex Miq.) Engl., *Picrasma crenata* (Vell.) Engl., *Myrcia hebepetala* DC. and *Plinia cauliflora* (Mart.) Kausel; Subgroup 3: *Cinnamomum sellowianum* (Nees & Mart.) Kosterm., *Ocotea odorifera* (Vell.) Rohwer, *Psychotria vellosiana* Benth., *Ocotea corymbosa* (Meisn.) Mez and *Diatenopteryx sorbifolia* Radlk.; Subgroup 4: *Matayba elaeagnoides* Radlk., *Sloanea hirsuta* (Schott) Planch. ex Benth. and *Ocotea diospyrifolia* (Meisn.) Mez.

CLIMAX - Subgroup 1: *Eugenia involucrata* DC., *Myrciaria floribunda* (H.West ex Willd.) O.Berg and *Myrciaria delicatula* (DC.) O.Berg; Subgroup 2: *Ocotea porosa* (Nees & Mart.) Barroso.

Seeking to compare and evaluate the efficiency of grouping in the diametric increment modeling, in addition to the subgroups formed in the clustering analysis, all species belonging to each ecological group were joined in their respective main group and named Pi (Pioneer), Si (early secondary), St (late secondary) and Cl (climax). Additionally, the diametric increment modeling was carried out for the forest as a whole, that is, considering all the species used in the grouping without stratifying.

Tables 2 and 3 present, respectively, the results of adjustments carried out based on the models whose

Table 2. Statistics and coefficients of the diametric increment models adjusted to the forest, ecological group and groups formed by cluster analysis in a Mixed Ombrophilous Forest fragment.

	PIONEER					EARLY SECONDARY				
	Group 1	Group 2	Group 3	Group 4	Pi	Group 1	Group 2	Group 3	Group 4	Si
Model	3	2	5	1	3	3	5	5	1	8
N	1034	363	498	626	2521	1972	2341	1212	335	5860
R^2 adj	0.201	0.158	0.016	0.076	0.254	0.019	0.042	0.027	0.035	0.030
Syx (%)	49.10	53.08	82.21	64.24	60.16	92.76	74.91	76.56	63.31	81.80
β_0	0.0050	0.3030	-1.1968	0.2059	0.0115	0.1124	-1.1456	-1.1923	0.3566	-1.9508
β_1	1.6150	0.1613	-5.7069	-0.0084	1.1973	0.4197	-8.4223	-6.5356	-0.0049	0.0149
β_2	-0.0337	-0.5371	---	0.0006	-0.0200	-0.0478	---	---	0.0001	---

	LATE SECONDARY					CLIMAX			FOREST
	Group 1	Group 2	Group 3	Group 4	St	Group 1	Group 2	Cl	
Model	1	1	1	6	1	8	2	2	1
N	51	699	1477	690	2917	304	469	773	12071
R^2 adj	0.044	0.093	0.077	0.034	0.047	0.013	0.004	0.115	0.133
Syx (%)	52.26	66.17	88.83	72.25	79.58	59.13	64.57	69.28	76.54
β_0	-0.3202	-0.0160	0.0594	0.1421	0.0868	-1.8921	0.5700	0.4291	0.0806
β_1	0.0675	0.0220	0.0062	0.0025	0.0072	0.0146	-0.0708	0.0455	0.0075
β_2	-0.0019	-0.0003	0.0001	---	-0.0001	---	-0.7907	-0.5393	-0.0001

Pi = pioneer; Si = early secondary; St = late secondary; Cl =climax; N = number of observations; R^2 adj = adjusted coefficient of determination; Syx (%) = standard error estimate; β_0, β_1, β_2 = coefficients to estimate.

independent variable was the DBH and the equations to estimate the diametric increment obtained by regression analysis using the Stepwise procedure.

The results obtained presented R^2 adjusted lower than 0.368 and means errors higher than 45.89%. Several studies have found results similar to those

Table 3. Diametric increment equations obtained by Stepwise procedures for the different species groups in a Mixed Ombrophilous Forest fragment.

Group (N)	Equation	R^2 adj.	Syx (%)
	PIONEER		
Group 1 (1034)	Id = 0.0879 + 0.0623 (CP) + 0.0592 (CS) - 0.0709 (G_{plot}) - 0.0001 (DBH^2) - 1.3552 (1/DBH)	0.302	45.89
Group 2 (363)	Id = -0.1432 + 0.0909 (SP) + 0.0331 (CS) + 0.0336 (CP)	0.244	50.31
Group 3 (498)	Id = 0.0537 - 0.3252 ($G_{sp.ha^{-1}}$) + 0.0488 (CS) + 0.0418 (CP) - 0.0036 (CC) + 0.0348 (SP)	0.245	72.55
Group 4 (626)	Id = -0.8396 + 0.0312 (CS) - 0.3096 (IGH) + 0.4635 ($G_{sp.ha^{-1}}$) - 0.1438 (G_{plot}) + 0.0253 (HE) + 0.0174 (CP) + 0.0013 (BAL) + 0.0451 (DBH + 2DBH)	0.238	58.31
Pi (2521)	Id = -0.0846 + 0.0436 (CP) + 0.0520 (CS) + 0.0105 ($G_{sp.ha^{-1}}$) - 0.0518 (G_{plot}) + 0.0353 (SP)	0.368	55.23
	EARLY SECONDARY		
Group 1 (1972)	Id = 0.0914 - 0.1788 ($G_{sp.ha^{-1}}$) + 0.0267 (CS) + 0.0335 (HE) - 0.0033 (CC) - 0.0221 (G_{plot}) + 0.0104 (CP)	0.112	88.24
Group 2 (2341)	Id = 0.3382 + 0.0227 (CP) + 0.0290 (CS) - 0.0409 (G_{plot}) + 0.0266 (SP) + 0.0234 ($G_{sp.ha^{-1}}$) + 0.0178 (SF) - 1.7673 (1/DBH) - 0.0897 (ln DBH)	0.157	70.30
Group 3 (1212)	Id = - 0.0622 + 0.0448 (CS) + 0.0201 (CP) - 0.0430 (G_{plot}) + 0.0331 (SP) + 0.0242 (HE)	0.143	71.86
Group 4 (335)	Id = - 0.0283 + 0.0345 (CS) - 0.1458 ($G_{sp.ha^{-1}}$) + 0.0400 (CP) + 0.0831 (HE)	0.148	59.45
Si (5860)	Id = 0.0083 + 0.0266 (CS) + 0.0002 (DBH^2) - 0.0317 (G_{plot}) + 0.0348 (HE) + 0.0290 ($G_{sp.ha^{-1}}$) + 0.0151 (CP) - 0.0039 (CC) + 0. 0139 (SP) - 0.0089 (SF) - 1.5298 (g)	0.101	78.76
	LATE SECONDARY		
Group 1 (51)	Id = 0.0748 + 0.0446 (CS)	0.086	51.09
Group 2 (699)	Id = 0.0414 + 0.0440 (CP) + 0.0342 (CS) - 0.7390 (1/DBH)	0.181	62.88
Group 3 (1477)	Id = 0.4417 - 0.1655 ($G_{sp.ha^{-1}}$) + 0.0361 (CS) + 0.0005 (BAL) - 0.0763 (G_{plot}) - 1.8612 (1/DBH) - 0.0250 (SF) + 0.0243 (SP)	0.352	74.42
Group 4 (690)	Id = -0.0735 + 0.0311 (CS) - 0.0541 (G_{plot}) + 0.0312 (SF) + 0.0400 (HE) + 0.0209 (CP)	0.149	67.79
St (2917)	Id = -2.7687 - 0.0925 ($G_{sp.ha^{-1}}$) + 0.0335 (CS) + 0.0206 (CP) + 0.0007 (BAL) - 0.0732 (G_{plot}) + 0.5386 (ln DBH) + 0.0276 (D_{max} - DBH) + 0.0002 (DBH^2)	0.230	71.50
	CLIMAX		
Group 1 (304)	Id = 0.0503 + 0.0257 (CS) + 0.0341 (SF) - 0.0003 (BAL)	0.131	55.49
Group 2 (469)	Id = 0.1327 + 0.0521 (CS) - 0.1203 (G_{plot}) + 0.0758 (SP)	0.146	59.75
Cl (773)	Id = 0.0307 + 0.0622 ($G_{sp.ha^{-1}}$) + 0.0480 (CS) - 0.0958 (G_{plot}) + 0.0507 (SP)	0.280	62.47
	FOREST		
(12071)	Id = -0.1934 + 0.0231 (CP) + 0.0177 ($G_{sp.ha^{-1}}$) + 0.0368 (CS) - 0.0544 (G_{plot}) + 0.0544 (DBH + SD) + 0.0288 (HE) + 0.0243 (SP) - 0.0095 (SF) + 0.0003 (BAL) - 0.2651 (g) - 0.0019 (CC)	0.239	71.74

N = number of observations; Id = periodic annual diameter increment ($cm.year^{-1}$); BAL = BAL index; CC = diameter class center (cm); DBH = diameter at breast height (cm); D_{max} = maximum diameter (cm); SD = standard deviation diameter (cm); CS = crown shape; SF = stem form; HE = healthy; g = cross-sectional area (m^2); G_{plot} = plot basal area ($m^2.ha^{-1}$); $G_{sp.ha^{-1}}$ = species basal area per hectare ($m^2.ha^{-1}$); IGH = Glover and Hool index; ln = naperian logarithm; CP = crown position; SP = sociological position.

presented in this research, with low coefficient of determination and high standard errors of estimation (Palahí et al., 2003; Palahí & Grau, 2003; Phillips et al., 2004; Della-Flora et al., 2004; Nebel & Meilby, 2005; Bueno & Bevilacqua, 2010; Stepka et al., 2012).

The use of other independent variables, besides DBH, in the diametric increment estimate, positively influenced the adjustments. In this sense, the equations to predict diametric increment obtained by Stepwise procedures presented higher results, in all situations under evaluation and, even for the forest in general, when compared to the models that only used the DBH as the independent variable at the beginning of the evaluation period.

The most common variables in the equations obtained by Stepwise procedure, to estimate diametric increment were, respectively: crown shape (100%), crown position (73.7%), plot basal area (68.4%), species basal area per hectare (57.9%) and sociological position (52.6%).

Modeling the increment in basal area of individual trees of *Cedrela odorata* L., in the Amazon Forest, Cunha (2009) showed that some dimensional characteristics of trees, such as total height, degree of slenderness, crown length and crown shape contributed to a greater degree to explaining the variation of basal area increment (82.7%). Most of the variables that expressed tree morphometry were associated with the crown, indicating it as a reference for use in predicting growth when higher accuracy and reliability of mathematical models is desired.

The DBH variable was hardly ever selected in the equations generated by Stepwise procedure, indicating low correlation between the diametric increment and the diameter at the beginning of the evaluation period.

The diametric increment estimate per ecological group presented positive effects on the pioneer and climax species, when compared to the estimates obtained for the forest in general. In this case, the best fit obtained for the forest as a whole by the models using only DBH as independent variable was model 1, with R^2adj = 0.113 and Syx%= 76.5%. In the Pioneer and Climax groups, the adjusted R^2 was 0.254 and 0.115, and the Syx% was 60.2% and 69.3%, respectively. In relation to the equations obtained by Stepwise procedure, the forest presented R^2adj = 0.239 and Syx%= 71.1%, while the referred groups presented R^2adj= 0.368 and 0.280, and Syx% = 55.2 and 62.5%, respectively.

Data stratification in subgroups of greater similarity, in relation to growth, by cluster analysis, indicated a reduction in the standard error of estimate, when compared to the adjustments by ecological groups, with some exceptions, as was the case with subgroups 3 and 4 of the pioneer species, subgroup 1 of the early secondary species and subgroup 3 of the late secondary species. On the other hand, no relation was observed between data stratification and the adjusted coefficient of determination.

The highest adjusted coefficient of determination was observed for the Pioneer group, both in the traditional model and the equations obtained by Stepwise procedure, whose values were 0.254 and 0.368, while the standard error of estimate values were 60.2 and 55.2%, respectively. However, two subgroups deserve emphasis: subgroup 1 and subgroup 2 in the pioneer group, represented by the species *Araucaria angustifolia* and *Cedrela fissilis,* respectively. Subgroup 1 presented R^2adj = 0.201 and Syx% = 49.1% in the traditional models and R^2adj = 0.302, and Syx% = 45.9% for the equations obtained by Stepwise procedure; these were the lowest errors observed of all the groups/subgroups under evaluation. Subgroup 2 presented R^2adj = 0.158 and Syx% = 53.1% (traditional models), and R^2adj = 0.244 and Syx% = 50.3% (Stepwise). This indicates that the adjustments carried out at the species level might present higher results than those obtained per species group, or even for the forest as a whole.

Similarly, Vanclay (1991) tested different ways of grouping 237 species in a forest in Queensland, Australia, and concluded that grouping produces more robust equations than when individual species are used, although the equation R^2 value for species that were not grouped (0.51) was higher than that of the grouped species (0.49). In that study, a diametric increment function was developed with six coefficients using DBH, site quality, basal area and a competition index.

Rossi (2007) tested some models for the adjustment of mean increments grouped by DBH class and noticed that the adjustments for pine in general presented better statistics than those obtained from the increment adjustment for all species. This author found that of the 168 cases tested, only 22 presented a standard error of estimate lower than 15% and in only one case was it lower than 10%. Regarding the adjusted coefficient of determination, there was variation from 0.00 to 0.87, presenting 22 cases with values over 0.80. This author also modeled the mean annual increment obtained in periods of 1, 2, 3 and 4 years of monitoring; the best adjustments occurred with data obtained in the of 2-year monitoring period.

Chai & Lemay (1993) developed a diametric model for the forests of Sarawak, Malaysia, using DBH, square DBH, competition index, age since exploitation, basal area, number of trees and crown position as independent variables. These authors found an adjusted coefficient of determination varying from 0.08 to 0.48, and the modeling per species caused an 11.2% reduction in the standard error of estimate when compared to the modeling by species group.

Other studies can be cited to compare the results obtained in this study. Palahí et al. (2003) used DBH, competition index, site index, basal area and population age as independent variables to model *Pinus sylvestris* growth in Spain. These authors obtained $R^2 = 0.24$ and Syx% = 64.1%.

Palahí & Grau (2003), when estimating *Pinus nigra* increment in northern Spain, obtained $R^2 = 0.14$ and Syx% = 67.7%, using increment data with a 5-year measuring interval. These authors used DBH, competition index and population age as variables.

Phillips et al. (2004) applied an individual increment model in the Brazilian Amazon forest, using DBH and competition index as independent variables, which resulted in an R^2 varying between 0.033 and 0.186, according to the species group.

Della-Flora et al. (2004) used a model for the current annual increment modeling in basal area of the species *Nectandra megapotamica* in a Seasonal Deciduous Forest in the State of Rio Grande do Sul. Using DBH, competition index and site representative as independent variables, adjusted coefficient of determination values ranging from 0.223 to 0.339 were obtained.

Nebel & Meilby (2005) employed DBH and a competition index to model the diametric increment of eight species in the Peruvian Amazon forest. The coefficient of determination varied from 0.13 to 0.45 for the species under study.

Low performance in diametric increment modeling using the DBH at the beginning of the monitoring period is explained by the great variability of tree increment in native forests, in terms of a common initial diameter. In these forests there is great variation in tree increments (biological variation) sometimes related to genetic factors, age differences between trees, soil quality and competition. A number of trees showing the same dimensions can present different growth rates due to diverse factors that can interfere with the dynamics of each individual, that is, this variable yield from the same size trees affects the low performance in terms of adjustments (Stepka et al., 2012).

The difficulties for prognosis of growth in natural forests are related to tree growth variability, which is influenced by the characteristics of the species in relation to the forest structure and environment, since several of them are environmental factors that affect tree development, such as climatic, pedological, topographical and competition factors (Husch et al., 1982; Prodan et al., 1997).

In this sense, Swaine (1990) states that tree growth rates are highly variable, with variations between species, as well as between trees of the same species, but of different sizes or genetic constitution, or established in different habitats. Terborgh et al. (1997) said that individual trees of a given size may represent a significant age difference. Therefore, trees of a given age can reach different sizes, which means that individuals of a given size or age may be growing at many different rates, negatively affecting the estimation of growth trajectory and life span.

According to Figueiredo et al. (2017), the size and shape of trees are directly affected by the site characteristics and conditions under which they develop such that trees of the same species and age may present marked differences in their dendrometric variables, which makes the prognosis of growth difficult.

Many studies on this topic develop modeling based on mean increment data. The adjustment statistics, in such cases, obviously present coefficients of determination close to 100% and very low errors. However, this does not represent the reality of data variability, since these adjustments do not reflect the actual forest growth rate (Stepka et al., 2012).

Finally, these results indicate that the use of other variables as indexes that represent the competition and the site, in addition to the diameter at the beginning of the evaluation period, to estimate diametric increment, positively influenced the adjustments, and an increase in the adjusted coefficient of determination was observed along with a reduction in the standard error of estimate, both in the subgroups formed and in the ecological groups and for the forest as a whole. Data stratification of a Mixed Ombrophilous Forest using cluster analysis, based on mean increment values, by species and DBH class, generally led to a reduction in the standard error of estimate; however, the results obtained still did not make it possible to model diametric increment with good performance.

Given this, the stratification of the data resulting from the proposed grouping or even by species, may be an option in this type of modeling. Therefore, stratification should also occur at the individual level, and may reduce the variation in the data set, improving the evaluation statistics. In this case, the independent variables used in the modeling, can also be considered in a discriminant analysis, aiming to identify the variables capable of better discriminating the subgroups, which would possibly be the variable most correlated with the increment.

The morphometric indexes (Hernández & Luna, 2008; Orellana & Koehler, 2008; Schneider & Schneider, 2008; Selle & Vuaden, 2010; Wink et al., 2012; Zimmermann et al., 2016) reflect, among other factors, the photosynthetic potential of the tree and are sensitive to the effects of competition (Tonini, 2007; Dimov et al., 2008; Fox et al., 2008; Boivin et al., 2010; Thorpe et al., 2010; Chassot et al., 2011; Cunha & Finger, 2013; Costa & Finger, 2017), thereby leading to variability in resource uptake, making them highly correlated with growth (Clark & Clark, 2001). Therefore, further research on the use of other variables for increment modeling, especially morphometric variables related to tree crowns, may be an option in modeling diametric increment in native forests.

4. CONCLUSIONS

- The DBH variable was almost never selected in the equations generated by Stepwise procedure, indicating the low correlation existing between the diametric increment and the diameter at the beginning of the evaluation period. Consequently, traditional models did not present reasonable statistical results from the data of the present study;
- The variables most correlated with diametric increment and, consequently, most used in its modeling were: crown shape, crown position, plot basal area, species basal area per hectare and sociological position, which resulted in improvements to the adjustments for all situations under evaluation compared to traditional modeling;
- The stratification of the data by cluster analysis did not make the model statistics suitable to estimate the diametric increment, however, they produced an improvement, reducing the standard error of estimation, suggesting that this technique can be better applied in the search to improve the diametric modeling of natural forests.

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REFERENCES

Alder D. *Growth modeling for mixed tropical forests*. Oxford: Oxford Forestry Institute, Department of Plant Sciences, University of Oxford; 1995.

Alemdag IS. *Evaluation of some competition indexes for the prediction of diameter increment in planted white spruce*. Ottawa: Canadian Forestry Service, Department of the Environment, Forest Management Institute Information; 1978. 39 p. Report FRM X 108.

Boivin F, Paquette A, Papaik MJ, Thiffault N, Messier C. Do position and species identity of neighbours matter in 8-15-year-old post harvest mesic stands in the boreal mixedwood? *Forest Ecology and Management* 2010; 260(7): 1124-1131. http://dx.doi.org/10.1016/j.foreco.2010.06.037.

Bueno S, Bevilacqua E. Modeling stem increment in individual *Pinus occidentalis* Sw. trees in La Sierra, Dominican Republic. *Forest Systems* 2010; 19(2): 170-183. http://dx.doi.org/10.5424/fs/2010192-01312.

Carvalho PER. *Espécies arbóreas brasileiras*. Vol. 2. Brasília: Embrapa Floresta; 2006.

Carvalho PER. *Espécies arbóreas brasileiras*. Vol. 3. Brasília: Embrapa Floresta; 2008.

Chai FYC, Lemay VM. Development and testing of diameter increment models for mixed swamp forests of Sarawak. *Forest Ecology and Management* 1993; 58(1-2): 51-64. http://dx.doi.org/10.1016/0378-1127(93)90131-6.

Chassot T, Fleig FD, Finger CAG, Longhi SJ. Modelos de crescimento em diâmetro de árvores individuais de *Araucaria angustifolia* (Bertol.) Kuntze na Floresta Ombrófila Mista. *Ciência Florestal* 2011; 21(2): 303-313. http://dx.doi.org/10.5902/198050983234.

Clark DA, Clark DB. Getting the canopy: tree height growth in a neotropical rain forest. *Ecology* 2001; 82(5): 1460-1472. http://dx.doi.org/10.1890/0012-9658(2001)082[1460:GTTCTH]2.0.CO;2.

Costa EA, Finger AG. Efeito da competição nas relações dimensionais de Araucária. *Floresta e Ambiente* 2017; 24(1): 1-11.

Cunha TA, Finger CAG. Competição assimétrica e o incremento diamétrico de árvores individuais de *Cedrela odorata* L. na Amazônia ocidental. *Acta Amazonica* 2013; 43(1): 9-18. http://dx.doi.org/10.1590/S0044-59672013000100002.

Cunha TA. *Modelagem do incremento de árvores individuais de Cedrela odorata L. na Floresta Amazônica* [tese]. Santa Maria: Setor de Ciências Agrárias, Universidade Federal de Santa Maria; 2009.

Dawkins HC. *The management of natural tropical high forest with special reference to Uganda*. Oxford: University of Oxford, Imperial Forestry Institute; 1958.

Della-Flora JB, Durlo MA, Spathelf P. Modelo de incremento para árvores singulares – *Nectandra megapotamica* (Spreng.) Mez. *Ciência Florestal* 2004; 14(1): 165-177. http://dx.doi.org/10.5902/198050981791.

Dimov LD, Chambers JL, Lockhart BR. Five-year radial growth of red oaks in mixed bottomland hardwood stands. *Forest Ecology and Management* 2008; 255(1): 2790-2800. http://dx.doi.org/10.1016/j.foreco.2008.01.070.

Figueiredo A Fo, Retslaff FS, Retslaff FS, Santos TL, Stepka TF. Crescimento e idade de espécies nativas regenerantes sob plantio de *Araucaria angustifolia* no Paraná. *Floresta e Ambiente* 2017; 24(1): 1-9.

Fox JC, Bi H, Ades PK. Modelling spatial dependence in an irregular natural forest. *Silva Fennica* 2008; 42(1): 35-48. http://dx.doi.org/10.14214/sf.262.

Hernández EH, Luna JAN. Relaciones morfométricas de un bosque coetáneo de la región del El Salto, Durango. *Ra Ximhai* 2008; 4(1): 69-81.

Husch B, Miller CI, Beers TW. *Forest mensuration*. 3rd ed. New York: John Wiley & Sons; 1982. 402 p.

Kageyama PY, Gandara FB. Dinâmica de populações de espécies arbóreas: implicações para o manejo e a conservação. *Aciesp* 1994; 2(1): 1-9.

Lorenzi H. *Árvores brasileiras: manual de identificação e cultivos de plantas arbóreas do Brasil*. 2nd ed. São Paulo: Nova Odessa; 2002.

Nebel G, Meilby H. Growth and populations structure of timber species in Peruvian Amazon flood plains. *Forest Ecology and Management* 2005; 215(1): 196-211. http://dx.doi.org/10.1016/j.foreco.2005.05.017.

Orellana E, Koehler AB. Relações morfométricas de *Ocotea odorifera* (Vell.) Rohwer. *Revista Acadêmica* 2008; 6(2): 229-237. http://dx.doi.org/10.7213/cienciaanimal.v6i2.10496.

Palahí M, Grau JM. Preliminary site índex model and individual-tree growth and mortality models for Black pine (*Pinus nigra* Arn.) in Catalonia (Spain). *Forest Systems* 2003; 12(1): 137-148.

Palahí M, Pukkala T, Miina J, Montero G. Individual-tree growth and mortality models for Scots pine (*Pinus sylvestris* L.) in north-east Spain. *Annals of Forest Science* 2003; 60(1): 1-10.

Phillips PD, Azevedo CP, Degen B, Thompson IS, Silva JNM, Van Gardingen PR. An individual-based spatially explicit simulation model for strategic forest management planning in the eastern Amazon. *Ecological Modelling* 2004; 173(4): 335-354. http://dx.doi.org/10.1016/j.ecolmodel.2003.09.023.

Prodan M, Peters R, Cox F, Real P. *Mensura forestal*. San Jose: Deutsche Gesellschaft fur Technische Zusammenarbeit, Instituto Interamericano de Cooperacion para la Agricultura; 1997. 561 p.

Rossi LMB. *Processo de difusão para simulação da dinâmica de floresta natural* [tese]. Curitiba: Setor de Ciências Agrárias, Universidade Federal do Paraná; 2007.

Sawczuk AR, Figueiredo A Fo, Dias AN, Watzlawick LF, Stepka TF. Alterações na estrutura e na diversidade florística no período 2002-2008 de uma Floresta Ombrófila Mista Montana do centro-sul do Paraná, Brasil. *Floresta* 2012; 42(1): 1-10. http://dx.doi.org/10.5380/rf.v42i1.26286.

Schneider PR, Schneider PSP. *Introdução ao manejo florestal*. 2nd ed. Santa Maria: UFSM; 2008. 566 p.

Selle GL, Vuaden E. Crescimento de seis espécies nativas na região central do estado do Rio Grande do Sul. *Ambiência* 2010; 6(1): 169-192.

Sistema Meteorológico do Paraná – SIMEPAR [online]. 2012. [cited 2012 Apr 12]. Available from: http://www.simepar.br/

Stepka TF, Dias AN, Figueiredo A Fo, Machado SA, Sawczuk AR. Modelagem do incremento em diâmetro da *Araucaria angustifolia* em uma Floresta Ombrófila Mista no Centro-Sul do Paraná. *Floresta* 2012; 42(3): 607-620. http://dx.doi.org/10.5380/rf.v42i3.21718.

Swaine MD. Population dynamics of tree species in tropical forests. In: Nielsen LBH, Nielsen IC, Balslev H, editors.

Botanical dynamics, speciation and diversity. San Diego: Academic Press; 1990. p. 3-101.

Terborgh J, Flores N C, Mueller P, Davenport L. Estimating the ages of sucessional stands of tropical trees form growth increments. *Journal of Tropical Ecology* 1997; 14(1): 833-856. http://dx.doi.org/10.1017/S0266467400011020.

Thorpe HC, Astrup R, Trowbridge A, Coates KD. Competition and tree crowns: a neighbourhood analysis of three boreal tree species. *Forest Ecology and Management* 2010; 259(8): 1586-1596. http://dx.doi.org/10.1016/j.foreco.2010.01.035.

Tonini H. *Índices de competição e o seu uso na modelagem do crescimento das árvores*. Boa Vista: Embrapa; 2007. 30 p

United States Department of Agriculture – USDA. *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. Washington; 1999.

Vanclay JK. Aggregating tree species to develop diameter increment equations for tropical rainforests. *Forest Ecology and Management* 1991; 42(3): 143-168. http://dx.doi.org/10.1016/0378-1127(91)90022-N.

Von Bertalanffy L. Quantitative laws for methabolism and grown. *The Quarterly Review of Biology* 1957; 32(3): 217-231. http://dx.doi.org/10.1086/401873. PMid:13485376.

Wink C, Monteiro JS, Reinert DJ, Liberalesso E. Parâmetros da copa e a sua relação com o diâmetro e altura das árvores de eucalipto em diferentes idades. *Scientia Forestalis* 2012; 40(93): 57-67.

Zimmermann APL, Costa EA, Schröder T, Fleig FD. Modelagem do incremento diamétrico de *Pinus taeda* em função de variáveis da copa e índices de competição. *Floresta* 2016; 46(1): 115-122. http://dx.doi.org/10.5380/rf.v46i1.42424.