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Artigos

Temporal stability of stratifications using different dendrometric variables and geostatistical interpolation

Estabilidade temporal das estratificações utilizando diferentes variáveis dendrométricas e interpolação geoestatística

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ABSTRACT

Stratifying a forest results in more precise and cheaper inventories. This study aimed to select the stratifying variable that estimates more precise and stable inventory over the years for a eucalyptus plantation in Minas Gerais state, Brazil. The continuous forest inventory was performed annually from 2.7 to 6.8 years, and based on the field measurements, arithmetic mean diameter (d), height (h), dominant height (Hdom), basal area (G), volume (V), and mean annual increment in volume (MAI) were calculated. Semivariograms were generated and the exponential, spherical and Gaussian models were fit for each stratifying variable for each measurement date. The models were assessed by the reduced mean error and its deviation, being the exponential model selected. Maps showing the spatial distribution of all variables were generated for each measurement age, using ordinary kriging. Next, the study area was divided in four strata based on each stratifying variable for each measurement age. The stability of each stratifying variables for each measurement age were assessed by: 1) coincident strata area; 2) stability of total strata area; 3) plot permanency on each stratum; and 4) inventory error using stratified random sampling procedures. All variables in all ages presented spatial dependence structure. G and Hdom were the stratifying variables that generated the most and the least coincident strata area over the years, respectively. G and height (h and Hdom) were the stratifying variables yielding the least and most plot stratum changes, respectively. The same trend was observed for the total strata area stability. Stratifying based on MAI and V yielded the smaller inventory error, and h and Hdom yielded the largest. G was selected as the best stratifying variable because it yielded small inventory errors and was the most stable variable in terms of coincident strata area, total strata area and plot stratum changes over the years.

Keywords: Stratified random sampling; Eucalyptus; Forest inventory; Forest management

RESUMO

A estratificação de uma floresta resulta em inventários mais precisos e mais baratos. Este estudo teve como objetivo selecionar a variável estratificadora que estima inventários mais precisos e estáveis ao longo dos anos para um plantio de eucalipto no estado de Minas Gerais, Brasil. Foi realizado inventário florestal contínuo na área anualmente dos anos 2,7 a 6,8, sendo posteriormente calculados o diâmetro médio aritmético (d), altura (h), altura dominante (Hdom), área basal (G), volume (V) e incremento médio anual em volume (MAI). Foram gerados semivariogramas e os modelos exponencial, esférico e Gaussiano foram ajustados para cada variável estratificadora em cada época de medição. Os modelos foram avaliados pelo erro médio reduzido e seu desvio, sendo o modelo exponencial selecionado. Mapas mostrando a distribuição espacial de todas as variáveis foram construídos para cada idade de medição, utilizando krigagem ordinária. Em seguida, a área de estudo foi dividida em quatro estratos com base em cada variável estratificadora para cada idade de medição. A estabilidade de cada variável estratificadora para cada idade de medição foi avaliada por: 1) área coincidente dos estratos; 2) estabilidade da área total dos estratos; 3) permanência da parcela em cada estrato; e 4) erro de inventário utilizando formulação de amostragem casual estratificada. Todas as variáveis em todas as idades apresentaram estrutura de dependência espacial. G e Hdom foram as variáveis estratificadoras que geraram mais e menos área coincidente entre estratos ao longo dos anos, respectivamente. G e altura (h e Hdom) foram as variáveis estratificadoras que apresentaram menor e maior número de parcelas com mudança de estrato, respectivamente. A mesma tendência foi observada para a estabilidade da área total dos estratos. As estratificações baseadas em MAI e V renderam os menores erros de inventário, enquanto as estratificações baseadas em h e Hdom renderam os maiores erros. G foi selecionada como a melhor variável estratificadora, pois apresentou pequenos erros de inventário e foi a variável mais estável em termos da área coincidente dos estratos, estabilidade da área total dos estratos e permanência das parcelas no mesmo estrato.

Palavras-chave: Amostragem casual estratificada; Eucalipto, Inventário florestal; Manejo florestal

1 INTRODUCTION

Stratifying a forest involves subdividing it into smaller and more homogeneous areas based on a stand attribute of interest, with the aim of reducing the population variability (BATISTA; COUTO; SILVA FILHO, 2014). Despite the apparent homogeneousness of many forest plantations, several studies have shown significant spatial and temporal variability in the dendrometric variables (MELLO *et al*., 2009; GUEDES *et al*., 2012; LUNDGREN; SILVA; FERREIRA, 2015). Therefore, the use of stratified random sampling (STS) in forest inventory campaigns helps control the variability of forest characteristics, compared with simple random sampling (SRS), impacting the precision, sampling intensity, and costs of the forest inventory (ASSIS *et al*., 2009;

GUEDES *et al*., 2012; REIS *et al*., 2015; OLIVEIRA *et al*., 2018; ZECH *et al*., 2018).

Traditionally, forest stratification is based on planting records, such as age, species, clones, spacing, and management (KANEGAE JÚNIOR *et al*., 2006, 2007; ASSIS *et al*., 2009). However, this information does not account for all forest dynamics, such as the spatial variability and the interrelationship between variables that occurs over time. Hence, geostatistical interpolation, such as ordinary kriging, explains spatial variation that complements inventory data for a better understanding of the forest, which greatly supports the stratifying process (BOGNOLA *et al*., 2008; MELLO *et al*., 2009; MENG; CIESZEWSKI; MADDEN, 2009; LEAL; MATRICARDI; MIGUEL, 2014; PELISSARI *et al*., 2014; SILVEIRA *et al*., 2019).

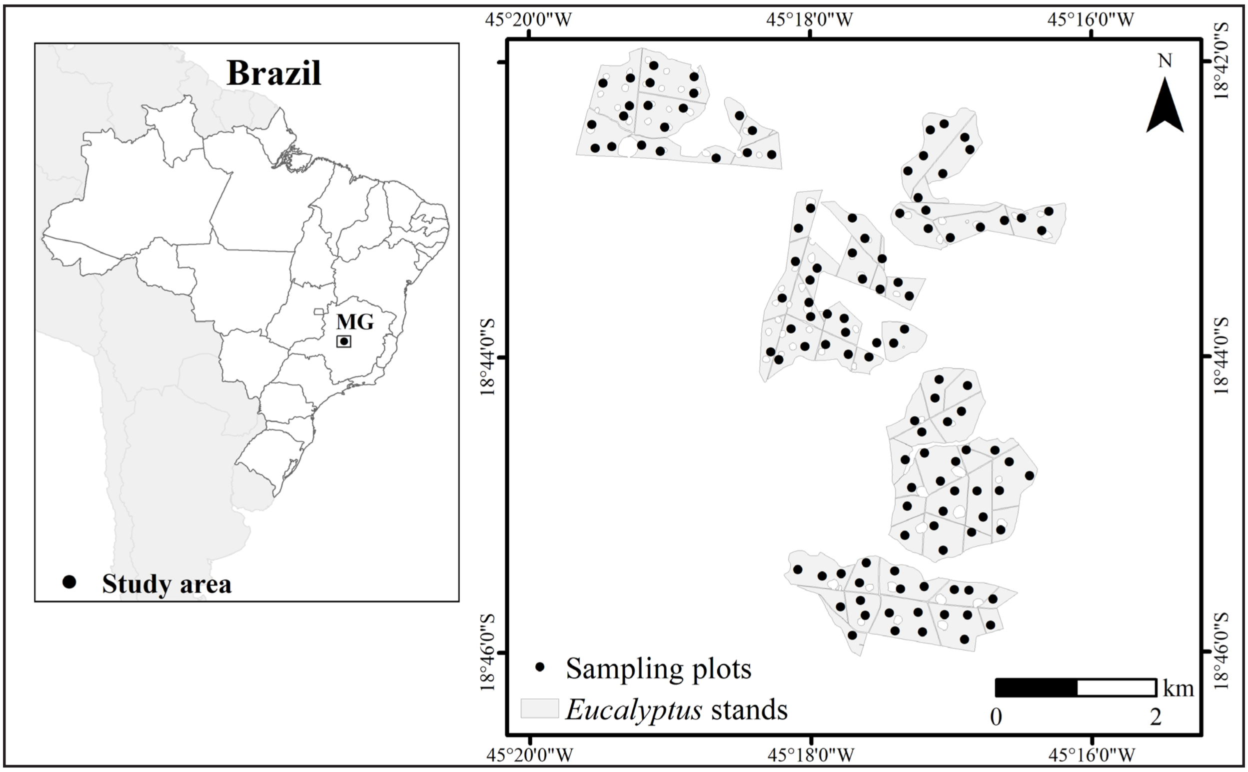
For forest management purposes, ordinary kriging (for strata delimitation) should be based on a stand attribute of interest (e.g. commercial volume) and strata range should change as little as possible over time (KANEGAE JÚNIOR *et al*., 2007). As a result, inventory plots do not shift from one stratum to another, and forest operations, such as harvesting and thinning, can be better planned. The goal of this study was to assess different dendrometric variables used as base for geostatistical interpolators and the resulting stratifying process, aiming to select the most precise and stable variable over the years for a *Eucalyptus* sp. plantation in Minas Gerais state, Brazil.

2 MATERIAL AND METHOD

The study site used in this study was a *Eucalyptus* sp. clonal plantation located in Morada Nova de Minas, Minas Gerais state, Brazil, between the geographic coordinates 18º45’50” S - 45°19’10” W and 18º41’40” S - 45°15’50” W. The area is composed of 61 stands, planted from June to December of 2003, in 3 x 3 m spacing, totaling 1,023.2 hectares (Figure 1).

The plantation area used in this study (Figure 1) had continuous forest inventory performed in it annually from 2006 to 2010. Thus, 116 permanent sampling plots of 400 m^2 each were allocated in the area using a stratified systematic unaligned sampling design. In this design, the population area frame is divided into cells of equal area (each with about 10 ha), followed by randomly locating one sample plot within each cell. In each plot, the height of the first 15 normal trees (no bifurcation or any other defect) and the 4 dominant trees (the height of the trees with largest diameter), if they were not measured within the previous 15, were measured, as well as the circumference at breast height (1.3 m from the ground) of all trees. The average height of the 4 thickest trees per plot represented the stand's dominant height. The dominant height is the average height of the 100 thickest trees per hectare, as is commonly used in plantation forestry (ASSMANN, 1970). All plots were georeferenced. From the data collected in the plots, arithmetic mean diameter (d, in cm), mean height (h, in m), mean dominant height (Hdom, in m), basal area (G, in m² ha^{-1}), volume (V, in m³ ha^{-1}), and mean annual increment in volume (MAI, in m³ ha^{-1} year^{-1}) were calculated.

Figure 1 – Study site location and plot arrangement in the eucalyptus plantation in Morada Nova de Minas, MG state, Brazil



Source: Authors (2021)

Descriptive statistical analysis was carried out for all variables (d, h, Hdom, G, V, and MAI). Experimental semivariograms were constructed for each variable and for each measurement occasion (2006 to 2010). Next, exponential, spherical and Gaussian models were fit by the weighted least squares approximation. Models were assessed by the reduced mean error and the reduced mean error deviation obtained from a cross validation, as described in Cressie (1993).

The dendrometric variables values in the non-sampled plantation areas were estimated using ordinary kriging, as in Isaaks and Srivastava (1989). Maps showing continuous spatial trends of each dendrometric variable (d, h, Hdom, G, V, and MAI) were generated for each measurement age. The stratification was carried using the ordinary kriging information for each variable at each measurement age. Using the ordinary kriging results, the area was divided into four strata for all variables in each measurement age. The number of strata was based on Kanegae Júnior *et al*. (2006), who stated that this number of strata is the best option in operational terms and the most efficient for controlling the variability of eucalyptus stands.

The assessment of the dendrometric variable that generated the most stable strata throughout the development of the forest was done by observing four criteria:

1) Coincident strata area: for each variable, maps of the different measurement ages were overlapped, and the coincident area was quantified via the linear correlation coefficient. The best variable was considered the one that generated the most coincident strata area over the measurement ages (i.e. highest correlation coefficient);

2) Stability of total strata area: for each variable, stability of the total strata area over the years for each stratifying variable was assessed graphically and by its coefficient of variation (CV). Variables with less change in the total area of each stratum over the years were considered better stratifiers;

3) Plot permanency on each stratum: for each variable, the permanency of each plot in the same stratum over time was assessed by attributing a score every time a plot changed the strata. Thus, if the plot remained in the same stratum over all

measurement ages, it was attributed a score of zero; if the plot changed stratum one time, it was attributed a score of one, and so on, up to the maximum of four (i.e. the total remeasurement campaigns). The scores of each plot were summed, being considered the most stable variable the one with the lowest score;

4) Inventory error: for each dendrometric variable in each measurement occasion, the inventory was processed (using volume) via the stratified random sampling estimators, as in Batista; Couto; Silva Filho (2014). The lower the inventory error and the lower its variation over the sampling ages, the better the stratifying variable.

Data were assessed in the software R (R CORE TEAM, 2016), using the package geoR (RIBEIRO JÚNIOR; DIGLLE, 2001) and ArcGIS version 10.1 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2010). The *Geostatistical Analyst* (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2010) extension was used to produce the maps.

3 RESULTS AND DISCUSSION

3.1 Data descriptive analysis

Arithmetic mean diameter was the variable with the smallest CV in all ages (4.7 to 7.4%), indicating the homogeneity of this variable (Table 1). Volume presented the highest variability among the plots, with CV varying from 14.2% to 21.4%.

All variables tended to present a more homogeneous data distribution after age 5.8 (Table 1), an indication that the stands' growth were stabilizing. The CV dropped slightly over time for all variables, which also indicates that older plots were more homogeneous. However, more homogeneity in older plantations is not always the rule, because of factors other than time affect variability, such as location, genetic material, and management (OLIVEIRA *et al*., 2018). For example, Guedes *et al*. (2012) studied three eucalyptus plantations in three different areas in northern Minas Gerais state, Brazil, and found different trends in variability over time, including increased variability as the stands aged.

Table 1 – Descriptive statistics separated by age for the mean, standard deviation and coefficient of variation for the variables used in this study

Variable	Age (year)	Mean	SD	CV (%)
d (cm)	2.7	11.37	0.84	7.39
	3.7	13.92	0.81	5.79
	4.8	15.14	0.75	4.96
	5.8	16.04	0.75	4.68
	6.8	16.33	0.77	4.72
h (m)	2.7	15.31	1.72	11.22
	3.7	19.88	1.65	8.30
	4.8	22.70	2.05	9.02
	5.8	25.11	1.94	7.74
	6.8	26.09	2.22	8.49
Hdom (m)	2.7	16.41	1.73	10.54
	3.7	21.00	1.61	7.64
	4.8	24.14	1.93	7.99
	5.8	26.86	2.01	7.49
	6.8	27.84	2.33	8.36
G (m^2 ha^{-1})	2.7	10.93	1.59	14.52
	3.7	16.33	1.81	11.09
	4.8	19.24	1.81	9.42
	5.8	21.52	1.85	8.58
	6.8	22.23	1.84	8.30
V (m^3 ha^{-1})	2.7	80.31	17.23	21.45
	3.7	150.36	24.45	16.26
	4.8	202.90	31.70	15.62
	5.8	253.60	36.02	14.20
	6.8	276.26	39.38	14.25
MAI (m^3 ha^{-1} $year^{-1}$)	2.7	29.01	5.66	19.51
	3.7	40.38	6.21	15.37
	4.8	41.98	6.27	14.94
	5.8	43.39	6.01	13.84
	6.8	40.69	5.79	14.23

Source: Authors (2021)

In where: standard deviation = SD; coefficient of variation = CV; arithmetic mean diameter = d; height = h; dominant height = Hdom; basal area = G; volume = V; mean annual increment in volume = MAI.

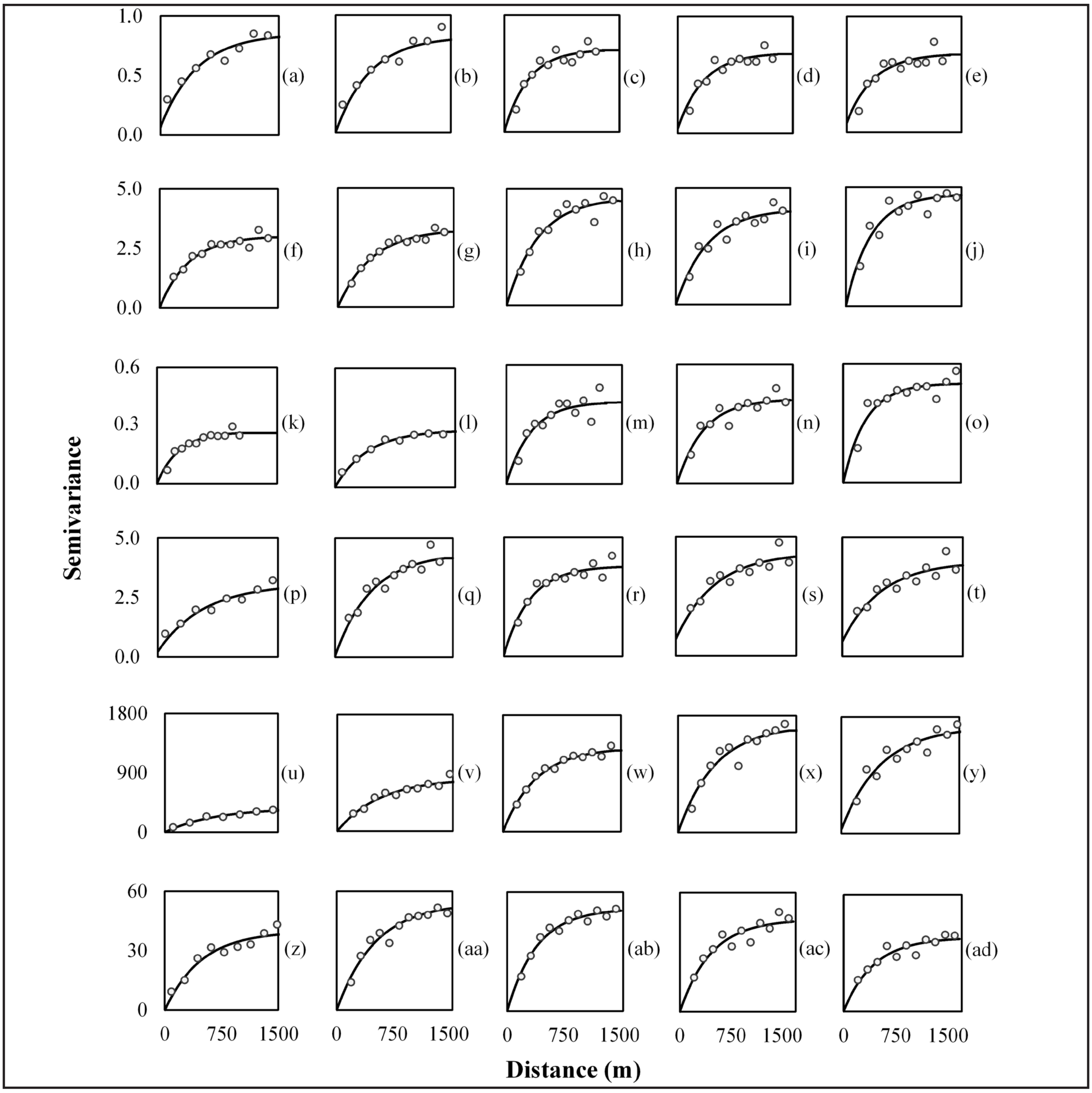
3.2 Spatial dependence structure

All analyzed variables presented consistent spatial dependence structures in all measurement ages (Figure 2). The exponential model outperformed the others in all cases, presenting lower goodness of fit statistics (reduced mean error and the reduced mean error deviation, data not shown), being this model used for the ordinary kriging process. The superiority of the exponential model over the other tested ones was expected, since many studies dealing with ordinary kriging of forest attributes also selected this model, such as: Assis *et al*. (2009), Alvarenga *et al*. (2012), Carvalho *et al*. (2015), Guedes *et al*. (2015), Lundgren, Silva and Ferreira (2015) and Scolforo *et al*. (2016).

The amount of variance that can be explained by the distance (i.e. the asymptotic value of the y scale in Figure 2) increased with age for: V; Hdom; h; G. This trend was not observed in MAI and d, which presented asymptotic values decreasing with age. The spatial dependence structure observed in all variables allowed the generation of stratified maps via ordinary kriging with no trends or bias (Figures 2 and 3). Geostatistical interpolators allow for better spatial distribution of the strata because they consider the spatial dependence structure and possible relations between the variables (GUEDES *et al*., 2012). This precise strata allocation is advantageous for forest inventory, since it optimizes the stratified random sampling (STS) technique, better controlling variability and providing more detailed population information.

Several researchers have found that STS overperformed SRS (KANEGAE JÚNIOR *et al*., 2006; ASSIS *et al*., 2009; GUEDES *et al*., 2012; OLIVEIRA *et al*., 2018; ZECH *et al*., 2018; SILVEIRA *et al*., 2019). For example, Assis *et al*. (2009) studied the effect of stratifying a eucalyptus plantation and observed that CV reduced on average 35.4% (51.4% to 16.0%) to when using STS instead of SRS. Oliveira *et al*. (2018) stratified a eucalyptus plantation using d as the variable of interest and was able to reduce CV in 52%. Kanegae Júnior *et al*. (2006) also stratified a eucalyptus plantation and reduced CV in 47%. Zech *et al*. (2018) stratified a *Pinus taeda* plantation based on basal area and found that CV reduced 73.4%. Reducing errors using STS instead of SRS is also true for native areas. For example, Silva *et al*. (2014) found that CV dropped from 35.5% to 14.2% in a savannah area in MG state, Brazil, when using STS instead of SRS. Silveira *et al*. (2019), likewise estimating biomass for a savannah area in MG state, Brazil, was also able to reduce inventory errors by stratifying the population.

Figure 2 – Experimental semivariograms and fitted exponential models for arithmetic mean diameter for the ages 2.7 (a), 3.7 (b), 4.8 (c), 5.8 (d), and 6.8 (e); mean height for the ages 2.7 (f), 3.7 (g), 4.8 (h), 5.8 (i), and 6.8 (j); dominant height for the ages 2.7 (k), 3.7 (l), 4.8 (m), 5.8 (n), and 6.8 (o); basal area for the ages 2.7 (p), 3.7 (q), 4.8 (r), 5.8 (s), and 6.8 (t); volume for the ages 2.7 (u), 3.7 (v), 4.8 (w), 5.8 (x), and 6.8 (y); and mean annual increment for the ages 2.7 (z), 3.7 (aa), 4.8 (ab), 5.8 (ac), and 6.8 (ad)



Source: Authors (2021)

3.3 Coincident strata area over time

Regarding the coincident strata area over time for the same variable (shaded values in Table 2), basal area, followed by volume, were the variables that generated the highest correlation values over the measurement ages. Mean height and dominant height were the variables that generated the lowest coincident strata area over time for the same variable. Considering the correlation among different variables (unshaded values in Table 2), we found that h and Hdom generated similar strata (i.e. values larger than 70%), as well as the variables V, G and MAI.

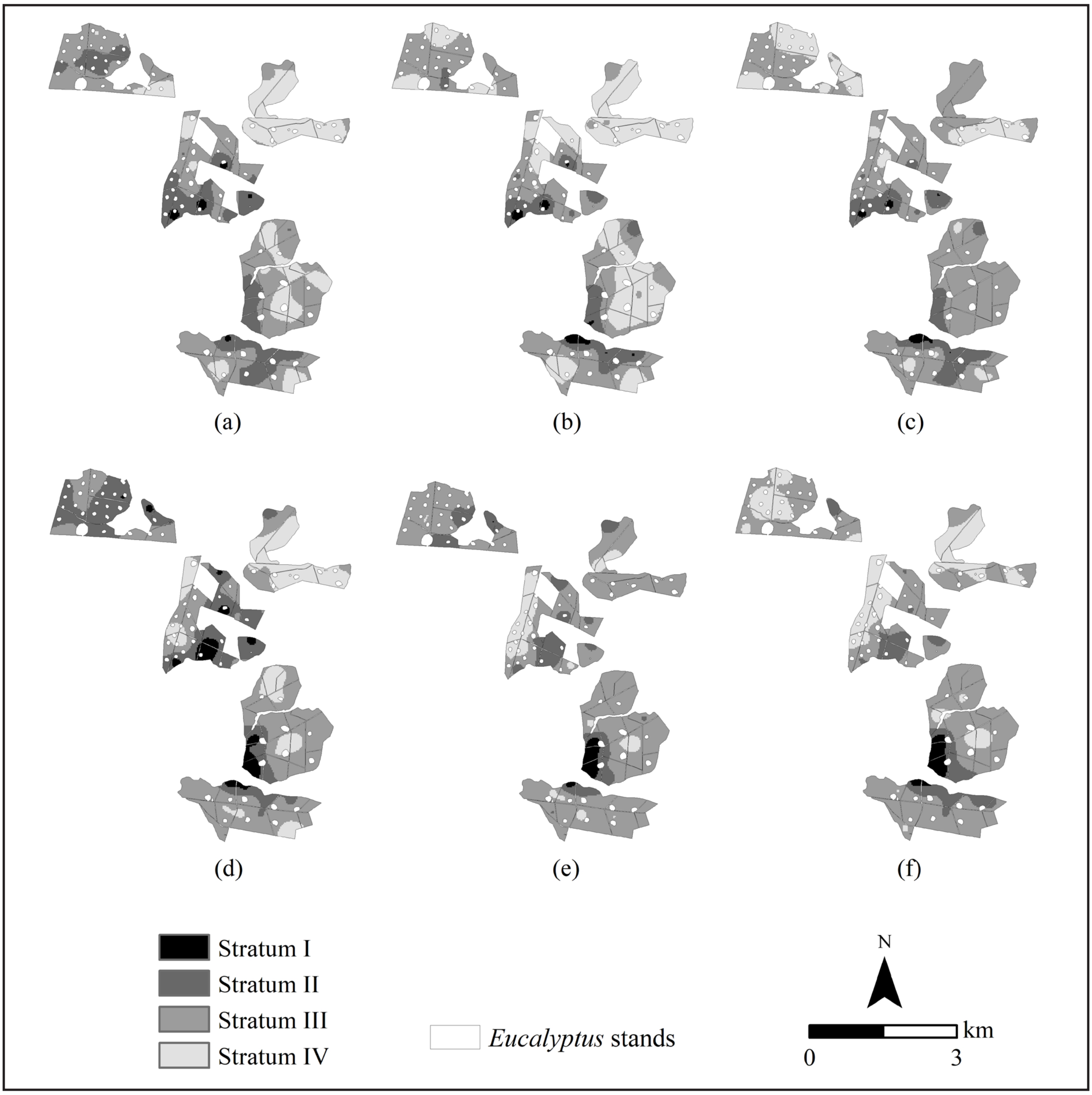
We found that regardless the variable, the highest correlation values between the areas of coincidence occurred at ages close to each other (Table 2). The correlation between the first and last measurement ages differed the most for all variables, indicating that the variables behaved differently on young and mature ages. Stratifications made with data aged 2.7 tended to have low correlation with the older strata. However, for the more stable variables, stratifying from the age 3.7 onwards tended to have better agreement with the older strata. In the young ages, competition for nutrients, water and light is not yet established and plants can grow similarly in the whole area. As the forest ages and plants start to compete, it is easier to identify the site quality differences and its spatial structure (RAIMUNDO *et al*., 2017).

The greatest strata coincident area for all variables occurred at similar ages (3 to 5 years after planting). Similarly, Raimundo *et al*. (2017), studying a eucalyptus plantation in Brazil found that stratification was reliable only after the age 3.1 years. Assis *et al*. (2009), also studying a eucalyptus plantation, found that plots shifted from one stratum to another more frequently at the first and second years, and after that tended to stabilize.

Figure 3 illustrates the spatial distribution of the different strata for the variables with the highest and lowest correlation between coincident areas (G and Hdom, respectively) for the youngest (2.7 years), middle (4.8 years) and oldest (6.8

years) measurement ages. The maps in Figure 3 corroborate with the previous findings in this study, mainly that the youngest and oldest stratifications present a greater disagreement than the middle and older stratifications, as well as confirming the greater stability of the variable G..

Figure 3 – Study area stratified based on dominant height (Hdom) for the ages 2.7 (a), 4.8 (b), and 6.8 (c); and basal area (G) for the ages 2.7 (d), 4.8 (e), and 6.8 (f)

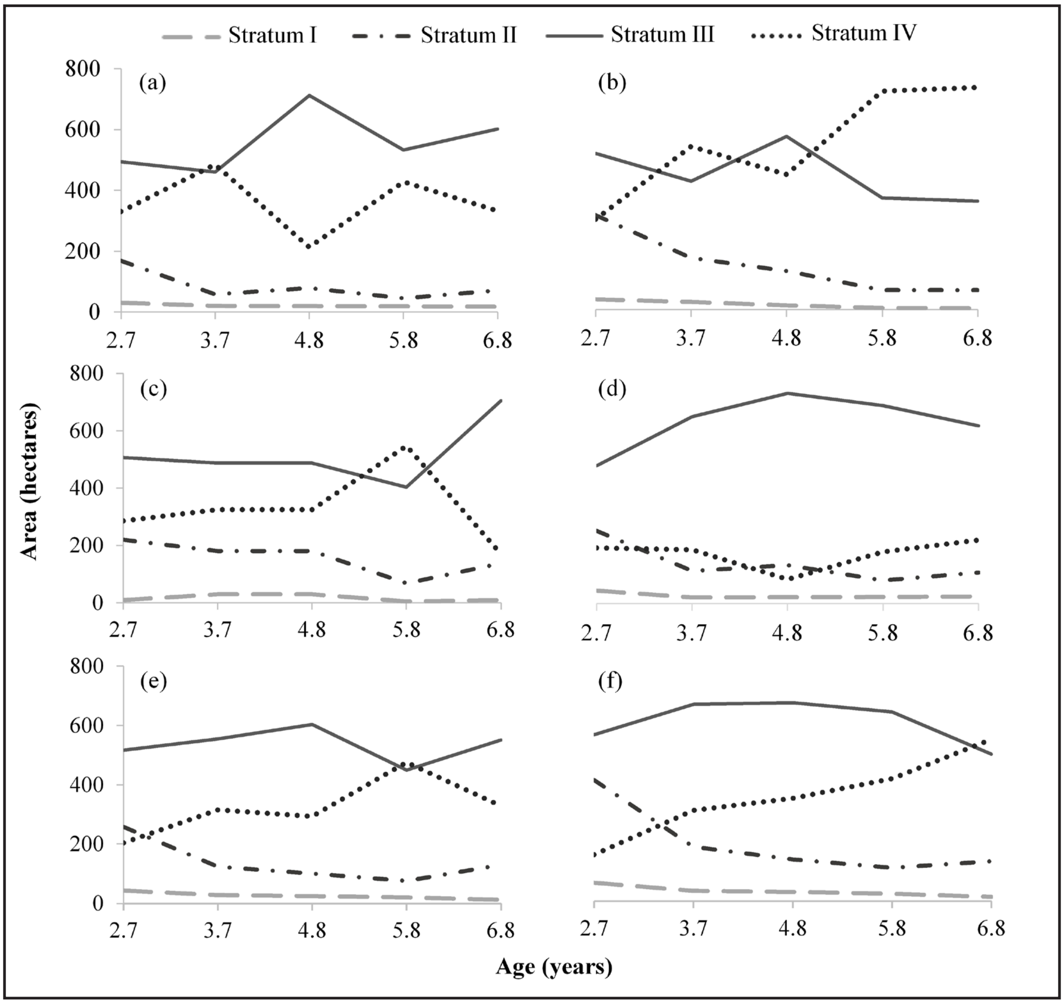


Source: Authors (2021)

3.4 Total strata area over time

Regarding the total strata area stability over the years, basal area yielded the most stable areas for all strata (Figure 4), except for stratum III. For this stratum, total area was the most stable when stratified by volume (Figure 4). In forest companies, the traditional stratification is based on the project records, and it is assumed that this stratification is stable over the production cycle. However, forests are dynamic systems, changing over time and space. For all variables, the most productive strata (III and IV), which were also the largest ones, changed the most over time in terms of area and location for all stratifying variables (Figure 4). The less productive strata (I and II) were the most stable over time, and also the smaller ones.

Figure 4 – Stability of total strata area over the years using the stratifying variables: arithmetic mean diameter (a), mean height (b), dominant height (c), basal area (d), mean annual increment (e), and volume (f).



Source: Authors (2021)

Table 2 – Linear correlation coefficient between the coincident areas at each measurement age for each variable used in this study. Shaded values indicate correlations between the same variable at different ages, all correlation values larger than 70% are shown in bold type

Variable		d					h					Hdom					G					MAI					V				
	Age	2.7	3.7	4.8	5.8	6.8	2.7	3.7	4.8	5.8	6.8	2.7	3.7	4.8	5.8	6.8	2.7	3.7	4.8	5.8	6.8	2.7	3.7	4.8	5.8	6.8	2.7	3.7	4.8	5.8	6.8
d	**2.7**	**100**																													
	3.7	63	**100**																												
	4.8	59	70	**100**																											
	5.8	55	**80**	**75**	**100**																										
	6.8	54	70	**78**	**83**	**100**																									
h	**2.7**	62	48	43	40	41	**100**																								
	3.7	58	58	41	50	49	64	**100**																							
	4.8	63	57	48	50	51	62	**75**	**100**																						
	5.8	50	60	39	56	53	43	70	66	**100**																					
	6.8	49	59	38	55	53	42	70	66	**89**	**100**																				
Hdom	**2.7**	63	49	42	42	43	**80**	69	66	50	50	**100**																			
	3.7	59	55	45	49	52	66	**75**	67	52	51	70	**100**																		
	4.8	60	57	44	50	50	60	**77**	**84**	66	66	67	**73**	**100**																	
	5.8	53	60	45	55	55	50	**74**	**71**	**84**	**82**	56	60	**74**	**100**																
	6.8	50	46	53	49	54	55	54	59	43	43	62	65	61	54	**100**															
G	**2.7**	**72**	44	49	42	46	60	46	49	35	35	59	55	48	40	50	**100**														
	3.7	69	64	**72**	59	61	53	44	54	37	35	56	55	51	44	57	68	**100**													
	4.8	58	51	**77**	56	63	44	33	45	26	25	46	45	41	35	57	62	**85**	**100**												
	5.8	61	62	**74**	62	65	51	44	54	38	35	54	53	51	44	58	62	**84**	**81**	**100**											
	6.8	54	60	**71**	63	70	52	48	55	43	42	53	56	52	47	57	58	**75**	**73**	**84**	**100**										
MAI	**2.7**	58	36	42	36	42	68	44	44	26	27	59	56	43	33	54	**81**	59	55	54	54	**100**									
	3.7	73	60	61	53	56	63	61	62	43	44	65	70	62	51	57	**73**	**79**	69	**74**	**72**	62	**100**								
	4.8	**71**	63	64	57	59	63	63	**74**	50	50	65	68	69	57	59	65	**76**	64	**71**	**71**	55	**81**	**100**							
	5.8	65	64	59	61	63	57	68	68	62	60	64	70	70	65	62	59	65	55	68	**71**	50	**77**	**77**	**100**						
	6.8	59	66	53	65	69	56	**74**	68	**72**	**73**	63	68	70	**72**	62	49	51	40	53	62	46	63	67	**78**	**100**					
V	**2.7**	70	43	47	39	43	**74**	57	54	36	37	70	65	56	43	57	**77**	64	57	59	55	**80**	**72**	65	62	53	**100**				
	3.7	64	66	62	59	61	57	67	62	50	51	63	**71**	66	58	60	62	**73**	63	**72**	**71**	54	**84**	**77**	**80**	68	66	**100**			
	4.8	67	65	66	60	63	59	65	**74**	52	52	62	68	**71**	59	62	61	**74**	63	**72**	**71**	54	**78**	**89**	**80**	68	65	**82**	**100**		
	5.8	56	66	54	66	68	50	68	63	**74**	70	57	64	67	**71**	57	50	55	44	58	64	42	64	66	**84**	**82**	52	**74**	**71**	**100**	
	6.8	57	60	61	62	**73**	57	65	62	59	59	61	68	62	63	70	54	59	52	63	**71**	55	66	67	**77**	**85**	61	**71**	**72**	**78**	**100**

Source: Authors (2021)

In where: arithmetic mean diameter = d; height = h; dominant height = Hdom; basal area = G; mean annual increment in volume = MAI; volume = V.

3.5 Plot permanency on each stratum over time

Similar to site index classification, for stratification, the ideal situation is when plots do not change from one stratum to another over time. This optimizes inventories operationally and helps forest management and planning. Regarding plot permanency on each stratum over the years, basal area again yielded the most stable stratification, presenting the lowest score (Table 3). Dominant height and mean height were the stratifying variables that presented the highest number of plots changing stratum over the years. This was expected, since stratification using basal area and height (mean and dominant) presented the greatest and smaller coincident strata area (spatial stability) over the measurement ages, respectively. Similar results were found by Schultz *et* al. (2006), who studied the operationally of a large-scale forest inventory stratified for basal area.

Table 3 – Plot permanency on each stratum over time and total score using the stratifying variables arithmetic mean diameter, mean height, dominant height, basal area, volume, and mean annual increment

	Number of plots by class of change					
Variable	**0x**	**1x**	**2x**	**3x**	**4x**	**Score**
d	51	31	15	18	1	119
h	38	38	28	12	0	130
Hdom	30	36	35	13	2	153
G	44	45	24	3	0	102
V	39	46	21	10	0	118
MAI	42	41	24	7	2	118

Source: Authors (2021)

In where: arithmetic mean diameter = d; height = h; dominant height = Hdom; basal area = G; volume = V; mean annual increment in volume = MAI.

3.6 Inventory error

Sampling error of the processed inventory varied from 0.8 to 2.2%, depending on the measurement age and on the stratifying variable (Table 4). Dominant height and mean height were the stratifying variables that yielded the highest errors, which corroborates the results presented previously. Mean annual increment and volume were the stratifying variables that yielded the smallest inventory errors, probably due to the fact that the inventory processing was made in function of volume, as is commonly done in production forestry.

Table 4 – Inventory error (%) using the stratified sampling estimators for the variable volume by age using the stratifying variables arithmetic mean diameter, mean height, dominant height, basal area, volume, and mean annual increment

Age (years)	d	h	Hdom	G	V	MAI
2.7	1.68	1.95	2.24	1.33	1.26	1.36
3.7	1.44	1.55	1.74	1.51	0.95	1.16
4.8	1.92	1.25	1.93	1.94	0.89	0.94
5.5	1.45	0.84	1.21	1.46	0.77	0.75
6.8	1.66	0.97	1.58	1.38	0.74	0.99
Mean	1.63	1.31	1.74	1.53	0.92	1.04
Standard deviation	0.20	0.45	0.39	0.24	0.21	0.23
CV (%)	12.06	34.42	22.16	15.87	22.38	22.15

Source: Authors (2021)

In where: arithmetic mean diameter = d; height = h; dominant height = Hdom; basal area = G; volume = V; mean annual increment in volume = MAI; coefficient of variation = CV.

For all stratifying variables, the sampling errors tented to be larger in younger ages than in older ages, when the forest presented less variation in its characteristics (Tables 1 and 4). The ability to process inventories with smaller errors for volume, especially at ages close to harvesting, is crucial for economic and logistic planning of forest companies. In this case, MAI and V were the stratifying variables yielding the smallest inventory errors, and h and Hdom yielded the highest. Similarly, Guedes *et a*l. (2012), studying volume stock in a eucalyptus plantation used volume as the stratifying variable for higher precision. Kanegae Júnior *et al*. (2006) stratified a eucalyptus plantation for volume, basal area, dominant height and site index, and found that stratifying the area for volume reduced the inventory error to up to 32% when compared to SRS. Alvarenga *et al*. (2012) stratified a Brazilian savannah area for volume and reduced the inventory error from 11.4 to 6.5%.

Nonetheless, we cannot affirm that volume is the stratifying variable that will result in lower inventory errors in all cases. The variation of dendrometric variables is affected by a number of factors and its interactions that affect tree growth, such as silvicultural treatments, management, and environment (topography, climate, and soil). For example, Oliveira *et al*. (2018), studying a eucalyptus forest, found that diameter was the best stratifying variable, reducing inventory error by 15%. Raimundo (2015) found that dominant height and basal area, in this order, were the best stratifying variables over the years in a eucalyptus plantation in southern Bahia state, enabling reduction of sampling intensity by 40%. Similarly, Zech *et al*. (2018) stratified a *Pinus taeda* plantation based on volume, basal area and dominant height. They found that basal area was the best stratifying variable, reducing the inventory error by 28.6%.

In the case of this study, though the inventory errors were lower using MAI and V to stratify the population, G was chosen as the best stratifying variable, since it generated small inventory errors and was stable over time in terms of coincident strata area, total strata area and permanency of plots in each stratum. Precise inventories with reduced inventory errors are important for forest planning, but also, the stability of strata is important for forest management and silviculture. G was the variable that contemplated all these issues.

Thus, we recommend the use of G as the stratifying variable considering forests similar to the ones studied here, even-aged monoculture plantations established with the same initial planting spacing. For planning scenarios with higher heterogeneity, such as stands with multiple initial spacings, thinning operations or mixed species plantations, basal area might not be the most stable variable, since it will change according to management practices. In these cases, the use of variables that are less affected by management practices, such as dominant height or site index (SKOVSGAARD; VANCLAY, 2008), might be a practical choice.

4 CONCLUSION

The stratifying variable that produced the most stable strata over the measurement years was basal area. The stratifying variables that produced the less stable stratification over the measurement years were dominant height and mean heightt. The stratifying variables that produced the lowest inventory errors were mean annual increment and volume. Basal area was identified as the best stratifying variable considering temporal stability of the generated strata.

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