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SAMPLING USING THE BITTERLICH METHOD IN *Pinus taeda* L. PLANTATIONS WITH DISTINCT MANAGEMENT SYSTEMS

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Resumo:
Amostragem utilizando o método de Bitterlich em plantios de Pinus taeda L. com regimes de manejo distintos. O método de Bitterlich foi estudado com múltiplos fatores de área basal (FAB) em 3 plantios de *Pinus taeda* L, com regimes de manejos diferenciados, sem desbaste (1344 árv.ha^{-1}), com um desbaste (789 árv.ha^{-1}) e com dois desbastes (475 árv.ha^{-1}), localizados em Santa Catarina, Brasil. Tendo como comparador os parâmetros advindos de censos das áreas, buscou-se verificar os dados de diferentes tratamentos amostrais para as variáveis volume por hectare (V.ha^{-1}), área basal por hectare (G.ha^{-1}), número de árvores por hectare (N.ha^{-1}) e diâmetro médio (d) por meio de um delineamento interiamente casualizado para cada regime de manejo e observando a precisão obtida pelo erro amostral e acurácia detectada pelo erro real. Observou-se que a variável "d" foi menos impactada pela mudança do FAB, porém as estimativas de V.ha^{-1}, G.ha^{-1} e N.ha^{-1} se apresentaram mais consistentes utilizando fatores iguais ou inferiores a 5, principalmente nas áreas desbastadas. Mesmo não apresentando diferenças significativas em nenhum FAB nos 3 experimentos, a amostragem realizada com fatores superiores a 5 apresentaram resultados contrastantes nas áreas manejadas dependendo do FAB utilizado. A precisão é influenciada pelos FAB's, diminuindo com a redução no número de árvores contadas dentro da unidade amostral de Bitterlich, consequência direta do aumento do FAB. Os erros amostrais foram sempre superestimados, independente da variável dendrométrica ou manejo da área. Mesmo as maiores diferenças entre estimativas e parâmetros sendo identificadas nos FAB's maiores ou iguais a 5, o experimento indicou o uso de qualquer FAB, sendo que os maiores necessitam de intesidade amostral superior.
Palavaras-chave: Inventário florestal, Relascopia, plantios florestais.

Abstract:
The Bitterlich method was studied with multiple basal area factors (BAF) in 3 *Pinus taeda* L. plantations located in the Midwest of Santa Catarina, Brazil using different management regimes: without thinning (1344 trees.ha^{-1}), with one thinning (789 trees.ha^{-1}), and with two thinnings (475 trees.ha^{-1}),. Using the parameters obtained from censuses, we sought to verify the data from different sample treatments for the variables V.ha^{-1}, G.ha-1, N.ha^{-1} and “d” through a completely randomized design for each management regime and observing the precision obtained by the sampling error and the accuracy detected by the real error. It was observed that the variable “d” was less impacted by the change in the basal area factor (BAF), but the estimates of V.ha^{-1}, G.ha^{-1} and N.ha^{-1} were more consistent (precision and accuracy) using factors equal to or less than 5, mainly in thinned areas. Even with no significant differences in any BAF in the 3 experiments, the sampling performed with BAF greater than 5 showed contrasting results in the managed areas depending on the BAF used. Sampling precision is influenced by BAFs, decreasing with the reduction in the number of trees counted within the Bitterlich sampling unit, a direct consequence of the BAF increase. Sampling errors were always overestimated, regardless of the dendrometric variable or area management. Even the largest differences between estimates and parameters being identified in BAF greater than or equal to 5, the experiment indicated the use of any BAF, with the largest requiring greater sampling intensity.
Keywords: Forest inventory, Relascopy, forest plantations

INTRODUCTION

Forestry products are essential for the well-being of society, commonly used in the form of assorted wood, reconstituted panels, charcoal, paper and cellulose, among other products. With the development of society, pressures on forests (native and planted) and their by-products have increased, requiring managers to develop the necessary management plans to guarantee the sustainable use of forest resources (FARIAS *et al.*, 2002; FIORENTIN *et al.*, 2015; MIRANDA *et al.*, 2022).

It is necessary to know the attributes of forests in order to carry out forest management plans, among other activities in its production chain (DRUSZCZ *et al*., 2015), as this information on a forest population, whether native or planted, is obtained through conducting a forest inventory. This activity is considered one of the first developed within the scope of forestry sciences, and arose from the need to quantify wood and products from native forests originally in European countries such as France and Germany (LAAR; AKÇA, 2010; SANQUETTA *et al.*, 2014; AVERY and BURKHART, 2015).

Authors such as Grosenbaugh (1958), Pellico Netto and Brena (1997), Sanquetta *et al*. (2014), Avery and Burkhart (2015), Farias *et al*. (2002) and Miranda *et al*. (2022) stated that there are two basic forms of forest inventories: through a census (or 100% inventory of the trees), but which is unfeasible in most cases due to the high costs and time involved in the field survey; or by sampling (from a part of the population that rarely exceeds 2% of the whole), which is a safer and cheaper way of estimating the parameters.

According to Pellico Netto and Brena (1997) and Sanquetta *et al*. (2014), sampling methods are in turn divided into two basic groups, defined by the size and shape of the sample units (SUs): those with fixed sizes (circular, rectangular or square formats), the oldest and most common form even today, in which the selection of individuals in the field is made proportionally to the sample space; and SUs of varying sizes (PRODAN, BITTERLICH, STRAND, among others), which were designed to gain efficiency and accuracy in sampling, as well as reduce the survey cost.

Relascopy, also known as the Bitterlich Method, Variable Radius Sampling, Point Sampling, Angle Count Sampling, or simply Bitterlich point, was originally devised to estimate the basal area per hectare, and is widely recognized as a breakthrough in forest measurement (LAAR and AKÇA, 2010).

In the Bitterlich method, individuals are selected proportionally to the size of the trees and their distance from the center of the sampling unit. The theory is based on performing a 360º turn around a predetermined point (center of the sampling unit), counting all the trees whose diameters at breast height (“d”) are equal to or greater than an equivalent angular opening to $\mathbf{2} \times \boldsymbol{sen}\frac{\boldsymbol{\alpha}}{\mathbf{2}}$ (PÉLLICO NETTO; BRENA, 1997), where the angle α is fixed, and the vertex is the center of the SU, which coincides with the point of view of the observer.

This critical angle of observation, which is also known as the basal area factor (BAF) according to Laar and Akça (2010), defines the ratio between the “d” of the tree and its distance to the center of the sampling unit, and will predict the $G.ha^{-1}$ parameter of a forest. Machado and Figueiredo Filho (2014) stated that the methodology was controversial among researchers at the time, as it directly provided an estimate of the basal area per hectare with a simple count of trees, without the need to measure them or establish a fixed area SU in the field. Grosenbaugh (1958) then introduced the methodology in North America in the 1950s, improving the Bitterlich sampling method to estimate other dendrometric variables: volume, number of trees, mean diameter, height, diametric distribution, in addition to estimating growth.

The first step after choosing the Bitterlich sampling method in a forest inventory is choosing the appropriate basal area factor (BAF), which will depend on the size and arrangement of trees within a compartment or forest stand (PÉLLICO NETTO; BRENA, 1997; AVERY; BURKHART, 2015). The chosen BAF will influence the number of individuals counted within the SU, and some authors, such as Pellico Netto and Brena (1997), Avery and Burkhart (2015), Machado and Figueiredo Filho (2014) and Sanquetta *et al*. (2014), have suggested that the safe number to establish a sampling unit by this method is between 20 and 30 trees. Scientific works involving Bitterlich samplings in *Pinus taeda* L. stands by Druszcz *et al.* (2015), Farias *et al.* (2019) and Miranda *et al.* (2022), and in *Tectona grandis* stands by Miranda *et al.* (2015) are based on this range of 20 or 30 trees per SU.

However, there is no consensus or pre-established rule for the number of trees within the counting point, and Bitterlich himself stated that it is possible to establish a SU from 10 trees (FIORENTIN *et al.*, 2016). Grosenbaugh (1958) stated that any BAF can be used as an independent tool capable of generating results, making no restriction on the number of trees within the sampling unit. Studies performed by Marshall *et al*. (2004) studying relascopy in US natural forests also suggest the use of larger BAFs, accounting for fewer trees per point (reduction in the amount of data), aiming at reducing the costs of forest inventories to the desired precision level.

The Bitterlich method is still very little used in forest inventories carried out in Brazilian native or planted populations, being more used in Japan, the United States and Europe. It is only valued in Brazil in academia, but according to Sanquetta *et al*. (2014), it is an alternative measurement technique that ensures accuracy and sampling efficiency and aims at reducing survey costs.

The methodology has proven to be effective, providing compatible information from a traditional forest inventory, and can be more efficient and accurate when performed by experienced teams and adequate equipment, as observed in the works by Druszcz *et al*. (2015) and Farias *et al*. (2019). Faced with doubts as to which BAF to use, mainly in places subjected to thinning, this study demonstrated the effects caused on the main dendrometric variables, and on the precision and accuracy of the sampling by varying the BAF within the SU in forest inventories carried out in 3 *Pinus taeda* L. plantations with different managements: with one thinning, two thinnings and without thinning.

MATERIAL AND METHODS

Experiment location

Three areas with *Pinus taeda* L. plantations with spacing of 2.5 x 2.5 meters and different managements were used, all located in the state of Santa Catarina (SC), belonging to the southern region of Brazil.

The first experiment (EXP1) is inserted in the municipality of Ponte Serrada (centroid X= 412,968 and Y= 7,022,108), is 12.3 years old, has an area of 5.72 hectares (ha) and smooth-undulating topography; it did not undergo any pruning or thinning intervention, being conducted for pulp production. The second experiment (EXP2) is located in the municipality of Irani (centroid X= 410,930 and Y= 7,007,357), is 12.9 years old, has an area of 2.92 ha and undulating topography, and was pruned and selectively thinned in the 10th year. The third and last area (EXP3) also located in Irani (centroid X= 414,416 and Y= 7,005,006) is 17.6 years old, has 4.16 ha with flat topography, was managed with pruning and thinning (systematic + selective) on two separate occasions in the 10th and 15th years. The EXP1 map was provided by the local pulp and paper company, and the areas of the other experiments were obtained using a digital topographic station, with a half-spacing buffer in addition to the edge trees.

The study sites are inserted in the region known as the Midwest of Santa Catarina where araucaria forests naturally occur (Mixed Ombrophylous Forest - MOF), with altitudes varying between 950 and 1,150 meters and predominance of Cambisol and Oxisol soils. The climate is humid subtropical (Cfb - according to the Köppen classification), with average temperatures of 17 degrees Celsius, and precipitation close to 2000 millimeters per year (ALVARES *et al.*, 2013).

Survey or field data collection

Census or 100% inventory

Tree censuses were carried out in the three experiments, thus enabling knowledge of the parametric values of the main dendrometric variables which were used as comparators: volume per hectare ($m^3.ha^{-1}$), basal area per hectare ($m^2.ha^{-1}$), number of trees per hectare ($N.ha^{-1}$) and average diameter – “d” (cm).

Next, 100% of the diameters at breast height (cm) were measured, and individual quality codes were identified (dead, broken, bifurcated, tortuous, dominated, etc.). Heights were estimated from the test of six hypsometric models developed with data from measurements of 797 trees in EXP1, 644 trees in EXP2 and 574 trees in EXP3, where the best performance equations for each study site were the following: EXP1 selected by the equation: $\boldsymbol{h = 10^{(1.381-2.532.d^{-1})}}$, whose adjusted coefficient of determination (R^2adj.) was calculated at 0.562 and the standard error of the estimate (Sxy%) equal to 6.3%; then in EXP2, the selected equation was: $\boldsymbol{h = 10^{(1.395-2.514.d^{-1})}}$, with R^2adj.=0.393 and Sxy%=5.5; and in EXP3 the equation used was: $\boldsymbol{h = 10^{(1.430-54.356.(d^2)^{-1}}}$, which had R^2adj.=0.349 and Sxy%=5.5.

Next, five volumetric models were tested in calculating the individual volume of the census and sampling trees for each experiment based on cubing data carried out by the Smalian method, following the diametric distribution of each census (106 trees were cubed in EXP1, 28 trees in EXP2, and 23 trees in EXP3). The best performing equations for each experiment were the following: in EXP1 the equation: $\boldsymbol{v = 10^{(-4.390+0.982.\log(d^2.h))}}$, obtained R^2adj.=0.987 and Sxy%=8.6; in EXP2 the equation: $\boldsymbol{v = 10^{(-4.894+1.755.\log d+1.639.\log h)}}$, obtained R^2adj.=0.965 and Sxy%=7.0; and in EXP3 the equation: $\boldsymbol{v = 10^{(-4.678+1.727.\log d+1.484.\log h)}}$, obtained R^2adj.=0.952 and Sxy%=7.5.

Bitterlich sampling

Then, a forest inventory of the areas was performed using the Bitterlich sampling method by a simple tree selection device with a basal area factor (BAF) equal to 1, with 12 sampling points being selected in each study area distributed randomly.

All trees included in the 360º rotations at the Bitterlich points had their diameters measured (d), as well as their respective distances (R_i) from the center of the SUs.

For the hypsometric adjustment of the samples, the heights of the 5 trees closest to the center of the SU were measured, resulting in the following equations for each experiment: In EXP1 the equation: $\boldsymbol{h = 10^{(1.313-20.969.(d^2)^{-1})}}$, R^2adj.=0.520 and Sxy%=1.3; in EXP2 the equation: $\boldsymbol{h = 6.121 + 9.773.\log d}$, R^2adj.=0.184 and Sxy%=1.0; and in EXP3 the equation: $\boldsymbol{h = 1.059 + 15.151.\log d}$, R^2adj.=0.318 and Sxy%=1.2.

Database

The data set containing the “d” and the distances of the trees (R_i) to the center of the SU enabled calculating the K value of each individual, being grouped under any BAF that one wants to use in the sampling (for example: K=1, K2, K3, ..., K10, ..., Kn).

The mathematical relationship presented by Machado and Figueiredo Filho (2014), developed by Walter Bitterlich, for calculating the constant K of trees is described by the following function:

$$K = 2500 \times \left(\frac{di}{Ri}\right)^2$$

In which: ***K*** is the basal area factor (BAF or band); ***di*** is the diameter of the tree "i" at breast height (1.30 m) in meters; and ***Ri*** is the distance from the tree to the center of the sampling unit (m).

The data were grouped by BAF following the logic that "K1" is the treatment composed of trees whose individual K values are equal to or greater than 1, "K2" is formed by grouping factors equal to or greater than 2, adding a unit to the BAF up to K20. Thus, forest inventories were processed with the following basal area factor compositions: K1, K2, K3, K4, K5, K6, K7, K8, K9, K10, K15 and K20.

Calculation of dendrometric variables

The estimates of the grouped variables of the Bitterlich sampling method were the same used by Druszcz *et al*. (2015) and Miranda *et al*. (2022), developed by Grosenbaugh (1958), and for average diameter by Nishizawa (1972), contained in Table 1.

Table 1. Formulation for obtaining dendrometric variables by the Bitterlich method.
Tabela 1. Formulação para obtenção das variáveis dendrométricas pelo método de Bitterlich.

Variables	Formulas	Variables	Formulas
Diameter (cm)	$d = \frac{\sum_1^n \left(\frac{di}{gi}\right)}{\sum_1^n \left(\frac{1}{gi}\right)}$	Number of trees ($N.ha^{-1}$)	$N.ha^{-1} = \sum(\frac{K}{g_i})$
Basal area ($m^2.ha^{-1}$)	$G.ha^{-1} = K.n$	Volume ($m^3.ha^{-1}$)	$V.ha^{-1} = \sum(\frac{K}{g_i}).v_i$

In which: "***d***" is the mean diameter at breast height at 1.30 meters from the ground (cm); ***K*** is basal area factor (m².ha); ***di*** is the diameter of tree "i"; ***gi*** is the cross-sectional area of tree "i" (m²); ***vi*** is the average individual volume (m³); ***n*** is the number of trees within the Bitterlich point; ***π*** is the constant PI.

Processing the inventory data

The processing of forest inventories of the Bitterlich treatments was done in the same way as a traditional inventory with fixed-sized SUs using the simple random sampling process for infinite populations (since infinite points can be distributed in areas using Relascopy). Statistics were calculated for the selected dendrometric variables: mean, variance, standard deviation, coefficient of variation (CV%), relative sampling error (Es%), and actual error (Ea%) for each one of them.

Effectiveness, or accuracy, or actual error, is the difference between the measurement or estimate of some variable and its actual value. In this work the Ea% was calculated by the following mathematical formula:

$$Ea\% = \frac{(Vest - Vobs)}{Vobs}.100$$

In which: ***Ea%*** is the actual error of the estimation (%); ***Vobs*** is the value observed in the census of the variables (volume, basal area, number of trees and average diameter); and ***Vest*** is the value estimated by treatments for the same dendrometric variables.

Experimental statistics

The work included three independent experimental designs with distribution of SUs made by lot, opting for the use of 3 Completely Randomized Designs (CRDs) with 12 repetitions each (SUs) plus the census (100% inventory), evaluating the variables $V.ha^{-1}$, $G.ha^{-1}$, $N.ha^{-1}$ and "d". When verifying significant differences using the F-test at 5%, the means were submitted to the Scott-Knott mean test. It is noteworthy that the statistical assumptions for the development of the experimental analysis (homogeneity of variances) were met for all analyzed variables.

RESULTS

Parameters

The results from the censuses of the 3 experiments were as follows: in EXP1 (unmanaged), 1,344 trees were estimated per hectare, the basal area was calculated at 52.7 $m^2.ha^{-1}$, the total volume of 432.6 $m^3.ha^{-1}$ and mean tree diameter of 21.9 cm; in EXP2 (one thinning), 789 trees per hectare were estimated, 35.8 $m^2.ha^{-1}$ of basal area, 347.4 $m^3.ha^{-1}$ of total volume and "d" of 23.8 cm; in EXP3 (two thinnings), the estimates were 475 $trees.ha^{-1}$, 35.2 $m^2.ha^{-1}$ of basal area, 399.5 $m^3.ha^{-1}$ of volume and "d" of 30.4 cm.

Estimates of dendrometric variables

The main statistics obtained by the treatments in EXP1 (without thinning) are presented in Table 2. Precision is represented by the sampling error (Es%) and the coefficient of variation (CV%), for which it was identified that the greater the BAF, the more imprecise the sampling becomes. Treatment K1 was the most accurate in all variables studied, and K20 had the highest Es% and CV%, being the least accurate. Moreover, "d" was the variable least affected by the change in factors, and $N.ha^{-1}$ was the variable most affected by the changes in BAF, both in terms of precision and accuracy. However, the sampling errors (Es%) were all overestimated, and no significant differences were detected between the BAFs for any dendrometric variable in the area without forest management.

Table 2. Estimates obtained from Bitterlich sampling in EXP1.
Tabela 2. Estimativas obtidas pelos tratamentos de Bitterlich no EXP1.

Var.	Stat.	Treatments tested in the Bitterlich sampling											
		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**K15**	**K20**
$V.ha^{-1}$	Mean	427.0a	444.1a	423.3a	416.0a	442.3a	460.0a	455.4a	432.4a	430.6a	450.8a	441.4a	465.4a
	Es%	±4.8	±7.7	±10.0	±8.5	±8.9	±10.1	±11.5	±14.3	±14.3	±13.9	±21.9	±22.9
	CV%	7.6	12.1	15.7	13.4	14.0	15.9	18.1	22.5	22.6	22.0	34.5	36.0
	Ea%	-1.3	2.7	-2.2	-3.8	2.2	6.3	5.3	-0.1	-0.5	4.2	2.0	7.6
$G.ha^{-1}$	Mean	51.8a	54.0a	51.5a	50.7a	53.8a	56.0a	55.4a	52.7a	52.5a	55.0a	53.8a	56.7a
	Es%	±4.7	±7.8	±9.8	±8.4	±8.8	±10.2	±11.6	±14.5	±14.6	±14.4	±22.0	±23.1
	CV%	7.4	12.2	15.5	13.2	13.8	16.0	18.2	22.9	22.9	23.5	34.6	36.3
	Ea%	-1.6	2.5	-2.3	-3.8	2.0	6.3	5.2	0.0	-0.4	4.4	2.0	7.5
$N.ha^{-1}$	Mean	1305a	1391a	1337a	1336a	1376a	1466a	1444a	1388a	1401a	1476a	1406a	1480a
	Es%	±8.2	±12.2	±13.4	±13.3	±10.8	±13.6	±14.9	±19.0	±19.3	±20.9	±24.4	±29.0
	CV%	12.9	19.2	21.2	20.9	17.1	21.4	23.5	29.9	30.4	32.9	38.3	45.6
	Ea%	-2.8	3.5	-0.5	-0.6	2.4	9.1	7.4	3.3	4.3	9.9	4.7	10.2
d	Mean	22.2a	22.0a	21.9a	21.8a	22.0a	21.8a	21.9a	21.8a	21.7a	21.7a	21.9a	22.2a
	Es%	±3.8	±4.7	±5.4	±5.8	±4.5	±4.2	±4.4	±4.3	±4.5	±4.9	±6.1	±8.3
	CV%	5.9	7.3	8.5	9.1	7.0	6.6	6.9	6.7	6.6	7.7	9.6	13.0
	Ea%	1.5	0.6	0.1	-0.5	0.7	-0.2	0.1	-0.2	-0.9	-0.8	0.2	1.3

In which: Var. = Variable; Stat. = Statistics. $\boldsymbol{V.ha^{-1}}$ is the variable volume in m³ per hectare; $\boldsymbol{G.ha^{-1}}$ is the basal area in m² per hectare; $\boldsymbol{N.ha^{-1}}$ is the number of trees per hectare; ***d*** is the average diameter in centimetres; ***Es%*** is the sampling error in percent; ***CV%*** is the coefficient of variation in percentage; ***Ea%*** is the actual percentage error; "a" is the SCOTT-KNOTT test reference letter for estimated means within each variable.

Figure 1 shows the estimates of the variables obtained by the treatments in EXP1, the comparisons with the parameters and their respective confidence intervals (95%).

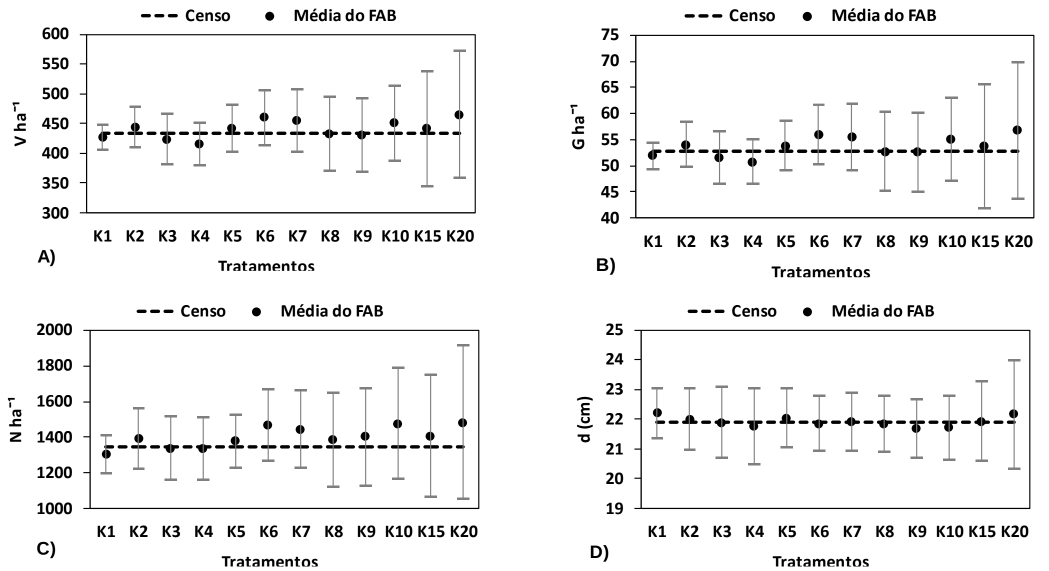

Figure 1. Dendrometric variables, means and confidence interval of the treatments tested in EXP1.
Figura 1. Variáveis dendrométricas, médias e intervalo de confiança dos tratamentos testados no EXP1.

Estimates in EXP2 (with selective thinning) are shown in Table 3, making it possible to identify an increase in sampling errors (Es%) and coefficients of variation (CV%) when compared to the unmanaged area. It is also notable that the accuracy is higher in obtaining the average diameter, and the accuracy for the pooled dendrometric variables (V.ha^{-1}, G.ha^{-1} and N.ha^{-1}) are similar. Sampling errors (Es%) were also overestimated, decreasing precision with increasing BAF in all dendrometric variables. No significant differences were detected between BAFs for any dendrometric variable in EXP2.

Table 3. Estimates obtained from Bitterlich sampling in EXP2.
Tabela 3. Estimativas obtidas pelos tratamentos de Bitterlich no EXP2.

Var.	Stat.	Treatments tested in the Bitterlich sampling											
		K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**	**K10**	**K15**	**K20**
V.ha^{-1}	Mean	344.2a	346.5a	355.2a	342.8a	338.7a	328.2a	303.4a	300.6a	294.4a	330.0a	360.9a	321.5a
	Es%	±7.8	±8.0	±10.1	±13.8	±14.2	±13.2	±18.9	±18.5	±26.1	±24.1	±18.5	±27.6
	CV%	12.3	12.7	16.0	21.7	22.4	20.8	29.7	29.1	41.0	35.8	27.6	41.1
	Ea%	-0.9	-0.3	2.2	-1.3	-2.5	-5.5	-12.7	-13.5	-15.3	-5.0	3.9	-7.4
G.ha^{-1}	Mean	35.1a	35.3a	36.3a	35.0a	34.6a	33.5a	30.9a	30.7a	30.0a	30.8a	33.8a	30.0a
	Es%	±7.7	±8.0	±10.1	±13.9	±14.4	±13.3	±18.9	±18.5	±26.1	±32.8	±28.8	±35.7
	CV%	12.2	12.6	16.0	21.9	22.6	20.9	29.7	29.1	41.1	51.2	42.9	53.2
	Ea%	-2.1	-1.4	1.1	-2.4	-3.5	-6.5	-13.8	-14.4	-16.3	-14.0	-5.8	-16.3
N.ha^{-1}	Mean	772a	778a	810a	789a	781a	750a	673a	681a	653a	672a	747a	635a
	Es%	±7.5	±8.1	±10.6	±16.3	±18.2	±14.9	±19.3	±19.5	±28.1	±34.0	±34.3	±39.4
	CV%	11.8	12.7	16.7	25.6	28.7	23.4	30.4	30.7	44.2	50.6	51.1	58.7
	Ea%	-2.2	-1.3	2.7	0.0	-1.0	-4.9	-14.7	-13.7	-17.2	-14.8	-5.3	-19.5
d	Mean	23.8a	23.9a	23.7a	23.7a	23.8a	23.8a	24.1a	23.9a	24.4a	24.3a	24.5a	24.8a
	Es%	±1.8	±1.4	±1.5	±1.8	±3.0	±2.8	±3.3	±3.0	±4.0	±4.1	±5.9	±5.6
	CV%	2.8	2.2	2.4	2.8	4.8	4.5	5.2	4.8	4.3	6.1	8.8	8.4
	Ea%	0.3	0.5	-0.1	-0.2	0.1	0.1	1.6	0.7	2.8	2.3	3.1	4.2

In which: Var. = Variable; Stat. = Statistics. ***V.ha^{-1}*** is the variable volume in m³ per hectare; ***G.ha^{-1}*** is the basal area in m² per hectare; ***N.ha^{-1}*** is the number of trees per hectare; ***d*** is the average diameter in centimetres; ***Es%*** is the sampling error in percent; ***CV%*** is the coefficient of variation in percentage; ***Ea%*** is the actual percentage error; "a" is the SCOTT-KNOTT test reference letter for estimated means within each variable.

Figure 2 shows the estimates obtained by the treatments tested in EXP2, the comparison with the parameters and the confidence intervals of the means.

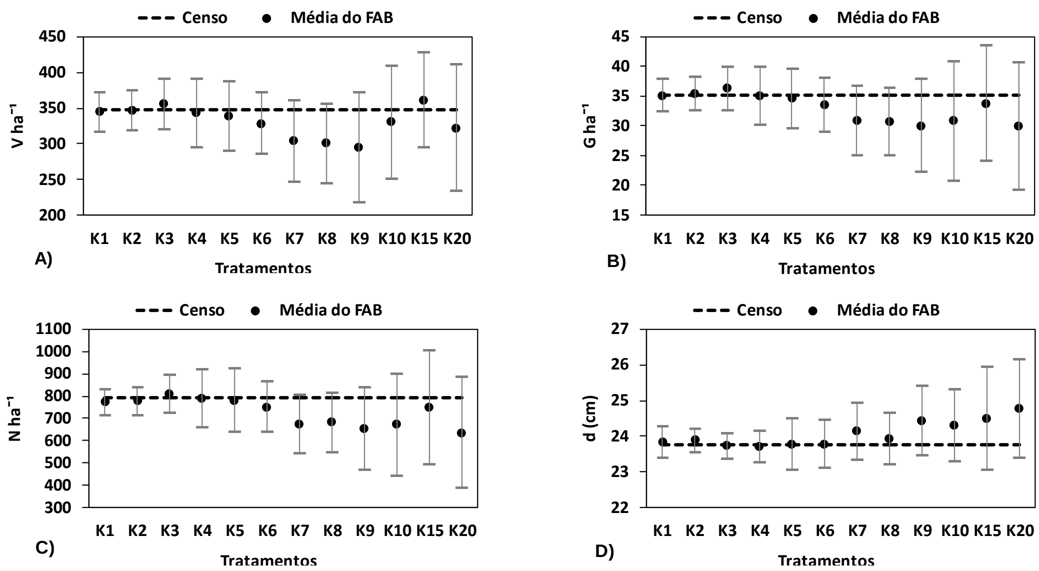

Figure 2. Dendrometric variables, means and confidence interval of the treatments tested in EXP2.
Figura 2. Variáveis dendrométricas, médias e intervalo de confiança dos tratamentos testados no EXP2.

The estimates obtained by the treatments in EXP3 (two thinnings) are shown in Table 4, noting that the smallest sampling errors (Es%) and coefficients of variation (CV%) were estimated for the variable "d" (as well as estimated in the two other experimental areas), and as in the other managed experiment, the precision of the variables per hectare ($V.ha^{-1}$, $G.ha^{-1}$ and $N.ha^{-1}$) are similar. Sampling errors (Es%) were also overestimated, regardless of the dendrometric variable, and tended to increase with the increase in BAF for variables per hectare. No significant differences were detected between BAFs for any dendrometric variable in EXP3. The accuracy of treatment estimates was generally higher in EXP3 due to the homogenization of tree diameters and distribution caused by the thinning interventions.

Table 4. Estimates obtained by Bitterlich sampling in EXP3.
Tabela 4. Estimativas obtidas pelos tratamentos de Bitterlich no EXP3.

Var.	Stat.	Treatments tested in the Bitterlich sampling											
		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K15	K20
$V.ha^{-1}$	Mean	398.1a	415.9a	391.5a	400.5a	391.1a	378.4a	381.3a	374.6a	387.0a	391.2a	400.1a	399.2a
	Es%	±5.5	±12.3	±10.6	±14.6	±16.2	±20.4	±22.5	±24.8	±25.5	±28.4	±29.5	±27.5
	CV%	8.6	19.3	16.6	23.0	25.5	32.1	35.5	39.0	40.1	44.6	46.4	43.3
	Ea%	1.3	5.8	-0.4	1.9	-0.4	-3.7	-3.0	-4.7	-1.5	-0.4	1.8	1.6
$G.ha^{-1}$	Mean	34.8a	36.3a	34.3a	35.0a	34.2a	33.0a	33.3a	32.7a	33.8a	34.2a	35.0a	35.0a
	Es%	±5.4	±12.2	±10.5	±14.2	±15.8	±20.0	±22.2	±24.3	±25.2	±28.0	±29.2	±27.4
	CV%	8.5	19.2	16.5	22.4	24.8	31.5	34.9	38.3	39.6	44.1	46.0	43.1
	Ea%	0.3	4.9	-1.1	1.0	-1.4	-4.8	-4.0	-5.7	-2.6	-1.4	1.0	1.0
$N.ha^{-1}$	Mean	466a	492a	472a	475a	461a	436a	438a	432a	446a	460a	480a	494a
	Es%	±7.9	±13.8	±13.5	±13.1	±12.7	±17.1	±19.6	±19.9	±23.0	±25.0	±28.6	±27.6
	CV%	12.4	21.8	21.3	20.6	20.0	26.8	30.8	31.3	36.2	39.3	45.0	43.4
	Ea%	-1.9	3.5	-0.6	-0.1	-2.9	-8.2	-7.8	-9.2	-6.2	-3.3	1.0	4.0
d	Mean	30.7a	30.6a	30.4a	30.5a	30.5a	30.9a	30.9a	30.7a	30.9a	30.6a	30.5a	30.2a
	Es%	±3.3	±3.8	±4.2	±4.3	±4.1	±5.1	±5.6	±5.8	±5.4	±5.5	±4.4	±4.7
	CV%	5.2	6.0	6.6	6.8	6.4	8.0	8.8	9.2	8.0	8.7	7.0	7.4
	Ea%	0.8	0.5	-0.2	0.3	0.3	1.5	1.6	0.8	1.6	0.7	0.2	-0.8

In which: Var. = Variable; Stat. = Statistics. ***$V.ha^{-1}$*** is the variable volume in m³ per hectare; ***$G.ha^{-1}$*** is the basal area in m² per hectare; ***$N.ha^{-1}$*** is the number of trees per hectare; ***d*** is the average diameter in centimetres; ***Es%*** is the sampling error in percent; ***CV%*** is the coefficient of variation in percentage; ***Ea%*** is the actual percentage error; "a" is the SCOTT-KNOTT test reference letter for estimated means within each variable.

Figure 3 shows the estimates obtained by the treatments tested in EXP3, the comparison with the parameters and the confidence intervals of the means. As in the other thinned area, treatments with BAF equal to or less than 5 were the most accurate and consistent for estimating the variables per hectare.

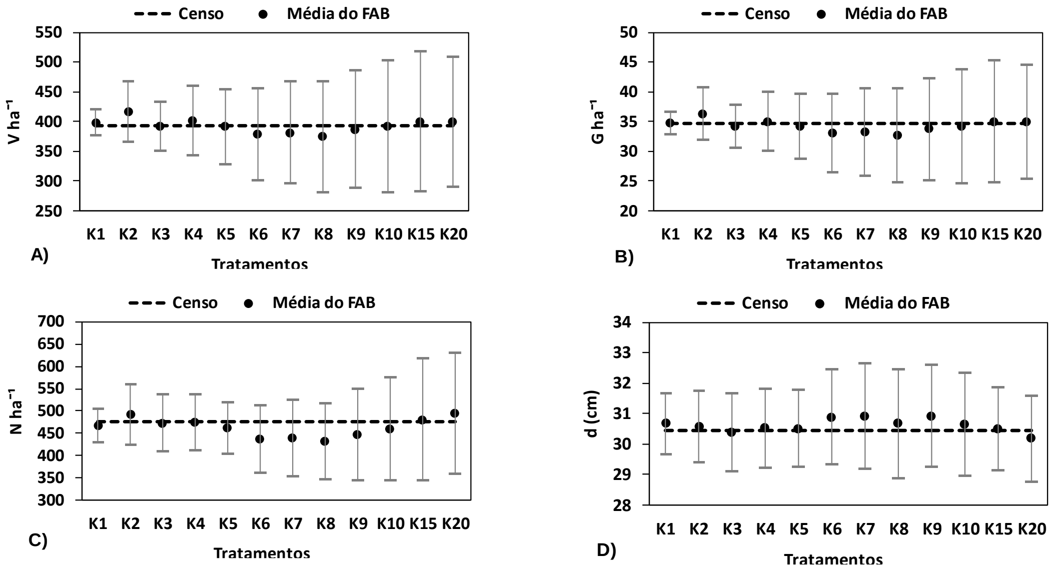

Figure 3. Dendrometric variables, means and confidence interval of the treatments tested in EXP3.
Figura 3. Variáveis dendrométricas, médias e intervalo de confiança dos tratamentos testados no EXP3.

Sample space and precision of treatments

Figure 4 shows in EXP1 (unmanaged area) that CV% stabilization (for the variable volume per hectare) occurs when between 10 and 15 trees are counted (on average) per Bitterlich point, corresponding to treatments K5 and K4, respectively. Treatments whose BAF’s are equal to or greater than 6 did not reach sampling sufficiency, and estimated sampling errors (Es%) greater than the maximum error stipulated in this study (±10% or CV% greater than 15%) and included less than 10 trees on average within the sampling unit. CV% stabilization in EXP2 (area with thinning) also occurred between 10 and 15 trees per Bitterlich point using the K3 treatment. The first three BAF’s reached sample sufficiency (Es% close to ±10%) in EXP3 where treatments included more than 10 individuals on average in the SU.

Still regarding the sample size in surveys with the Bitterlich method, regardless of the BAF used, or the planting management, it was possible to perform precise sampling with a little more than 100 trees in 12 sample units, which corresponds to an average of 8.3 trees per sample unit.

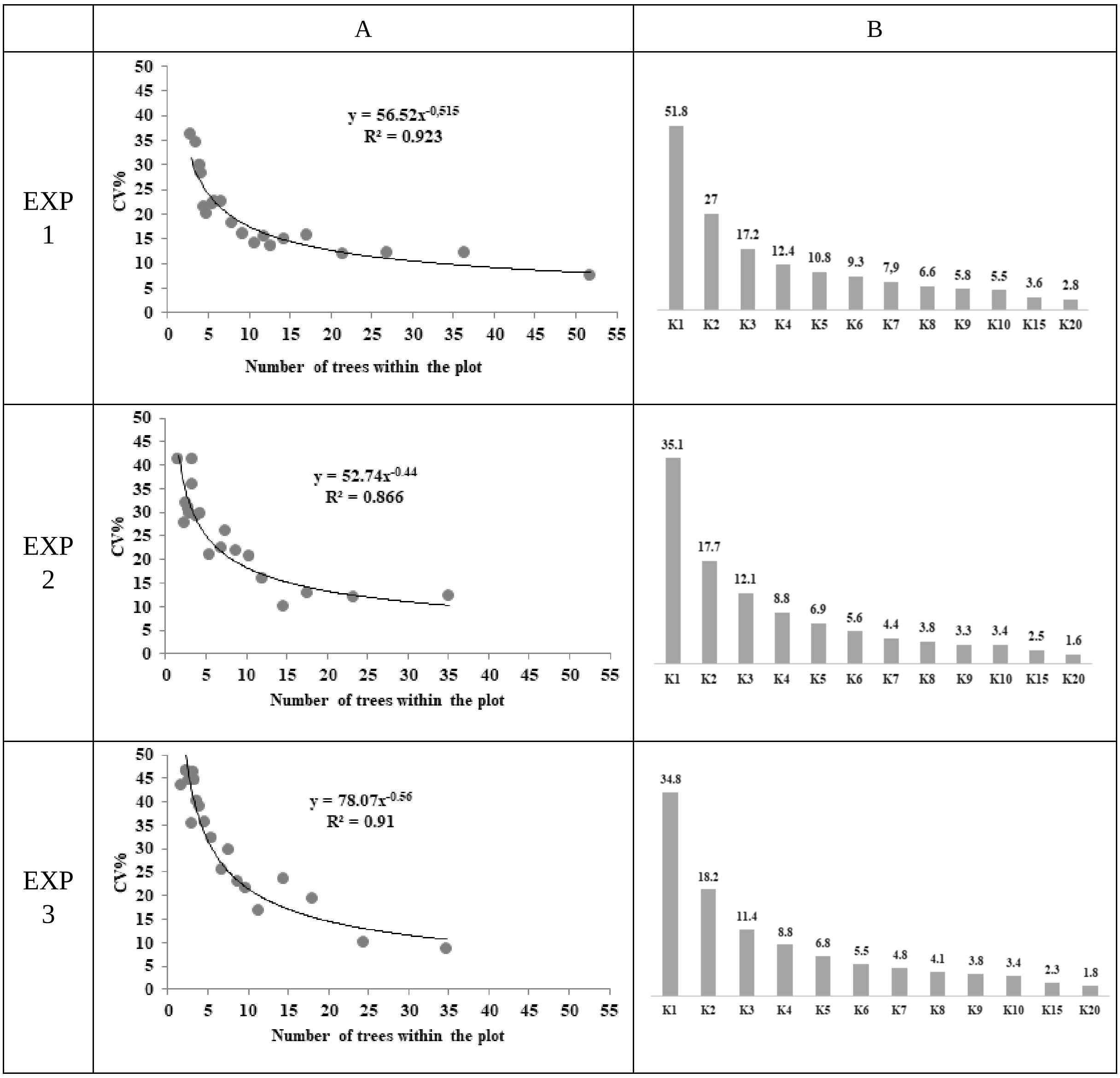

Figure 4. Maximum curvature point (A) and the number of trees counted (B) in the treatments tested in the three experiments.

Figura 4. Ponto de máxima curvatura (A) e a quantidade de árvores contadas (B) nos tratamentos testados nos tres experimentos.

DISCUSSION

The Bitterlich method itself is very little used in Brazil due to lack of knowledge of its potential in terms of accuracy and efficiency in the survey (SANQUETTA *et al*., 2014). Studies involving tests with more than one basal area factor are quite rare. For example, it is customary to use "appropriate" BAFs equal to 1 or 2 in Brazil, standardizing the count between 20 and 30 trees per point, being identified in studies involving different sampling methods in forest inventories carried out in forest plantations such as by Druszcz *et al*. (2015) in *Pinus taeda* plantations with and without thinning, Miranda *et al*. (2015) in commercial areas with *Tectona grandis*, Farias *et al*. (2019) in a *Pinus* sp. stand with low tree density, and Miranda *et al*. (2022) in thinned *Pinus taeda* plantations similar to the EXP3 of this study.

Even in native forests, Bitterlich point sampling is planned to include 20 or 30 trees per AU, supported by the literature. (PÉLLICO NETTO and BRENA, 1997; MACHADO and FIGUEIREDO FILHO, 2014; SANQUETTA *et al.,* 2014; among others). However, according to Fiorentin *et al*. (2016), Bitterlich himself suggested using up to 10 trees per scan. Grosenbaugh (1958) makes no restrictions on the number of trees within the SUs, stating that each BAF can be used as a sample independently, leaving the manager with the strategic decision to equalize the survey cost to the desired precision level.

In this study, the sampling proposed by Bitterlich demonstrated great ability to estimate the variables grouped by area unit $V.ha^{-1}$, $G.ha^{-1}$, $N.ha^{-1}$ and "d", regardless of area management, not showing significant differences between the treatments tested, including using "bigger" BAFs which compute a number of less than 10 trees on average per point.

In the sampling studies carried out by Santos *et al*. (2016) in *Eucalyptus grandis* plantations in Espírito Santo, no statistically significant differences were identified in the estimates of the $V.ha^{-1}$ and $G.ha^{-1}$ variables obtained by different BAFs (K equal 1, 2 and 4), and the fixed area method (rectangular with an area of $600m^2$). The same type of study involving an Atlantic Forest fragment in Lavras, Minas Gerais carried out by Farias *et al*. (2002) also showed no significant differences between estimates obtained by Relascopy (BAFs equal to 1, 2 and 3) and the rectangular fixed area method for the same dendrometric variables in this study.

Moreover, Fiorentin *et al.* (2016) applied Bitterlich sampling with 9 different factors (1/16, 1/4, 9/16, 1, 25/16, 9/4, 49/16 and 4) in an Araucaria forest located in Curitiba, PR, and identified no significant difference between treatments only for the mean diameter variable (d); however, the study showed statistical differences between BAFs for the other variables. These authors stated that the results were more consistent using BAFs equal to or less than 1 for the sampled population.

In terms of statistical precision considering 12 repetitions (sampling points), the estimates obtained with BAF between 1 and 5 reached the sampling sufficiency in the unmanaged area (EXP1) and in the area with one thinning (EXP2), with the most adequate factors being between 1 and 3. Only the BAF equal to 1 did not exceed the maximum error limit stipulated in ±10% in EXP3.

In working with natural *Pinus* sp. forests in California and Oregon (both in the USA), Marshall *et al.* (2004) proved that the combination of a small BAF for determining the basal area ($m^2.ha^{-1}$) and a larger factor for determining the volume ($m^3.ha^{-1}$) greatly reduces the inventory cost without affecting accuracy and consistency using the Bitterlich method. This study also showed that it is possible to work in this way; taking EXP3 as an example, with two thinnings and with greater homogenization of "d" and more random distribution of trees, in which almost all tested factors were accurate for volume and basal area, with actual errors (Ea%) equal to or less than ±5%. Combined sampling could be performed using K1, K3 or K4 to perform the angular count and estimate the basal area per hectare, and a second scan with K9, K10 or K15 to estimate the volume and number of trees, thus drastically reducing the number of trees to be measured.

It was observed herein that the simultaneous evaluation of the estimates arising from sampling using different BAFs enables us to have a much broader and safer view of Relascopy, both in the analysis of each variable, as well as for the precision behavior and when the accuracy parameters are available regarding BAF alterations.

CONCLUSIONS

The results of this research demonstrate that:

- The Bitterlich method proved to be able to provide consistent results for the dendrometric variables $V.ha^{-1}$, $G.ha^{-1}$, $N.ha^{-1}$ and "d" for several basal area factors, regardless of area management, not showing significant differences between BAFs in the 3 experimental areas.
- The sampling errors estimated by the treatments were all overestimated, regardless of the dendrometric variable and the area management, with the sampling precision tending to decrease with the increase of the BAF used in the tree count.

- It was observed from the various BAFs tested that smaller BAFs could be used for evaluating $G.ha^{-1}$ in a single sampling unit, and larger ones to evaluate $V.ha^{-1}$, resulting in fewer measured trees, superior accuracy and lower survey cost.
- BAFs equal to or less than 5 were generally the most precise, accurate and adequate to sample the three plantations. The BAFs above 5 obtained contrasting results, sometimes accurate and sometimes not, and proved to be inaccurate.
- The study enabled analyzing several independent samplings, changing the basal area factor in a single field survey from the measurement of all "d" and distances of the trees to the center of the sampling unit.

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