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ORIGINAL ARTICLE – Forest Management

Estimate of Dendrometric Variables by Fixed Area and Bitterlich Methods for Thinned *Pinus Taeda* Stands

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Abstract

This study aimed to assess the precision, accuracy, and compatibility of dendrometric estimates both individually and per hectare using the fixed area and Bitterlich methods. This study was performed in a *Pinus taeda* stand in Pinhão, Paraná, Brazil. A census was carried out in the area (8 ha) in addition to the fixed area and Bitterlich methods with basal area factors 1, 2 and 4 (B1, B2, and B4, respectively). The individual variables (diameter at breast height, total height, basal area and volume) did not differ significantly among the sampling methods. For the variables per hectare (number of trees and basal area), minor sampling errors were found for the fixed area method and B2 and B4 showed similar values to the parametric means. For total volume and by wood assortment, B2 and B4 were close to the real value (Census), however, they showed higher sampling errors comparatively to the others.

Keywords: Sampling, circular sampling units, variable area method, census.

1. INTRODUCTION AND OBJECTIVES

Forest planning and management require quality data in all aspects, which are usually obtained through forest inventory (Rice *et al.*, 2014). Forest inventory consists of the systematic collection of qualitative and quantitative information of forest species in a given area and space in time (Comas and Mateu, 2019) and should also assess the characteristics of trees and land where the stand is located (Retslaff *et al.*, 2014).

One of the main variables assessed in a forest inventory is volume, total or by assortment, depending on the purpose use of the wood. When wood is traded to different consumer markets, it is necessary to know the wood assortment and volume in its different classes.

Forest inventories can be performed in different ways, such as a forest census or a given sampling method. There are two different sampling methods, the fixed area and the variable area method, each with their advantages and disadvantages. In Europe, most inventories are carried out using the fixed area method, followed by the Bitterlich method (Gschwantner *et al.*, 2016). In Brazil, the fixed area method is prevalent for most forest inventories.

Fixed area is the most known and traditional sampling method for forest inventories (Osman and Idris, 2012; Santos *et al.*, 2013). Péllico Netto and Brena (1997) described it as a method where the area of the sampling unit is known, and tree selection is made proportionally to the frequency of trees in the sampling unit.

A disadvantage of this method is the need to sample a higher number of trees per sampling unit in comparison to other sampling methods, what results in cost increase and low efficacy when information is needed quickly (Sanquetta *et al.*, 2014). Even with the broad use of fixed area, there are other sampling methods that can be used essentially when one is aiming for quickness and efficiency. Among them, the Bitterlich method is worth mentioning (Sanquetta *et al.*, 2014; Berger *et al.*, 2020).

One of the main advantages of the Bitterlich method is its flexibility in the choice of basal area factor (BAF) according to characteristics of forest typology (Fiorentin *et al.*, 2016), which establishes the angle to be projected, thus interfering with trees that will or will not be included in the sampling unit. Other advantages refer to the shortest time spent when the sole aim is to know the basal area, and the decrease in errors of demarcation in sampling units.

Although intensely used in the United States and Europe, the Bitterlich method has virtually not been used in forest inventories in Brazil neither in surveys of native forests nor forest plantings. Despite the existence of studies involving the use of this method (Couto *et al.*,1990; Druszcz *et al.*, 2010; Druszcz *et al.*, 2015; Miranda *et al.*, 2015; Santos *et al.*, 2016), few are compared with values obtained in the census (Retslaff *et al.*, 2014; Fiorentin *et al.*; 2016; Sydow *et al.*, 2017).

Two hypotheses were assessed in this work. The first is that the Bitterlich method can provide accurate estimates of forest plantings, compatible with or even higher than those obtained with the fixed area method, especially when considering assortment classes. The second hypothesis is to test the influence of the Basal Area Factor (BAF) used on the estimates obtained by the Bitterlich method. Thus, this study aimed to assess precision, accuracy and compatibility of estimates of individual parameters and parameters per area unit in a *Pinus taeda* L. stand, obtained with fixed area and Bitterlich methods, comparatively to the forest census performed.

2. MATERIALS AND METHODS

This study was performed in a *Pinus taeda* L. stand, located in the municipality of Pinhão, in the south-central region of Paraná state, Brazil. According to the Köppen-Geiger classification, the climate is Cfb (humid temperate), being defined as humid subtropical with dry summers, frequent frosts, and no dry season, with mean annual temperature 17.2 ºC and mean annual rainfall 1.999 mm (Climate-Data, 2023).

During the sampling period, the stand was 11 years old, planted with 2.5 x 2.5m spacing, with a mixed thinning performed at 10 years old. Four areas were delimited for data collection, each with 1.16; 2.36; 0.48 and 4.00 ha, totalling 8.00 ha.

A forest census was performed in the four areas, diameter at breast height (*d*, measured at 1.30 m above ground) was measured with a caliper, with two measurements perpendicular to each other. For the estimate of total height, equation 1 was used with adjusted coefficient of determination (R^2_{aj}) 0.3329 and standard error of estimate (S_{yx}) 4.3%.

$$h = e^{(2.1883 + 0.2284\ \ln(d))} \quad [1]$$

Where: h = total height (m); e = natural exponential; Ln = naperian logarithm; d = diameter at 1.3 m above ground (cm).

This equation was adjusted with the database obtained from the measurement of the sampling units from the sampling methods, where the height of the 15 first trees plus five dominant trees was measured in each sampling unit using the fixed area method. When analyzing Pinus stands planted in Brazil for around 15 years and already thinned or with low site quality, it is common to observe a low R^2 value, considering that growth in height tends to stabilize due to these factors (Barros *et al.*, 2002; Figueiredo Filho *et al.*, 2010; Kohler *et al.*, 2017). Although the studied stand is a little younger (11 years old) and with the first thinning carried out only recently, it presented this characteristic, resulting in a low R^2.

Trees whose total height were not measured in the census, the fixed area and Bitterlich methods had their heights estimated by equation 1.

From the data measured in the census, the following individual dendrometric mean parameters were obtained: diameter at breast height (*d*), total height (*h*), transversal area (*g*), and individual volume (*v*). Also, the following variables per area unit were obtained: number of trees per hectare (N ha^{-1}), basal area per hectare (G ha^{-1}), total volume per hectare (V ha^{-1}), and commercial value in assortment classes per hectare.

After the census, the same areas were inventoried with the sampling methods of fixed area and Bitterlich, having in common the central plot of the sampling unit. In total, 30 sampling units were allocated for each sampling method, according to the unrestricted random process.

For the fixed area method (FA), circular sampling units with a 13.82 m radius (600 m^2 area) were used. In each sampling unit, the diameter of all trees and total height of the 15 first tree were measured with a caliper and a Vertex IV hypsometer, respectively.

For the Bitterlich method, three basal area factors (BAF) were used: 1, 2 and 4 (B1, B2, and B4). In each sampling plot, the qualified trees had their *d* measured and total height estimated by equation 1. For the border trees, the diameter and the distance from the central plot of the sampling unit to the centre of the tree were measured in order to algebraically confirm their inclusion or not in the sampling unit with expression 2 (Retslaff *et al.*, 2014).

$$R_i = \frac{50\ d_i}{\sqrt{BAF}} \quad [2]$$

Where: : critical radius of dubious tree *i* (m); *:* diameter at breast height of dubious tree *I*; BAF: basal area factor.

The total individual volume and volume by assortment of the three procedures (census, fixed area and Bitterlich sampling methods) was estimated by the 5th degree polynomial adjusted with data from a stand of the same species, same age, and region as the one from the present study (Retslaff, 2018). The equation is given by expression 3, with R^2_{aj} 0,9893 and S_{yx} 7,1%. For the classification of commercial volume, assortment classes shown in Kohler *et al.* (2015) were adopted (Table 1). These classes were established according to the sizes used by timber companies that use *Pinus taeda* wood in the South of Brazil.

Table 1. Assortment classes for a *Pinus taeda* stand in Pinhão, Paraná, Brazil.

Destination	Diameter of thin tip with bark (cm)	Log length (m)
Type 2 sawmill	23	3.1
Type 1 sawmill	16	3.1
Cellulose	8	2.4
Residues	5	2.4

Source: Adapted from Kohler *et al.* (2015).

$$d_i = d\left(1.216661 - 3.1888286\left(\frac{h_i}{h}\right) + 13.247441\left(\frac{h_i}{h}\right)^2 - 30.048558\left(\frac{h_i}{h}\right)^3 + 28.783659\left(\frac{h_i}{h}\right)^4 - 10.00994\left(\frac{h_i}{h}\right)^5\right) \quad [3]$$

Where: d_i = diameter (cm) at height h_i (m); h_i = height (m) in diameter d_i; d = diameter at breast height (cm); h = total height (m).

The same parameters, individual and per area unit, described for the census, were estimated for the sampling methods. The estimates per hectare of the fixed area method were obtained with the proportionality factor (F) (Sydow *et al.*, 2017), and the ones of the Bitterlich method were obtained with the estimators shown by Druszcz *et al.* (2015).

The basic statistics of the unrestricted random sampling process (mean, coefficient of variation, sampling error) were calculated for the individual variables *d*, *h*, *g* and *v*. For the variables per area unit, N, G, V and commercial volume in assortment classes per hectare, the confidence interval was also calculated. The real percentual error was determined by expression 4. The sampling error limit of 10% and the 5% significance level were established for the data processing of the inventory.

$$\text{ER}(\%) = 100\frac{v_r - v_e}{v_r} \quad [4]$$

Where: ER(%) = real error (percentage); V_r = mean of variable obtained by census; V_e = mean of variable estimated in the sampling.

For the statistical analysis of the means of individual variables and variables per unit area estimated by the sampling methods, the experiment was considered a completely randomized design (CRD) with five treatments (census, fixed area method and Bitterlich method with BAF 1, 2, and 4) and 30 repetitions each (sampling units measured in each method). Since the CRD demands an equal number of repetitions between treatments and having in sight that the census provides only the parametric value of each variable analysed, to compare the census with other sampling methods, the same number of repetitions of these methods was adopted, where each repetition of the census corresponded to the parametric value of the analysed variable.

The variables analysed were *d*, *h*, *g*, *v*, N, G, V and volume in assortment classes per hectare. For these analyses, the software R (R Core Team, 2021) was used with the help of packages "*agricolae*" (Mendibiru, 2019) and "*nortest*" (Gross and Ligges, 2015).

Data normality and homogeneity of variances were confirmed with the Lilliefors and Bartlett tests, respectively. As homogeneity of variances was not observed between samples even after data transformation, the non-parametric statistical analysis was performed with the Kruskal-Wallis test, in order to confirm a possible difference among treatments. When differences were verified, the Nemenyi test was performed aiming to identify which treatments differed (Zar, 2010).

In order to confirm adherence between diametric distribution of data from the census and the sampling methods, the Kolmogorov-Smirnov (K-S) test was performed (Téo *et al.*, 2012; Orellana *et al.*, 2014). A significance level of 5% was used for all analyses.

3. RESULTS AND DISCUSSION

The analysis of the individual variables *d* and *h* showed low coefficient of variation, with maximum value of 0.68% and 0.19%, respectively. On the other hand, the highest coefficients of variation were observed for g and v, with maximum values of 1.34% and 1.52%.

The low range of variation for the variables "diameter" and "height" could have happened due to the effect of thinning. In these cases, the values of *h* estimated with the equation tend to stabilize because of the lower number of remaining trees in the area, which is a mean value for the majority of trees. This effect pronounces with the increase in tree age and number of thinnings in the forest stand (Barros *et al.*, 2002).

Regarding the sampling errors, all methods and variables showed values lower than 6.6%. The highest sampling errors were observed for the variables estimated by the Bitterlich method with BAF 4. In most cases, the real error indicated that the sampling methods tended to overestimate the variables, however values were lower than 2%. The FA method showed the lowest sampling and real errors for variables *d*, *g* and *v*.

In the case of sampling errors of the individual variables, a study performed in a *Pinus taeda* stand, in the Ponta Grossa region, Paraná, when comparing the Bitterlich and the fixed area methods with structural variations of circular units, Druszcz *et al.* (2010) obtained the lowest sampling error for the fixed area method with a circular sampling unit, as also observed in this study.

For all the individual variables analysed, the Kruskal-Wallis test did not show a significant difference between the sampling methods tested. In all variables analysed, the estimate with any BAF showed similar accuracy to FA and, consequently, values similar to the parametric value. It is important to emphasize that the sampling errors of the methods tested were low yet always higher than the real errors, which were close to zero (Figure 1).

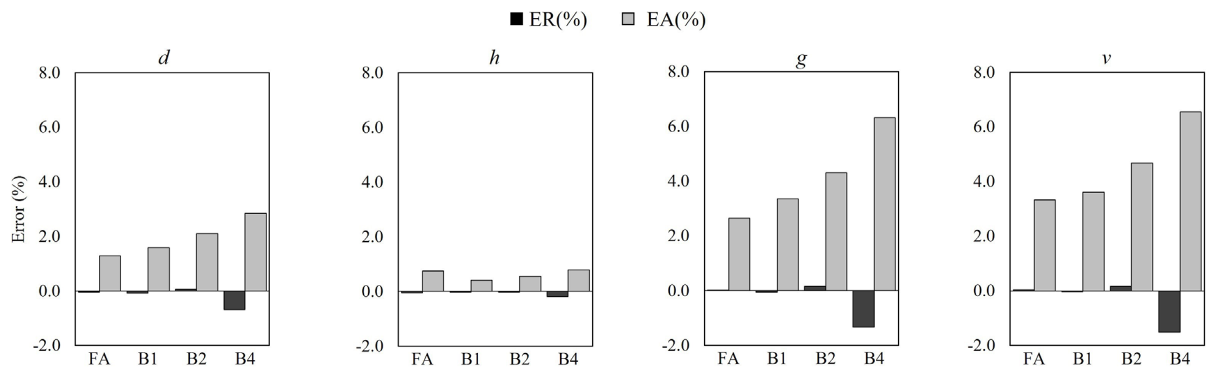

Figure 1. Real error (ER%) and sampling error (EA%) for variables *d*, *h*, *g* and *v* for each sampling method.

According to the results shown in Table 2, B1 was statistically different from the others for the variable "number of trees per hectare". Although this method has the second lowest sampling error, it generated the highest real error for all the variables per area unit. It means this method estimated 118 less trees in relation to the real number of trees in the stand per hectare, what affected the estimates of the other variables dependent on this variable. B2 showed closer estimates to the number of trees in the stand (underestimate of 2 trees per hectare) but not having the lowest sampling error.

Table 2. Statistical evaluation of variables per hectare (ha) for census and sampling methods and result of the test of means of *Pinus taeda* stands, located in Pinhão, Paraná, Brazil.

Variable	Method	Mean	CV (%)	Sampling error (%)	Real error (%)	CI Mín	CI Máx
Number of trees (N ha^{-1})	Census	660 a	-	-	-	-	-
	FA	648 a	9.52	3.55	1.86	624.20	670.20
	B1	542 b	17.97	6.71	17.86	505.34	578.04
	B2	658 a	20.30	7.58	0.28	607.77	707.48
	B4	669 a	25.40	9.48	-1.41	605.39	732.25
Basal area (m^2 ha^{-1})	Census	28.78 a	-	-	-	-	-
	FA	28.22 a	11.30	4.22	1.94	27.03	29.41
	B1	23.47 b	15.73	5.87	18.47	22.09	24.84
	B2	28.40 a	18.71	6.99	1.33	26.41	30.38
	B4	28.93 a	21.99	8.21	-0.52	26.55	31.31
Total volume (m^3 ha^{-1})	Census	256.32 a	-	-	-	-	-
	FA	251.16 a	12.09	4.51	2.01	239.81	262.50
	B1	208.75 b	15.77	5.89	18.55	196.46	221.05
	B2	252.69 a	18.95	7.07	1.41	234.81	270.58
	B4	257.46 a	22.11	8.25	0.44	236.21	278.72
Volume for type 2 sawmill (m^3 ha^{-1})	Census	61.38 a	-	-	-	-	-
	FA	59.95 a	38.35	14.32	2.32	51.37	68.54
	B1	48.34 b	40.21	15.01	21.23	41.08	55.60
	B2	59.42 ab	47.49	17.73	3.18	48.88	69.96
	B4	61.18 a	58.93	22.00	0.32	47.72	74.64

Table 2. Continued...

Variable	Method	Mean	CV (%)	Sampling error (%)	Real error (%)	CI	
						Mín	Máx
Volume for type 1 sawmill (m^3 ha^{-1})	Census	123.69 a	-	-	-	-	-
	FA	121.83 a	12.45	4.65	1.50	116.17	127.49
	B1	101.65 b	18.57	6.93	17.82	94.60	108.70
	B2	123.51 a	21.77	8.13	0.15	113.47	133.55
	B4	127.08 a	25.93	9.68	-2.74	114.78	139.39
Cellulose volume (m^3 ha^{-1})	Census	59.99 a	-	-	-	-	-
	FA	58.24 b	11.51	4.30	2.91	55.74	60.75
	B1	49.71 c	21.20	7.91	17.14	45.77	53.64
	B2	58.73 ab	23.25	8.68	2.10	53.63	63.82
	B4	57.93 ab	29.09	10.86	3.43	51.64	64.22

Where: FA: fixed area method; B1, B2 and B4: Bitterlich method with BAF 1, 2 and 4, respectively; CV: coefficient of variation; CI: confidence interval; Min: minimum value; Max: maximum value. Means with the same letter do not differ significantly among one another with the Nemenyi test, at 5% significance level.

It is important to note that the fixed area method showed the lowest sampling errors. On the other hand, the real errors were again close to zero (lower than 3.5%), except for Bitterlich BAF 1, and especially Bitterlich BAF 4 that in general showed the lowest real errors, although having the highest sampling errors (includes a lower number of trees, variance among plots tends to be higher). When we analyze the variables per area unit, the non-standard real error for BAF 1 can be justified by the lower number of counted trees per plot (average of 24 trees), which may not have included border trees that are more difficult to evaluate due to the greater reach distance from B1. This led to an underestimation of the variables per unit area, as the basal area factor is a significant element in estimating these variables. Therefore, it is essential to be careful when defining BAF while using the Bitterlich method.

Fixed area method includes a large number of trees (average of 39 trees per plot). This leads to lower variability among plots and consequently a lower sampling error, but not necessarily a lower real error.

When comparing the sampling performed with the fixed area method with a circular unit (648m^2) and the Bitterlich method with BAF 2, 3 and 4, in a *Eucalyptus saligna* stand, Couto *et al.* (1990) concluded that the number of trees per hectare estimated by the Bitterlich method with any BAF did not statistically differ from the fixed area method, being then adequate for the estimate of this variable.

Regarding the variable "basal area", a significant difference was observed between treatment B1 and the other treatments. The means of the other treatments (FA, B2 and B4) were statistically equal among themselves and the census, with sampling errors lower than 8.3% and real errors lower than 1.9%, with emphasis to FA and B4, respectively.

When comparing the methods of fixed area with circular sampling units and Bitterlich with BAF 2 in a *Pinus taeda* stand, Druzscz *et al.* (2010) observed that the fixed area method showed a lower sampling error and, with the student's t-test, was statistically different from Bitterlich, indicating a higher precision to estimate the number of trees per hectare. The same authors compared the basal area from the two sampling methods and found that the Bitterlich method showed a lower sampling error (±3.20%) although it did not statistically differ from the fixed area method. A similar result was obtained in this study, where the Bitterlich method (except B1) showed the best basal area estimate, with the lowest real error, even though with the highest sampling errors.

Santos *et al.* (2016) compared the fixed area method with 600 m^2 rectangular sampling units (20x30 m) and the Bitterlich method with BAF 1, 2 and 4, in a 6-hectare *Eucalyptus grandis* planting. The authors did not observe a statistical difference between the methods of fixed area and Bitterlich with any BAF for the basal area estimate.

For the variables "total volume", "type 2 sawmill volume", "type 1 sawmill volume" and "cellulose volume", at least one method showed statistical difference when compared to census and other treatments. For these same variables, it is noted that method B1 was statistically different from census in all cases, showing an underestimate of volumes in relation to the parametric values

The estimates of total volume and volume by assortment for methods B2 and B4 were very similar to the parametric values, however, they showed higher sampling errors comparatively to the others.

While assessing the precision and efficiency of different sampling methods (fixed area, Bitterlich with BAF 1 and Prodan) in a teak planting, in Sinop, Mato Grosso, Miranda *et al.* (2015) found that for the estimate of volume per hectare, the Bitterlich method showed more precise results, with lower sampling errors (±4.30%), followed by fixed area (±5.17%), and Prodan (±9.65%). The result obtained by these authors is similar to the ones of this study for Bitterlich BAF 1, since B1 was the method that showed the second lowest sampling error, being less precise than FA only. While comparing the Bitterlich sampling method with BAF 2 to fixed area in *Pinus taeda* plantings, Druszcz *et al.* (2010) concluded that Bitterlich was the most precise for the estimate of volume in relation to the fixed area method.

It is known that sampling error is calculated based on pre-established significance level for the inventory, sample size, and data variability. Thus, the relation between coefficient of variation and sampling error can be accepted. With the increase in data variability, there is an increase in the sampling error. This variability is due to the higher or lower tree count within a sampling unit, resulting in lower or higher variability between sampling units, respectively. However, this pattern is not observed when comparing data variability and real error. It is important to note that due to the inadequate tree count of B1, the other estimates per area unit which depended on this information also showed lower accuracy.

The coefficient of variation (CV%) and the sampling error had lower values for the FA method and higher values as the BAF of the Bitterlich method increased for all variables. This variance is related to the number of trees measured in each method, with mean values of 39, 24, 15, and 8 trees in FA, B1, B2 and B4, respectively. The FA method sampled larger number of trees per sampling unit, showing a lower variance between trees. With the Bitterlich method, less trees were counted and variance between sampling units was higher. This fact can explain the non-homogeneity of variance of residues in the variance analysis.

Due to the lower number of trees per sampling unit as the BAF increased, the variability increased among trees and, therefore, the sampling error increased. In the inventory by sampling, only precision of estimates is assessed with the sampling error (SE), making it possible to reach mistaken conclusions regarding the quality of estimates. Thus, according to the results observed in this study, a low sampling error does not necessarily indicate accurate estimates for the inventory.

Given all the information obtained in this research, B2 and B4 showed very similar estimates of the analysed variables in relation to the value from the census, being at times more precise than FA. Therefore, the Bitterlich method represents a good alternative when we need to obtain accurate data in a more practical way.

The diametric distribution resulting from the fixed area method was visually similar to that of the census (Figure 2), except for extreme classes (class center 9 and 37 cm), which had no trees sampled either by fixed area or Bitterlich, reflecting the low representativity of trees in this class, according to data from the census.

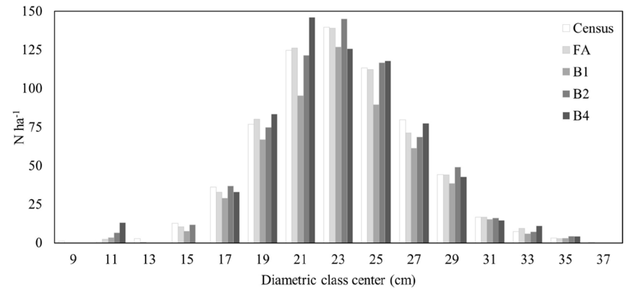

Figure 2. Parametric and estimated diametric distribution by the fixed area and Bitterlich method for *Pinus taeda* stand, located in Pinhão, Paraná, Brazil.

By visually analysing the parametric diametric distribution compared to those generated by the Bitterlich method, the use of BAF 1 resulted in the underestimate of the number of trees per diameter class, whereas BAF 4 overestimated these values in some classes (11, 19, 21, 25, 33 and 35 cm) and underestimated in others. The use of BAF 2 resulted in a number of trees similar to the parameter. Discrepancy in results was also observed for the 13 cm class, with no trees being sampled, for any BAF.

With the Kolmogorov-Smirnov (K-S) test, there was no statistical difference between the diametric distributions of the assessed sampling methods and the one from the census, indicating adherence of distribution at the 5% significance level. The result of the K-S test and the respective p-value, when comparing the diametric distribution of the census with those from the FA, B1, B2 and B4 methods, was 0.2667 (p-value = 0.6604), 0.400 (p-value = 0.1813), 0.1333 (p-value = 0.9993), and 0.200 (p-value = 0.9251), respectively. Regarding B1 for the variable N ha^{-1}, there was a statistical difference in comparison to the census. Nevertheless, when comparing the diametric classes from the census and B1, the K-S test did not show significant difference.

Regarding diametric distribution, a possible reason for B1 to show a statistical difference for the variable N ha^{-1} in relation to the census and no difference in the K-S test can be due to the number of trees distributed in virtually all classes. In case they were concentrated in fewer classes, the K-S test would have shown difference.

With the results, the first hypothesis was not rejected since the Bitterlich method was able to generate accurate and compatible estimates of forest plantings and even higher than those generated by the fixed area method, even for volumetric estimates for assortment classes. And the second hypothesis was not rejected since there was no statistical difference in the estimates generated by the BAF values used. In addition, for the variables per area unit, B2 and B4 showed estimates more similar to the parametric values in relation to the fixed area method, with only B1 being statistically different in all cases.

4. CONCLUSIONS

Based on the results of this study, we can conclude that the Bitterlich method is a viable and effective alternative for estimating forest parameters in *Pinus taeda* stands. With BAF 2 and 4, the Bitterlich method provided accurate estimates comparable to the parametric values obtained from the census. Even compared to the fixed area method, the Bitterlich method proved to be a competitive option, particularly for volumetric estimates for wood assortment classes.

Furthermore, when testing the influence of different BAFs, no statistically significant difference was observed in the estimates generated. However, it is important to note that the Bitterlich method with BAF 1 was not adequated for the planting conditions in study considering the high real errors.

Finally, the Bitterlich method has a great potential of application in plantings in Brazil, offering an effective and practical alternative for carrying out forest inventories and providing more accurate estimates than the fixed area method, including to estimate the wood assortment.

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Rodrigo Otávio Veiga de Miranda: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), supervision (equal), writing - original draft (equal), writing - review & editing (equal).

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