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ORIGINAL ARTICLE – Forest Management

Evaluation of Sampling with Partial Replacement and Double Sampling in a Managed Forest in the Brazilian Amazon

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Abstract

We compared sampling techniques in a managed native forest in Paragominas, Pará, Brazil. Our goal in this study was to evaluate the feasibility of using Double Sampling (DS) and Sampling with Partial Replacement (SPR), when compared to Continuous Forest Inventory (CFI), to estimate the wood stock for trees with DBH ≥ 20 cm in a managed forest. In our results, DS had the best volume prediction, generating a sampling error of 5.20% (11.48 m^3 ha^{-1}) on the second occasion 3.86% (8.78 m^3 ha^{-1}). The average volume increment, estimated for the forest in the monitored period (2014-2016) was 6.88 m^3 ha^{-1}, with a relative sampling error of 63.09%. Therefore, as an alternative and of low cost, we suggest using DS in successive forest inventories in monitoring areas of forest resources in the Brazilian Amazon.

Keywords: Sampling technique, Forest management, Forest inventory, Amazon.

1. INTRODUCTION AND OBJECTIVES

In the last six decades, surveys and monitoring of natural resources have increased rapidly in number and diversity, not only because of the significant increase in human pressure on natural resources, but also because of society's greater awareness of the vulnerability of these resources and the need to use them sustainably (De Gruijter et al., 2006).

Forest inventory, an important activity for forest management which is based on several sampling designs, provides quantitative and qualitative information on forest resources and their physical environments (Köhl el al, 2006; Van Laar & Akça, 2007; Burkhart & Tomé, 2012), either by means of census surveys or by the use of sampling procedures, using temporary or permanent plots (Cochran, 1977; Schreuder et al., 1993; Péllico Netto & Brena, 1997; Ubialli et al., 2009; Thompson, 2012). In addition to allowing characterizing the present state of the forest and its changes over time (Burkhart & Tomé, 2012; Felfili et al., 2005; Vidal et al., 2016), the information provided by forest inventories constitutes the basis for the management (Gadow et al., 2004; Räty & Kangas, 2019) and execution of conservation and management plans for forest resources, and also for the definition of forest public policies (Köhl et al., 2006; Van Laar; Akça, 2007). When combined with forest growth models, the information from an inventory also allows predicting the future development of the forest and, consequently, can contribute to its sustainable forest management (Hasenauer, 2006).

The choice of the type of forest inventory to be performed depends on the objectives of the inventory, the size and forest and environmental variability in the area to be inventoried, the form of obtaining the data (census or sampling), the detail of the results required, the approach of the forest in time and resources available to perform the inventory (Péllico Netto & Brena, 1997; Köhl et al., 2006). The formulation of objectives constitutes not only the basis for defining the design of the inventory, but is also an instrument to verify the success of the survey carried out.

However, besides the need to present reliable and accurate information, these inventories must present reduced costs (Von Lüpke & Saborowski, 2014), which can be achieved when determining, for example, the optimal time interval between monitoring. The determination of this interval depends on the correlation between measurements, and the intervals can be increased without affecting the estimates of population dynamics (Brena, 1979).

To estimate and monitor changes in the forest over time, particularly regarding growth, it is possible to use four types of multiple occasion sampling: Independent Sampling (IS), Continuous Forest Inventory (CFI), Sampling with Partial Replacement (SPR) (Vries, 1986; Philip, 1994; Péllico Netto & Brena, 1997; Köhl et al., 2006; Van Laar & B Akça, 2007; Queiroz, 2012) and Double Sampling (DS) (Vries, 1986; Cochran, 1977; Péllico Netto & Brena, 1997). Independent Sampling is the only one that uses only temporary plots, in all monitored occasions, and therefore is the one that generates the maximum sampling error for growth, since there is independence of sampling between monitored occasions. The other types include permanent plots in the sampling, but DS and SPR also make use of temporary plots (Péllico Netto & Brena, 1997).

In Continuous Forest Inventory, all the plots are permanent and therefore remediated over time, which allows for greater precision in growth estimation, due to the high correlation of sampling between monitored periods. Although this type of sampling is the most desirable, its implementation and maintenance is always more expensive than the other types, especially in heterogeneous areas that require high sampling intensity. Thus, to minimize the costs of remediation of the plots over time, one can make use of other statistical methods to estimate future variations in the population (Scott, 1998).

One possibility is the use of DS, which allows for cost reduction in measurements subsequent to the first inventory, because, of the total number of plots deployed on the first occasion, only a portion remains as permanent and the variable of interest is estimated for the remaining plots that were eliminated from the sampling, from the adjustment of a linear regression equation, which relates the data from the permanent plots on the second occasion to the data from the permanent plots on the first occasion. High correlation between the permanent plots of two occasions is important to increase the accuracy of the estimation of the variable of interest, since reducing the number of permanent plots on the second occasion tends to increase the relative error of the inventory (Von Lüpke et al., 2012; Kershaw et al., 2017).

The SPR is also an alternative, and is based on maintaining a number of permanent plots on all monitored occasions and deploying new temporary and independent plots at each monitoring occasion. This method has been improved over the years, with the replacement of simple linear regression by multiple regression for parameter estimation on subsequent occasions to the first one (Bokalo et al., 1996; Cunia, 1965). According to Köhl et al. (2015), the SPR allows for an increase in sampling intensity when one wishes to evaluate forest areas that have suffered some type of disturbance, or when permanent plots have been lost due to the occurrence of deforestation, for example.

In areas of forest management for selective logging, few studies have been conducted to evaluate the performance of different types of inventory. For this reason, we pose the following research question: Which forest inventory techniques provide the most effective statistical estimators for tropical forest management in Amazonia? The main objective of our study was to investigate the feasibility of the techniques of Double Sampling and Sampling with Partial Replacement from their statistical estimators for calculating the average volumes of the first occasion, second occasion and growth are efficient to be applied in the management of tropical forests in the Brazilian Amazon.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located at Fazenda Rio Capim (3° 39° 28° S and 48° 49°60° W), Paragominas Municipality, Pará State, Brazil (Figure 1a), in a forest management unit belonging to the company CKBV Florestal Ltd. The Fazenda Rio Capim has a total area of 140,000 ha, of which 121,000 ha are under forest management certified by the Forest Stewardship Council (FSC), since 2001. The forest formation of the forest management unit is described as Submontane Dense Ombrophylous Forest (IBGE, 2012).

According to the Köppen classification, the climate is of type "Aw", characterized as rainy tropical, with average annual rainfall of 1,800 mm and a well-defined dry season from July to September. The average annual temperature is 26.3°C and the relative humidity is 81% (ALVARES et al., 2013). The soils in the region are of yellow Latosols and yellow Argissolos type, being also found Plintossolos, Geissolos and Neossolos (Rodrigues et al., 2003).

The forest management unit at Fazenda Rio Capim is divided into 35 Annual Production Units (APUs), which are subdivided into Work Units (WUs). This study was carried out in APU 7 (7.59 ha), divided into 73 Working Units (WUs). WU 14 (Figure 1b), with a total area of 100 ha, was selected for data collection. In June 2004, before forest harvesting was carried out in WU 14, 18 permanent plots of one hectare each (100 m x 100 m) were installed, grouped into two transects, each with 9 plots (Fig. 1b) (Ferreira, 2005).

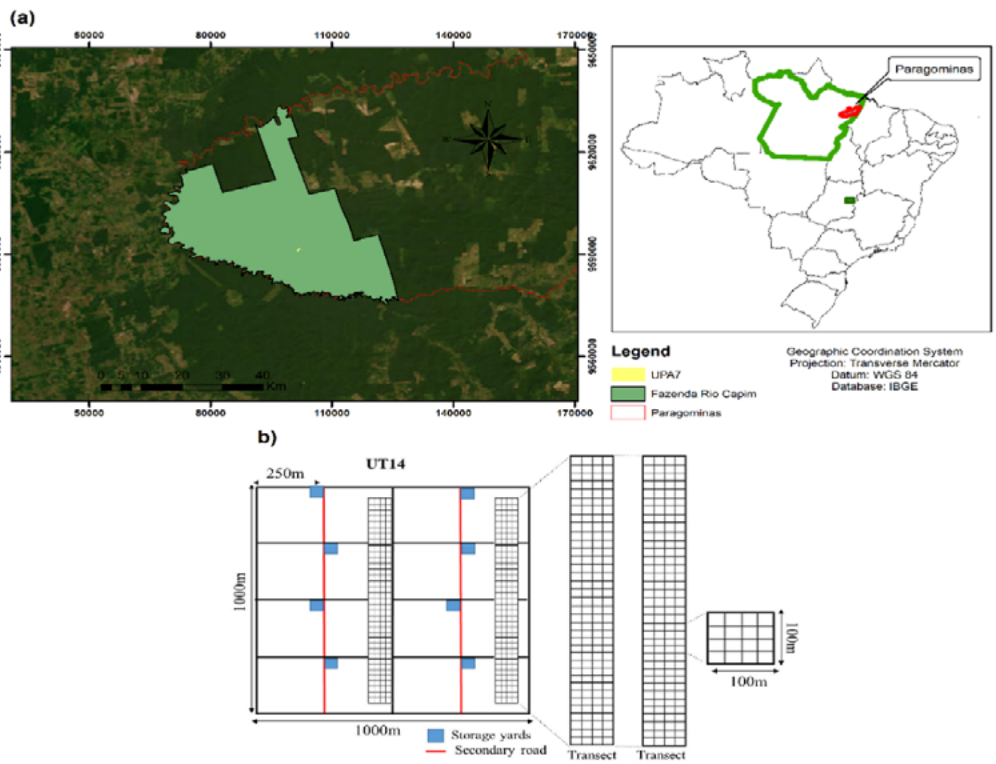

Figure 1. Localization of the Forest Management area, Rio Capim Farm, Paragominas Municipality, Pará State, Brazil (a). Schematic drawing of the transects with the random distribution of the subplots (in gray), at WU 14 of APU 7 (b), adapted from Ferreira (2005).

Monitoring in the permanent plots was conducted on eight occasions. The first measurement occurred in 2004 (before the exploration), and subsequent measurements occurred in 2005, 2006, 2008, 2010, 2012, 2014, and 2016. For the logging, which was conducted in July 2004, one month after the first inventory in the area, 34 species of commercial importance were selected. The minimum diameter for logging is 55 cm for all commercial species. On average, 7 trees ha^{-1} were logged, equivalent to an average volume of 21.3 m^3 ha^{-1} of roundwood, or 51.4 m^3 ha^{-1} of the wood volume of the plots (Ferreira, 2005; Sist & Ferreira, 2007). The average cutting rate on the plots was equal to 67.7% (Sist & Ferreira, 2007). For the present study, only data from the inventories conducted in 2014 and 2016 were used for plots of one hectare each (100 m x 100 m).

2.2. Data analysis

2.2.1. Wood volume estimate per plot

The volume per tree was calculated by the following equation 1 developed in the Region of Paragominas, with the rigorous sizing of 1,153 trees made in the Management Plan of the company “Grupo CIKEL Ltda.” in the year 2011, filed with the environmental agency:

$$V=10^{[(1{,}93*logDAP)-2{,}96]}$$

Where: V = commercial volume,

DBH = diameter at breast height.

Finally, the wood volume per plot was obtained considering all living trees from the 2014 and 2016 measurements. In each of the permanent plots, all trees were measured.

2.2.2. Estimation of the parameters for each sampling procedure on multiple occasions

For the estimation of wood volume parameters, considering each sampling process on multiple occasions, that is, CFI, SPR and DS, the recommendations suggested by Köhl et al. (2015) were followed, regarding the exclusion of permanent plots that showed a reduction in total wood volume (m^3) in the period selected for analysis (2014 and 2016). This with the purpose of not altering the calculations of the error estimate. Thus, we excluded plots 4, 5 and 6, from the analysis which showed a reduction in volume during the monitored period (Figure 2).

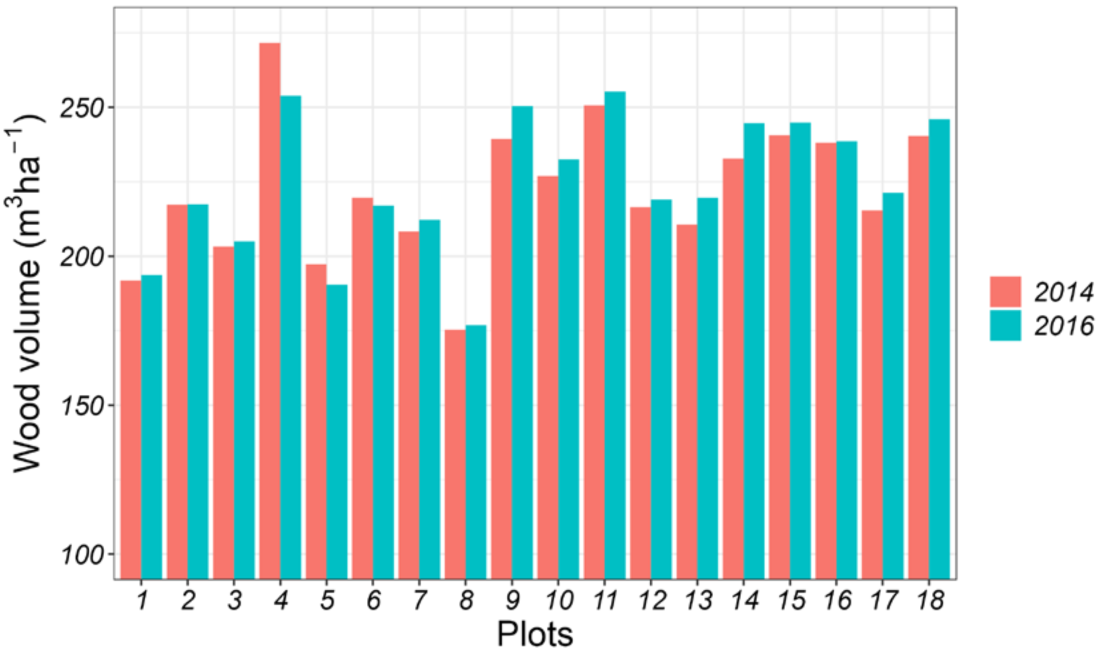

Figure 2. Wood volume per plot, recorded in 2014 and 2016, in the permanent plots sampled in WU 14 of APU 7, located in the Forest Management area, at Fazenda Rio Capim, Municipality of Paragominas, Pará State, Brazil.

With the exclusion of the plots that presented a reduction in volume during the monitored period, data analyses were performed considering only the information collected in 15 permanent plots. All analyses included individuals with DBH ≥ 20 cm, recorded in 2014 and 2016.

For the purpose of the analyses, CFI was regarded as a control sampling process, used to validate the results obtained by DS and SPR. In CFI, all 15 permanent plots measured in 2014, i.e., on the first occasion (m), were remensured in 2016, on the second occasion (m) (Table 1). Estimates of the sampled population parameters, for the wood volume variable, on each sampled occasion, using the CFI process, as well as the estimate of the change in volume growth were obtained from the formulas described in Table 2.

Notations used in the CFI estimators:

- m = number of units sampled on the first occasion and remensured on all subsequent occasions
- $n1$ = sampling intensity on all occasions
- X = wood volume of the sample units on the first occasion
- Y = wood volume of the sample units on the other occasions
- $\underline{d}_m$ = average annual change or growth
- $N1$ = total number of feasible plots in the study area

In DS, all 15 plots were measured in 2014, however, it was decided to separate the plots into two groups, i.e., the first 7 plots were considered temporary plots (u) and the remaining 8 plots were defined as permanent plots (m). On the second occasion (2016), only the m permanent plots were remediated (Table 1). Estimates of the sampled population parameters for the wood volume variable on each sampled occasion using DS, as well as the estimated change in volume growth, were obtained according to the formulas described in Table 2.

Notations used in the DS estimators:

- m = permanent sample units
- u = temporary sampling units of the first occasion

- $n1$ = sampling intensity (permanent + temporary plots) of the first occasion
- $n2$ = sampling intensity of subsequent occasions, where $n_2 < n_1$
- X = wood volume of the sample units on the first occasion
- Y = wood volume of the sample units on the other occasions
- $\underline{d}r$ = average annual change or growth
- $N1$ = total number of feasible plots in the study area

As for SPR, on the first occasion (2014) 10 plots were measured, with the first 5 (five) defined as temporary (u) and the next 5 (five) as permanent (m). However, on the second occasion (2016), only the five (5) permanent (m) plots were remensured and the temporary ones sampled in 2014 were replaced with new temporary ones, i.e. the remaining five (5) plots (n), not measured in 2014 (Table 1). Estimates of the sampled population parameters, for the wood volume variable, at each sampled occasion, using the SPR process, as well as the estimated change in volume growth, were obtained as in Table 2.

Notations used in the SPR estimators:

- m = permanent sample units
- u = temporary sampling units on the first occasion
- n = temporary sampling units on the second or third occasion
- $n1$ = sampling intensity (permanent + temporary) of the first occasion
- $n2$ = sampling intensity (permanent + temporary) of the second or third occasion
- P_m = proportion of the permanent sample from the first occasion that is remedied on the other occasions
- P_u = proportion of the temporary sample from the first occasion that is replaced on the other occasions
- X = wood volume of the sample units on the first occasion
- Y = wood volume of the sample units on the other occasions
- $\underline{d}_p$ = average annual change or growth
- $N1$ = total number of feasible plots in the study area

Table 1. Structuring the database for applying the analyzed successive occasion sampling procedures, where P represents plot; m is permanent plot; u is temporary plot and n is new temporary plot.

CFI		DS		SPR	
First occasion	Second occasion	First occasion	Second occasion	First occasion	Second occasion
P1 (m)	P1 (m)	P1 (u)		P1 (u)	
P2(m)	P2(m)	P2(u)		P2(u)	
P3(m)	P3(m)	P3(u)		P3(u)	
P4(m)	P4(m)	P4(u)		P4(u)	
P5(m)	P5(m)	P5(u)		P5(u)	
P6(m)	P6(m)	P6(u)		P6(u)	
P7(m)	P7(m)	P7(u)		P7(u)	
P8(m)	P8(m)	P8(u)		P8(u)	
P9(m)	P9(m)	P9(u)		P9(m)	P9(m)
P10(m)	P10(m)	P10(u)		P10(m)	P10(m)
P11(m)	P11(m)	P11(m)	P11(m)	P11(m)	P11(m)
P12(m)	P12(m)	P12(m)	P12(m)	P12(m)	P12(m)
P13(m)	P13(m)	P13(m)	P13(m)	P13(m)	P13(m)
P14(m)	P14(m)	P14(m)	P14(m)		P14(n)
P15(m)	P15(m)	P15(m)	P15(m)		P15(n)
P16(m)	P16(m)	P16(m)	P16(m)		P16(n)
P17(m)	P17(m)	P17(m)	P17(m)		P17(n)
P18(m)	P18(m)	P18(m)	P18(m)		P18(n)

Table 2. Equations used to calculate the estimators at each occasion and of growth for all sampling methods.

Continuous Forest Inventory (CFI)			
Estimators	**First occasion**	**Second occasion**	**Growth**
Sampling error	Absolute: $E_a = t \cdot S_{\bar{x}}$ Relative: $E_r = t \cdot S_{\bar{x}} / \bar{x} \cdot 100$	Absolute: $E_a = t \cdot S_{\bar{y}}$ Relative: $E_r = t \cdot S_{\bar{y}} / \bar{y} \cdot 100$	Absolute: $E_a = t \cdot S_{\bar{d}_m}$ Relative: $E_r = t \cdot S_{\bar{d}_m} / \bar{d}_m \cdot 100$
Standard error of the mean	$S_{\bar{x}} = \sqrt{S^2{}_{\bar{x}}}$	$S_{\bar{y}} = \sqrt{S^2{}_{\bar{y}}}$	$S_{\bar{d}_m} = \sqrt{S^2{}_{\bar{d}_m}}$
Variance of the Mean	$S^2{}_{\bar{X}} = \frac{S^2{}_X}{n_1} \cdot fc;$ $Where: fc = \left(1 - \frac{n_1}{N_1}\right)$	$S^2{}_{\bar{y}} = \frac{S^2{}_y}{n_1} \cdot fc;$ $Where: fc = \left(1 - \frac{n_1}{N_1}\right)$	$S^2{}_{\bar{d}_m} = S^2{}_{\bar{x}} + S^2{}_{\bar{y}} - \frac{2 \cdot S_{xy}}{m}$ $Where: S_{xy} =$ Covariance between the two occasions
Variance	$S^2{}_x = \frac{\sum_{i=1}^{n_1} \left(Xi - \bar{X}\right)^2}{n_1 - 1}$	$S^2{}_y = \frac{\sum_{i=1}^{n_2} \left(Yi - \bar{Y}\right)^2}{n_2 - 1}$	
Mean	$\bar{X}_m = \frac{\sum_{i=1}^{n_1} X_i}{n_1}$	$\bar{Y}_m = \frac{\sum_{i=1}^{n_2} Y_i}{n_1}$	$\bar{d}_m = \bar{Y}_m - \bar{X}_m$
Double Sampling (DS)			
Estimators	**First occasion**	**Second occasion**	**Growth**
Sampling error	Absolute: $E_a = t \cdot S_{\bar{x}_1}$ Relative: $E_r = t \cdot S_{\bar{x}_1} / x_1 \cdot 100$	Absolute: $E_a = t \cdot S_{\bar{y}}$ Relative: $E_r = t \cdot S_{\bar{y}} / v \cdot 100$	Absolute: $E_a = t \cdot S_{\bar{d}_r}$ Relative: $E_r = t \cdot S_{\bar{d}_r} / d_r \cdot 100$
Standard error of the mean	$S_{\bar{x}_1} = \sqrt{S^2{}_{\bar{x}_1}}$	$S_{\bar{y}} = \sqrt{S^2{}_{\bar{y}}}$	$S_{\bar{d}_r} = \sqrt{S^2{}_{\bar{d}_r}}$
Variance of the Mean	$S^2{}_{\bar{x}_1} = \frac{S^2{}_x}{n_1} \cdot fc;$ $Where: fc = \left(1 - \frac{n_1}{N_1}\right)$	$S^2{}_{\bar{y}} = \frac{S^2{}_y \cdot (1 - \rho^2)}{n_2} + \frac{\rho^2 \cdot S^2{}_y}{n_1}$ $Where: \rho = Cov(xy) / S_x S_y$	$S^2{}_{\bar{d}_r} = S^2{}_y \cdot \left(\frac{(1-\rho)^2}{n_1} + \frac{1-\rho^2}{n_2}\right)$
Variance	$S^2{}_{x_1} = \frac{\sum_{i=1}^{n_1} \left(X_i - \bar{X}\right)^2}{n_1 - 1}$	$S^2{}_y = \frac{\sum_{i=1}^{n_2} \left(Y_i - \bar{Y}\right)^2}{n_2 - 1}$	
Mean	$\bar{x}_1 = Pu\bar{x}_u + Pm\bar{x}_m$	$y_r = y_m + b \cdot (x_1 - x_m)$ $Where: b =$ b = angular coefficient of the regression	$\bar{d}_r = \bar{y}_r - \bar{x}_1$

Table 2. Continued...

Sampling with Partial Replacement (SPR)			
Estimators	**First occasion**	**Second occasion**	**Growth**
Sampling error	Absolute: $E_a = t \cdot S_{\bar{x}}$ Relative: $E_r = t \cdot S_{\bar{x}} / \bar{X} \cdot 100$	Absolute: $E_a = t \cdot S_{\bar{y}}$ Relative: $E_r = t \cdot S_{\bar{y}} / \bar{Y} \cdot 100$	Absolute: $E_a = t \cdot S_{\bar{d}_p}$ Relative: $E_r = t \cdot S_{\bar{d}_p} / \bar{d}_p \cdot 100$
Standard error of the mean	$S_{\bar{x}} = \sqrt{S^2_{\bar{x}}}$	$S_{\bar{y}} = \sqrt{S^2_{\bar{y}}}$	$S_{\bar{d}_p} = \sqrt{S^2_{\bar{d}_p}}$
Variance of the Mean	$S^2_{\bar{x}} = \frac{s^2_x}{n_1} \cdot fc;$ $Where: fc = \left(1 - \frac{n_1}{N_1}\right)$	$S^2_{\bar{x}} = a^2 \cdot S^2_x \left(\frac{1}{u} + \frac{1}{m}\right) + c^2 \cdot \frac{S^2_y}{m} + (1+c)^2 \cdot \frac{S^2_y}{n} -$ $-2 \cdot a \cdot c \cdot r \cdot \frac{S_x S_y}{m}$ $Where: r = Cov(xy) / S_x S_y$	$S^2_{\bar{x}} = a^2 \cdot S^2_x \left(\frac{1}{u} + \frac{1}{m}\right) + c^2 \cdot \frac{S^2_y}{m} + (1+c)^2 \cdot \frac{S^2_y}{n} -$ $-2 \cdot a \cdot c \cdot r \cdot \frac{S_x S_y}{m}$ $Where:$ $A = \frac{m}{n_2 - P_u \cdot n \cdot r^2} + \frac{n \cdot P_m}{n_2 - P_u \cdot n \cdot r^2} \cdot r \cdot \frac{S_x}{S_y}$ $B = \frac{-m \cdot P_m}{n_2 - P_u \cdot n \cdot r^2} \cdot r \cdot \frac{S_y}{S_x} - \frac{n_2 \cdot P_m}{n_2 - P_u \cdot n \cdot r^2}$
Variance	$S^2_x = \frac{\sum_{i=1}^{n1} (X_i - \bar{X})^2}{n_1 - 1}$	$S^2_y = \frac{\sum_{i=1}^{n1} (Y_i - \bar{Y})^2}{n_2 - 1}$	
Mean	$\bar{X} = (1-b) \cdot \bar{x}_u + b \cdot \bar{x}_m + c \cdot \bar{y}_m - c \cdot \bar{y}_n;$ $Where: b = n_2 \cdot P_m / n_2 - P_u \cdot n \cdot r^2$ $c = \frac{-n \cdot P_m}{n_2 - P_u \cdot n \cdot r^2} \cdot r \cdot \frac{S_y}{S_x}$	$\bar{Y} = a \cdot \bar{x}_u - a \cdot \bar{x}_m + c \cdot \bar{y}_m + (1-c) \cdot \bar{y}_n;$ $Where: c = m / n_2 - P_u \cdot n \cdot r^2$ $a = \frac{m \cdot P_u}{n_2 - P_u \cdot n \cdot r^2} \cdot r \cdot \frac{S_y}{S_x}$	$\bar{d}_p = A \cdot \bar{y}_m + B \cdot \bar{x}_m + (1-A) \cdot \bar{y}_n - (1+B);$ $Where: A = \frac{m}{n_2 - P_u \cdot n \cdot r^2} + \frac{n \cdot P_m}{n_2 - P_u \cdot n \cdot r^2} \cdot r \cdot \frac{S_x}{S_y}$ $B = \frac{-m \cdot P_m}{n_2 - P_u \cdot n \cdot r^2} \cdot r \cdot \frac{S_y}{S_x} - \frac{n_2 \cdot P_m}{n_2 - P_u \cdot n \cdot r^2}$

2.2.3. Comparing and validating the sampling techniques on the first and second occasion

The sampling procedures DS and SPR were compared to the CFI, considering the latter as the control treatment, because it contains all the measurements of the plots on both occasions. The mean wood volume estimates for the first and second occasion in the DS and SRP techniques were compared to the mean values obtained in CFI. The Kruskal-Wallis test was applied as a non-parametric alternative to the one-way ANOVA test, at a 5% significance level (p value < 0.05).

3. RESULTS AND DISCUSSION

The CFI estimated for the first occasion sampled, i.e. in 2014, the average of wood volume was equal to 220.50 m^3 ha^{-1}, for the area of Submontane Dense Ombrophylous Forest, sampled at WU 14 of APU 7, of the forest management unit of Rio Capim Farm. The standard error of sampling was 20.74 m^3 ha^{-1}, which corresponds to a standard error of the mean of 5.35 m^3 ha^{-1} and a sampling error of 5.30 %. On the second occasion sampled in 2016, the estimated mean volume of wood in the area was 225.18 m^3 ha^{-1}, with a standard error of 22.41 m^3 ha^{-1}, standard error of the mean of 5.78 m^3 ha^{-1}, and sampling error of 5.51 % (Figure 3a). The average increment in volume or change in volumetric growth in the sampled area was approximately 4.69 m^3 ha^{-1}, over the two-year period. The standard error of the increment was 0.87 m^3 ha^{-1}, which indicates a sampling error of 38.05 % (Figure 3b).

With the application of DS, the estimated average wood volume, considering trees with DBH ≥ 20 cm, was equal to 220.50 m^3 ha^{-1}, on the first occasion (2014). This sampling generated a standard error of 20.74 m^3 ha^{-1}, corresponding to a standard error of the mean of 5.35 m^3 ha^{-1} and a sampling error of 5.20% (11.48 m^3 ha^{-1}). On the second occasion (2016), the mean volume estimated by DS was equal to 227.38 m^3 ha^{-1}, with standard deviation equal to 10.37 m^3 ha-1 and standard error of the mean of 3.16 m^3 ha^{-1}. The sampling error was 3.86% (8.78 m^3 ha^{-1}) (Figure 3a). The mean increment in wood volume, estimated for the forest, in the monitored period, was 6.88 m^3 ha^{-1}, with standard error of the mean of 2.07 m^3 ha^{-1} and relative sampling error of 63.09% (Figure 3b).

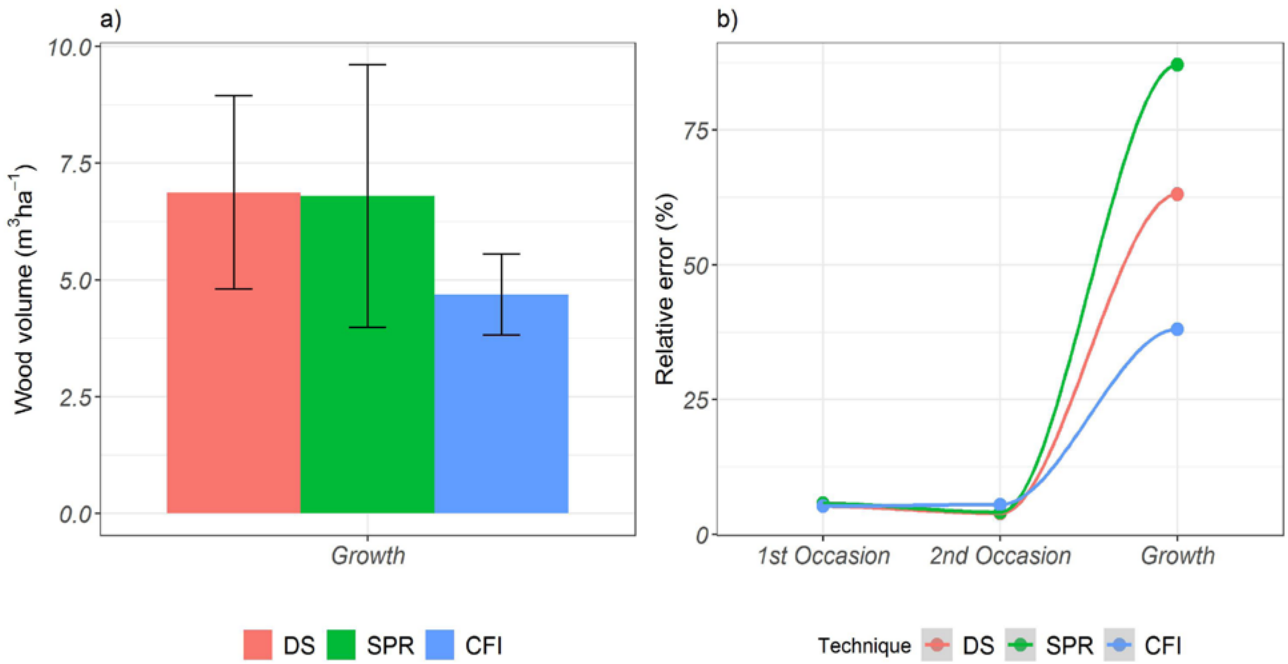

Figure 3. Representation of the mean and estimated standard deviation for growth (a) and relative error by simulations (b) in inventories with double sampling (DS), sampling with partial replacement (SPR), and continuous forest inventory (CFI). O CFI is control of treatment.

The SPR estimated for the first occasion sampled (2014), an average volume of 211.27 m^3 ha-1, with standard deviation equal to 21.68 m^3 ha-1 and sampling error equal to 6.89% (14.55 m^3 ha-1). On the second occasion (2016), the estimated mean volume was 223.76 m^3 ha-1, with standard deviation of 14.17 m^3 ha-1 and relative error of 4.08% (Figure 3a). The best estimate of the mean volume for the first occasion was calculated, as suggested by Péllico Netto & Brena (1997), and an average volume of 216.95 m^3 ha-1 was obtained, higher than previously estimated. The best estimate of the average volume provided a reduction in the standard error of the mean to 5.67 m^3 ha-1 (Figure 3a). The average increment in volume estimated by SPR was 6.80 m^3 ha-1, with standard error of 2.81 m^3 ha-1 and relative error of 87.11%.

The result of the statistical analysis shows that there is no significant difference between the sampling techniques (Figure 4). The standard deviation was also similar in both techniques for the two occasions. This was also observed in the work developed by Paula Neto & Scolforo (1983) in an inventory on multiple occasions in Eucalyptus spp. plantations, i.e., in a forest formation less complex than the formation studied in this work. Furthermore, in the dense ombrophilous forest of the state of Pará, sampling with partial replacement showed better estimates, for the first and second occasions compared to the estimates of continuous forest inventory, given that the values of relative error were lower for this process (Ribeiro et al., 2019).

Between the sampling processes DS and SPR, it is observed that the DS showed a lower error when estimating the total volume on the first and second occasion, demonstrating superior precision in the estimates of total volumes. The estimated volume for the first occasion was similar between the two techniques, but there was an increase in the relative error in SPR which may be related to the sample size used to make the estimates, because in DS 15 sample units were used, while in SPR 10 were used on the first occasion.

We observed that the estimated error for the second occasion of SPR was close to that found in CFI, demonstrating that SPR is an efficient technique for estimation on successive occasions when there is loss of permanent plots due to forest fires or clear cutting of native vegetation (Köhl et al., 2015). This accuracy depends on the proportion of the permanent subsample, which can be determined by the correlation between the sampling units on the two occasions and the cost ratio between the measurement of temporary and permanent plots (Netto & Brena, 1997). To increase the accuracy of the SPR, Bokalo et al. (1996) suggested a modification of the SPR proposed by Ware & Cunia (1992), with the expansion of the sample on the second occasion, by projecting the growth of temporary plots from the first occasion to the second occasion, thus increasing the correlation between sampling units. However, the difference presented between the modified SPR and original SPR was not significant, with a variance of 35.13 and 35.59, respectively.

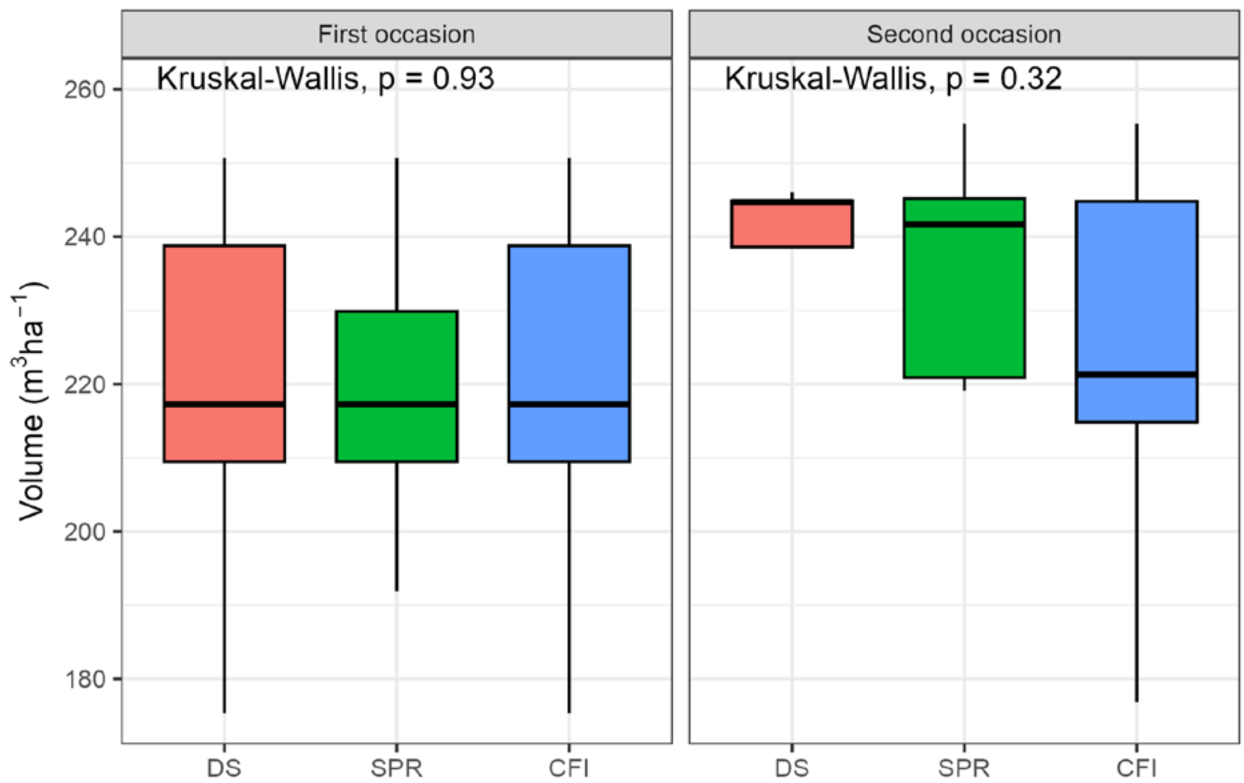

Figure 4. Boxplot that explains that statistical analyses with the volume values for double sampling (DS), sampling with partial replacement (SPR) and continuous forest inventory (CFI). O CFI is control of treatment.

According to Von Lüpke et al (2012), in native forests where most individuals are in the largest diametric classes, a considerable increase in relative error may occur with the reduction of sampling units on the second occasion.

In regions with constant progression of the agricultural frontier over native areas, and with irregular logging in the initial phase, as occurs in the Amazon region, it is essential to create strategies that enable continued forest inventories even with the loss of permanent plots due to clear cutting.

With the identification of accurate sampling processes and proper estimation methods, unbiased estimates, such as mean and total, can be obtained about the population of interest. In addition, the sampling process should be reasonably accurate and with reduced cost of execution (Thompson, 2012).

Regarding the estimation of the volumetric increment of the forest between the years 2014 and 2016, sampling from the DS technique showed better estimates with an error of 63.09%, while the SPR technique showed an error of 87.11%. The insertion of new temporary plots, especially in environments where the occurrence of thinning of individuals, as observed by Köhl et al. (2015), or in extremely diverse and heterogeneous environments such as the tropical forest of this study, may have caused inaccuracy in the estimation of growth in the period. Thus, for estimation of volumetric increment on multiple occasions, sampling permanent plots with the DS technique can be considered as a good alternative for cost reduction, since there is a reduction in the number of measurements, without compromising the accuracy of the inventory, while saving hours of field work (Kershaw et al., 2016).

4. CONCLUSIONS

Sustainable forest management requires an appropriate inventory sampling method that is accurate, efficient, and cost-effective. Double sampling and sampling with partial replacement offer an added advantage compared to the continuous forest inventory with higher costs.

With regard to growth or changes in wood volume, the double sampling inventory showed better error estimates in measuring stock volume and forest growth and production than the partial repeat sampling inventory.

Thus, the double sampling inventory can be successfully recommended as an alternative for continuous monitoring of forest production areas in the Brazilian Amazon, allowing lower sampling costs in forest planning.

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REFERENCES

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JDM, Sparovek G. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 2013; 26(6): 711–728.

Bokalo M, Titus SJ, Wiens, DP. Sampling with partial replacement extended to include growth projections. *Forest Scienc*e 1996; 42(3): 328-334.

Brena DA, Comparação dos métodos de inventários florestais sucessivos em relação a amostragem com repetição parcial, aplicados em uma população estratificada. *Dissertação* (Mestre em Ciências) – Universidade Federal do Paraná, Curitiba, 1979.

Burkhart HE, Tomé M. *Modeling forest trees and stands.* Dordrecht: Springer Netherlands 2012; v. 9789048131

Cochran, WG. *Sampling Techniques.* 3rd. ed. John Wiley & Sons., 1997.

Cunia T. Continuous forest inventory, partial replacement of samples and multiple regression. Forest Science 1965; 11(4): 480 - 502, 1965.

De Paula Neto F, Scolforo JRS. Eficiência relativa dos procedimentos de inventários repetidos em plantações de Eucalyptus spp. *Revista Arvore* 1983, 7(2): 123

De Gruijter J, Brus DJ, Bierkens MF, Knotters M. S*ampling for natural resource monitoring* (Vol. 665). Berlin: Springer, 2006.

Felfili JM, Carvalho FA, Haidar RF. *Manual para o monitoramento de parcelas permanentes nos biomas Cerrado e Pantana*l. Brasília: Universidade de Brasília, Departamento de Engenharia Florestal; 2005.

Ferreira FN. *Análise da sustentabilidade do manejo florestal com base na avaliação de danos causados por Exploração de Impacto Reduzido (EIR) em floresta de terra firme no município de Paragominas-PA*. Universidade Federal Rural da Amazônia; 2005.

Gadow KVon, Sánchez OS, Calderón AOA. *Manejo forestal con bases científicas.* Madera y Bosques 2004; 10(2): 3 – 16.

Hasenauer H. Concepts within tree growth modeling. In S*ustainable forest management Springer,* Berlin, Heidelberg; 2006.

Kershaw Jr JA, Ducey MJ, Beers TW, Husch, B. *Forest mensuration*, 5th ed.; Wiley: Chichester, UK, 2017.

Köhl M, Scott CT, Lister AJ, Demon I, Plugge D. Avoiding treatment bias of REDD+ monitoring by sampling with partial replacement. Carbon balance and management 2015; 10(1): 1-11.

Péllico Netto S, Brena DA. *Inventário Florestal,* Curitiba, Edição Autores; 1997.

Queiroz, WT. *Amostragem em inventário florestal.* Belém, PA: Universidade Federal Rural da Amazônia; 2012.

Räty M, Kangas, AS. Effect of permanent plots on the relative efficiency of spatially balanced sampling in a national forest inventory. *Annals of Forest Science 2019*; 76(1) 1-14.

Ribeiro LOMM, Silva JNM, Netto SP, Queiroz WT. Avaliação da amostragem com substituição parcial com duas medições sucessivas em floresta manejada no município de Paragominas. Pará. S*cientia Forestalis 2019*; 47: 778-790.

Rodrigues TE, Silva RDC, Da Silva JML, De Oliveira Junior RC, Gama JRNF, Valente MA. Caracterização e classificação dos solos do município de Paragominas, Estado do Pará. *Embrapa Amazônia Oriental-Documentos* (INFOTECA-E); 2003.

Schreuder HT, Gregoire TG, Wood GB. *Sampling methods for multiresource forest inventory.* John Wiley & Sons, 1993.

Scott CT. *Sampling methods for estimating change in forest resources.* Ecological Applications 1998; 8(2): 228 - 233.

Sist P, Mazzei L, Blanc L. Rutishauser E. Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon. Forest Ecology and Management 2014; 318: 103 – 109.

Sist P, Ferreira FN. Sustainability of reduced-impact logging in the Eastern Amazon. Forest Ecology and Management 2007; 243(2): 199 -209.

Thompson SK. *Sampling*. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2012.

Ubialli JA, Figueiredo Filho A, Machado SDA, Arce JE. Comparação de métodos e processos de amostragem para estimar a área basal para grupos de espécies em uma floresta ecotonal da região norte matogrossense. *Acta Amazonica 2009*; 39: 305-314.

Van Laar A, Akça A. Forest mensuration (Vol. 13). *Springer Science & Business Media*, 2007.

Vidal C, Alberdi I, Hernández L, Redmond JJ. *National forest inventories* - assessment of wood availability and use, 1st edn. Springer International Publishing; 2016.

Von Lüpke N, Hansen J, Saborowski J, A three-phase sampling procedure for continuous forest inventory with partial remeasurement and updating of terrestrial sample plots. European *Journal of Forest Research 2012*; 131(6): 1979 – 1990.

Von Lüpke N, Saborowski J. Combining double sampling for stratification and cluster sampling to a three-level sampling design for continuous forest inventories. E*uropean Journal of Forest Research 2014*; 133(1): 89 – 100.

Vries PGDe. *Sampling theory for forest inventory*. Cambridge: Cambridge University Press; 1986.

Ware KD, Cunia T. Continuous forest inventory with pamal replacement of samples. *Forest Science*. Monograph 3; 1962.