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Sampling system for estimating woody debris in an urban mixed tropical forest

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ABSTRACT

Woody debris, defined as standing and downed deadwood, consists in an essential component of the forest carbon stock. However, few studies have been carried out to get an efficient and accurate sampling procedure for estimating it. This work proposes two methodologies to estimate the woody debris volume in a Brazilian mixed tropical forest: 1) two-stage systematic sampling, using a mixed methodology, in which the Strand's method is applied to standing dead trees and stumps, and line intercept sampling is used to fallen trees and branches; and 2) ratio estimate of the sum of cross-sectional areas of deadwood pieces and forest basal area, aiming to obtain the total woody debris volume indirectly in the natural forest. Conversions for biomass and carbon stocks were made applying the mean basic density on the estimates of deadwood volumes. Both methodologies are accurate for woody debris volume estimates, with a sampling error equal to 16.1% (methodology 1) and 5.7% (methodology 2), at a 95% probability level. Thus, the methodology 2 has potential to be used in strategic forest inventories of woody debris, such as in National Forest Inventories, due to increasing importance of its quantification in all forest ecosystems.

Key words: Line intercept sampling, ratio estimate, systematic sampling, Strand's method.

INTRODUCTION

Until recently, forest inventories have been concentrated for sampling the live woody stratum, where the aim is often the commercial volume. After the United Nations' invitations to discuss the climate change, mitigation measures were raised, in which forests are described as important agents for neutralizing greenhouse gases, and new studies are required for modeling the equivalent CO_2 in different forest typologies. On the other hand, the National Forest Inventory is expanding in Brazil, as a result of numerous experiences acquired by Brazilian researchers over the last 20 years (Brena 1996, Scolforo et al. 2006, Vibrans et al. 2012), when it was proposed to estimate woody debris as part of the carbon neutralization.

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Woody debris is understood as the downed and dead woody biomass present in forest ecosystems (Woodall et al. 2008), being an important component of forest diversity (Fridman and Walheim 2000), and an essential indicator of sustainable forest management (Castagneri et al. 2010). In forest inventories, woody debris estimates are still restricted to the dead trees in the sampling units, however, the survey can be extended to fallen trees, branches, and other woody pieces on the ground (Nordén et al. 2004, Woldendorp et al. 2004).

Quantifying woody debris is required for forest fire research (van Wagner 1968, Donato et al. 2016), making it an important resource for evaluation and control of the deadwood in the forest (Montes and Cañellas 2006). In addition, the woody debris inventory enables to estimate its potential use for fuel purpose (Waddell 2002), as well as ecological aspects (Clark et al. 2002), wildlife habitat assessment (Haughian and Frego 2017), carbon stock (Eaton and Lawrence 2006), and nutrient dynamics (Song et al. 2017).

These pioneering experiences in forestry were also important for introducing the line intercept sampling (LIS) method, aiming to evaluate downed trees and branches on the ground, whose design was first showed by Georges-Louis Leclerc, Count of Buffon, in 1770, namely the Buffon's needle problem. Leclerc launched needles over a sheet of paper with lines and developed the probability of each needle to cross the lines (de Vries 1974). Nonetheless, considering that only 13% of the countries carry out woody debris inventories (Woodall et al. 2009), the sampling system does not converge to a common sense, although LIS was the most appropriate method for quantifying woody debris in some forest surveys (Waddell 2002, Densmore et al. 2004, Woldendorp et al. 2004, Herrero et al. 2016).

Therefore, statistical procedures are necessary to estimate woody debris stocks using variables commonly measured in forest inventories. Thus, this work proposes two methodologies to estimate the woody debris volume in an urban Brazilian mixed tropical forest, specifying the conditions for application in native forest inventories. For this purpose, the following hypotheses are proposed: 1) woody debris is randomly distributed on the forest; and 2) woody debris can be estimated by the basal area of the live trees.

MATERIALS AND METHODS

STUDY AREA

Data were collected in 9.5 hectares of an urban mixed tropical forest located in an urban area of Curitiba, Brazil, between the coordinates 25°26'50" S and 25°27'33" S, and 49°14'16" W and 49°14'33" W, characterized as a secondary forest, previously under anthropic action, composed of a high frequency of pioneer species. The region's climate is classified as temperate oceanic (Cfb - Köppen), with cold summer and without dry season, and mean annual temperature and rainfall are 17°C and 1,400 mm, respectively. The forest remnant is located between 890 m and 915 m above sea level, in Podzolic and Hydromorphic soils.

CONCEPTION OF THE SAMPLING SYSTEM WITH CLUSTERS

The sampling variance from a systematic sample is highly dependent on the distribution of the units in the population and is possible to be efficient when units arranged together are as homogeneous as possible. Therefore, we decided to draw in each block area of 2,500 m^2 (50m x 50 m), four random starts and then combine them in clusters to approximate this structure as much as possible to an unbiased estimate of the sampling error.

Such conception resulted in a systematic structure with 40 clusters integrated by four lines (15.71 m) as subunits of the clusters, distributed in a Maltese Cross design on the second stage

(Figure 1). In such structure we have *k* blocks, all sampled, which corresponds to *k* clusters, and each cluster with *M* subunits, and, consequently, the total number of subunits in the population is *N*, such that *N = kM*.

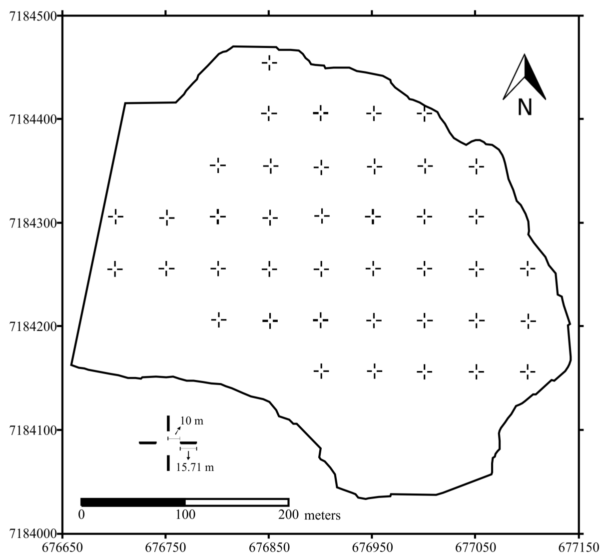

Figure 1 - Systematic clusters allocated in an urban mixed tropical forest.

A conception to obtain the sampling error in systematic sampling is presented in Chacko (1965) and nominated as the Method of First Differences (MFD). In such a proposal, in any one-dimensional systematic sampling, an approximation to the standard error may be obtained from the differences between pairs of successive units. As we have *N* units enumerated in the systematic sample, there will be (*N-1*) differences. The variance per unit is, therefore, given by the sum of squares of the differences divided by twice the number of differences. The variance per unit is obtained by (1):

$$S_s^2 \simeq \frac{\sum_{i=1}^{N} \left[X_i - X_{(i+1)}\right]^2}{2\,(N-1)} \qquad (1)$$

The estimate of the variance of $\bar{X}$ is given by (2):

$$S_{\bar{X}\,s}^2 \simeq \frac{\sum_{i=1}^{N} \left[X_i - X_{(i+1)}\right]^2}{2N\,(N-1)} \qquad (2)$$

As the sampling structure proposed in this work included an additional stage organized in clusters, then the estimates (1) and (2) should be adapted for two-stage systematic sampling. In the specific case of the proposed cluster, the pair-wise plots can be formed such that the last plot can also make a pair with the first plot of the cluster, because they are positioned in an equivalent condition of the other pairs. The differences between pairs of successive units are then calculated per cluster and added for the *k* clusters for the entire sampling. The variance per unit is obtained by (3):

$$S_c^2 \simeq \frac{\sum_{j=1}^{k}\sum_{i=1}^{M} \left[X_{ji} - X_{j(i+1)}\right]^2}{2kM} = \frac{\sum_{j=1}^{k}\sum_{i=1}^{M} \left[X_{ji} - X_{j(i+1)}\right]^2}{2N} \qquad (3)$$

The estimate of the variance of $\bar{X}$ is given by (4):

$$S_{\bar{X}_c}^2 \simeq \frac{\sum_{j=1}^{k}\sum_{i=1}^{M} \left[X_{ji} - X_{j(i+1)}\right]^2}{N(2N)}$$

or

$$S_{\bar{X}_c}^2 \simeq \frac{\sum_{j=1}^{k}\sum_{i=1}^{M} \left[X_{ji} - X_{j(i+1)}\right]^2}{2N^2} \qquad (4)$$

The standard error of the estimate (5), absolute sampling errors (6), and relative sampling errors (7) are obtained by:

$$S_{\bar{X}_c} \simeq \sqrt{\frac{\sum_{j=1}^{k}\sum_{i=1}^{M} \left[X_{ji} - X_{(i+1)j}\right]^2}{2N^2}} \qquad (5)$$

$$E_{as} \simeq \pm t S_{\bar{X}_s}$$

or

$$E_{ac} = \pm t S_{\bar{X}_c} \qquad (6)$$

$$E_{rs} \pm \left(\frac{E_{as}}{\acute{X}}\right) 100$$

or

$$E_{rc} \pm \left(\frac{E_{ac}}{\acute{X}}\right) 100 \quad (7)$$

where: k = number of clusters; M = subunits in the cluster; N = total number of subunits in the k clusters; $S^{2s}_{\bar{X}}$ = variance of the mean for conventional systematic sampling and $S^{2c}_{\bar{X}}$ = variances of the mean for systematic sampling with clusters; t = value of the t distribution for 95% probability; $S_{\bar{X}_s}$ and $S_{\bar{X}_c}$ = standard errors.

LINE INTERCEPT SAMPLING

The line intercept sampling (LIS) method was used for sampling woody debris pieces on the ground, and the Strand's method (Strand 1958) was applied to standing dead trees and stumps. It was used the systematic procedure in two-stages, where 40 sampling units were allocated on the first stage, while four subunits in lines (15.71 m) were distributed in Maltese Cross design (cluster) on the second stage. In addition, square-shaped sampling units (50 m x 50 m) were allocated to the central position of the clusters, aiming to measure the live trees with diameters (at 1.3 m height) equal to or greater than 10 cm. This procedure made it possible to quantity the forest basal area per hectare in the clusters' geographical spaces.

Length and diameter of deadwood pieces with central diameter greater than 3 cm were measured and classified in four groups: 1) fallen branches, 2) standing dead trees, 3) stumps, and 4) fallen trees. Strand's method was used for the second and third groups, while LIS method was applied to the first and fourth groups. The Strand's method was based on the probability proportional to height of standing dead trees and stumps, where they were selected on the left side of the sampling lines (15.71 m) in the clusters, whose distance was equal to or less than half of their heights. The volume (8) was calculated through Strand's estimator (Strand 1958), while the number of pieces (9) was obtained according to Péllico Netto and Brena (1996):

$$V = f\frac{1}{10}\sum_{i=1}^{m} d_i^2 \quad (8)$$

$$N_1 = \frac{20.000}{L}\sum_{i=1}^{m}\frac{1}{l_i} \quad (9)$$

where: V = volume (m^3 ha^{-1}), f = form factor for standing dead trees (0.7), m = number of standing dead trees or stumps, d_i = central diameter of dead standing trees or stumps (cm), N_1 = number of pieces per hectare, L = length of sampling line (15.71 m), and l_i = length of a piece crossing the line (m).

On the other hand, the LIS is a probability sampling method in which a transect of fixed length is used (de Vries 1974). We use a modification proposed by van Wagner (1968) for estimating the volume (10), including the diameter of sampled pieces that reach the sampling line, except those that overlap it completely in the longitudinal direction.

$$V = \frac{\pi^2}{8L}\sum_{i=1}^{m} d_i^2 \quad (10)$$

where: V = volume (m^3 ha^{-1}), d_i = central diameter of fallen trees and branches intercepted by the sampling line (cm), and L = length of the sampling line (15.71 m).

The number of fallen trees and branches per hectare was obtained through the estimator proposed by van Wagner (1968), although he considered an average size of pieces in the subunits. This estimator has been modified in this study, in which the lengths of the sampled pieces were considered as a random event along the sampling lines, as already applied in the similar derivation proposed by Péllico Netto and Brena (1996) to obtain the number of live trees in the Strand's method (Strand 1958).

According to de Vries (1974), the probability of fallen trees or branches (I) intercepting a line with size L is the probability of these falling inside a rectangular sampling unit with TL size. Thus, defining this conditional probability as p_i, we have:

p_i = P(I fell in TL) P(intersection of I with L I fell in TL) = $\frac{TL}{A}\frac{2l_i}{Tp} = \frac{2Ll_i}{Ap}$

Therefore, the inverse of this probability provides the number of fallen trees or branches per hectare (11):

$$p_i^{-1} = \frac{\pi A}{2Ll_i} \quad (11)$$

Considering a sample with m fallen pieces, the number of fallen trees or branches sampled in one hectare (A) is (12):

$$\sum_{i=1}^{m} p_i^{-1} = \frac{\pi A}{2L}\sum_{i=1}^{m}\frac{1}{l_i} = \frac{\pi 10.000}{2L}\sum_{i=1}^{m}\frac{1}{l_i} = \frac{\pi 5.000}{L}\sum_{i=1}^{m}\frac{1}{l_i} \quad (12)$$

Consequently (13):

$$N_1 = \frac{\pi 5.000}{L}\sum_{i=1}^{m}\frac{1}{l_i} \quad (13)$$

where: N_1 = number of fallen trees or branches per hectare, L = length of the sampling line (15.71 m), m = number of fallen trees or branches that crossed the line, and l_i = length of each piece (m).

TOTAL WOODY DEBRIS CROSS-SECTIONAL AREAS AND AVERAGE LENGTH ESTIMATORS PER HECTARE

The sum of woody debris cross-sectional areas per hectare (S) was conceived as an estimator to obtain a similar measure to the forest basal area (G). Thus, for the pieces of dead standing trees and stumps, the Strand's method provided the required estimates (14):

$$S = \frac{1}{10}\sum_{i=1}^{m} d_i \quad (14)$$

where: S = sum of woody debris cross-sectional areas (m^2 ha^{-1}), m = number of standing dead trees or stumps, and d_i = central diameter of standing dead trees or stumps (cm).

For fallen trees and branches that intercepted the sampling line (L), it was necessary to develop the estimator of the sum of woody debris cross-sectional areas, since it had not yet been required by the researchers involved with this sampling theme. Thus, taking the probability of the number of pieces per hectare for each group, it was possible to derive the estimator for S (15). Applying the Bernoulli's probability distribution, in which X_i is the dichotomous variable that indicates the tree inclusion (X_i = 1) or non-inclusion (X_i = 0) in the sampling unit, the mathematical expectation for the sum of woody debris cross-sectional areas per hectare, where Si is the cross-sectional area taken in the middle of each piece sampled, is given by:

$$E\left(\sum_{i=1}^{M_2} S_i\right) = \sum_{i=1}^{M_{2-m}}\left[S_i(X_i = 0)p_i^{-1}\right] + \sum_{i=1}^{m}\left[S_i(X_i = 1)p_i^{-1}\right]$$
$$= S = \sum_{i=1}^{m} S_i\frac{\pi A}{2Ll_i} = \sum_{i=1}^{m}\frac{\pi}{4}d_i^2\frac{\pi 10.000}{2Ll_i}$$

$$S = \frac{\pi^2 10.000}{8L(100)^2}\sum_{i=1}^{m}\frac{d_i^2}{l_i} = \frac{\pi^2}{8L}\sum_{i=1}^{m}\frac{d_i^2}{l_i} \quad (15)$$

Consequently (16):

$$S = \frac{\pi^2}{8L}\sum_{i=1}^{m}\frac{d_i^2}{l_i} \quad (16)$$

where: M_2 = number of fallen trees and branches per hectare, S = sum of woody debris cross-sectional areas (m^2 ha^{-1}), L = length of the sampling line (15.71 m), m = number of fallen trees and branches that intercept the line in the subunit, d_i = central diameter of fallen trees and branches (cm), and l_i = length of each piece (m).

In addition, an estimator of the average length of pieces ($\bar{l}$) was needed to obtain the volume per subunit. Likewise, the mathematical expectation for $\bar{l}$ (17) can be obtained as done for S, applying the Bernoulli's probability distribution, in which X_i is the dichotomous variable that indicates the tree inclusion (X_i = 1) or non-inclusion (X_i = 0) in the sampling unit:

$$E\left(\sum_{i=1}^{M_2} l_i\right) = \sum_{i=1}^{M_{2-m}} \left[l_i (X_i = 0) p_i^{-1}\right] + \sum_{i=1}^{m} \left[l_i (X_i = 1) p_i^{-1}\right] = \sum_{i=1}^{m} l_i p_i^{-1} = \sum_{i=1}^{m} l_i \frac{\pi 10.000}{2L} = \frac{\pi 10.000}{2L} \sum_{i=1}^{m} \frac{l_i}{l_i} \quad (17)$$

Therefore, the estimator of the total sum of lengths *C* is given by (18):

$$C = \frac{\pi 10.000m}{2L} = \frac{\pi 5.000m}{L} \quad (18)$$

Dividing *C* by the total number of pieces sampled per subunits, as specified in (16), we can get $\bar{l}$ (19):

$$\bar{l} = \frac{\frac{\pi 5.000m}{L}}{\frac{\pi 5.000}{L} \sum_{i=1}^{m} \frac{1}{l_i}} = \frac{m}{\sum_{i=1}^{m} \frac{1}{l_i}} \quad (19)$$

Consequently (20):

$$\bar{l} = \frac{m}{\sum_{i=1}^{m} \frac{1}{l_i}} \quad (20)$$

where: $\bar{l}$ = average length of woody debris (m), *m* = number of pieces by woody debris groups per subunits, and l_i = length of each piece (m).

WOODY DEBRIS SPATIAL ANALYSIS

The geostatistical analysis (Webster and Oliver 2007) was used to model the spatial patterns of the sum of woody debris cross-sectional areas and the forest basal area. Semivariances (21) were calculated considering the geographical position of the sampling units, the distances between them (*h*) and the numerical differences of each variable (*Z*) on the grid.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_i + h)\right]^2 \quad (21)$$

where: $\gamma(h)$ = semivariance of the variable $Z(x_i)$, h = distance (m), and $N(h)$ = number of measured point pairs $Z(x_i)$ and $Z(x_i + h)$ separated by a distance h.

CONCEPTION OF THE RATIO ESTIMATE

Linear relationship between the sum of woody debris cross-sectional areas per hectare and basal area of live trees was examined through linear correlation coefficients and frequency distributions. For this, the uniform continuous function, peculiar to these variables in the study area, was described by the rectangular distribution (22). The first (μ) and second (ς^2) statistical moments were determined by equations (23) and (24), respectively:

$$f(x) = \begin{cases} \left(\frac{1}{b-a}\right) \wedge a \leq x \leq b \\ 0, \wedge x < a \vee x > b \end{cases} \quad (22)$$

$$\mu = \frac{a+b}{2} \quad (23)$$

$$\sigma^2 = \frac{1}{12}(b-a)^2 \quad (24)$$

where: $f(x)$ = probability density function, μ = population mean, ς^2 = variance; a = lower limit of the variable x, and b = upper limit of the variable x.

In the specific case of the woody debris estimates, considering that these experimental evaluations presented a rectangular distribution, then the parameter a is the minimum woody debris estimate and b is its maximum.

This estimator is usually biased, since the numerator ($\bar{y}$) and the denominator ($\bar{x}$) of the ratio vary between sampling units (25), in which $\hat{R}$ often presents an asymmetric distribution. If a more intense sample is obtained, their distributions will tend to normality and, in this case, this tendency becomes very small and negligible (Cochran 1963).

$$\hat{R} = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i} = \frac{\bar{y}}{\bar{x}} \quad (25)$$

where: $\hat{R}$ = ratio estimate, $\bar{y}$ = sum of woody debris cross-sectional areas (m^2 ha^{-1}), and $\bar{x}$ = mean forest basal area (m^2 ha^{-1}).

The variance of the estimator can be obtained by (26):

$$S_{\hat{R}}^2 \simeq \frac{1-f}{n_2\bar{X}^2}\frac{\sum i=1^{N_2}\left(y_{ij}-R_jx_{ij}\right)^2}{N_2-1} \simeq \frac{1-f}{n_2\bar{X}^2}S_R^2 \quad (26)$$

where: f = sample proportion given by $f = n_2 . N_2^{-1}$, S_R^2 = variance of the quadratic deviations obtained with the ratio estimate, and index two (2) of total number of pieces and sample size = methodology 2.

Considering that the sum of woody debris cross-sectional areas per hectare can be estimated by $\bar{\hat{Y}} = \bar{X}\hat{R}$, its respective variance can be calculated in (27):

$$S_{\bar{\hat{Y}}}^2 \simeq \frac{1-f}{n_2}\frac{\sum i=1^{N_2}\left(y_{ij}-R_jx_{ij}\right)^2}{N_2-1} \quad (27)$$

According to Cochran (1963), considering the biased estimator ($1.n^{-1}$) and the variance of the quadratic deviations (S_R^2) defined in (25), s_R^2 can be estimated by (28). Therefore, we can obtain the variance of the mean (29) through the sum of woody debris cross-sectional areas (S).

$$s_R^2 = \frac{\sum_{i=1}^{n_2}\left(y_{ij}-R_jx_{ij}\right)^2}{n_2-1} \quad (28)$$

$$s_{\bar{\hat{Y}}}^2 = \frac{(1-nf)}{n(n-1)}\sum_{i=1} n\left(y_{ij}-R_jx_{ij}\right)^2 = \frac{(1-nf)}{n(n-1)}s_R^2 \quad (29)$$

The estimates of the standard errors of the ratio and the mean volume of deadwood pieces can be obtained by (30) and (31), according to Cochran (1963):

$$s_{\hat{R}} = \frac{\sqrt{1-f}}{\sqrt{n(n-1)}\bar{X}}\sum_{i=1}^{n}\left(y_{ij}-\hat{R}_jx_{ij}\right)^2 \quad (30)$$

$$s_{\bar{\hat{Y}}} = \sqrt{\frac{(1-nf)}{n(n-1)}\sum_{i=1}^{n}\left(y_{ij}-\hat{R}_jx_{ij}\right)^2} \quad (31)$$

As the population mean for the ratio is unknown, it can be replaced by its estimate $\bar{x}$ in (26) and (30), while the standard error is obtained with the extended and simplified sum of squares, using the operational formula presented in (32) and (33):

$$s_{\hat{R}} = \frac{\sqrt{1-f}}{\sqrt{n(n-1)}\bar{x}}\sqrt{\sum_{i=1}^{n}y_{ij}^{\;2} - 2\hat{R}_j\sum_{i=1}^{n}y_{ij}x_{ij} + \hat{R}_j^2\sum_{i=1}^{n}x_{ij}^2} \quad (32)$$

$$s_{\bar{\hat{Y}}} = \sqrt{\frac{(1-nf)}{n(n-1)}}\sqrt{\sum_{i=1}^{n}y_{ij}^2 - 2\hat{R}_j\sum_{i=1}^{n}y_{ij}x_{ij} + \hat{R}_j^2\sum_{i=1}^{n}x_{ij}^2} \quad (33)$$

If the distributions of sum of woody debris cross-sectional areas and forest basal area are normal or almost normal, the confidence intervals can be obtained in (34) for ratio of the areas and (35) for average of the areas:

$$R = \hat{R} \pm t\sqrt{s_{\hat{R}}^2} \quad (34)$$

$$\bar{Y} = \bar{\hat{Y}} \pm t\sqrt{s_{\bar{\hat{Y}}}^2} \quad (35)$$

The details of the respective estimates will be obtained in (36) for ratio of the areas and (37) for average of the areas:

$$E_{\hat{R}} = \frac{ts_{\hat{R}}}{\hat{R}}100 \quad (36)$$

$$E_{\bar{\hat{Y}}} = \frac{ts_{\bar{\hat{Y}}}}{\bar{\hat{Y}}}100 \quad (37)$$

Note that the variances of the estimates, considering $\bar{\hat{Y}} = \bar{\hat{X}}\hat{R}$, result in equal values, i.e., the relative precisions become equal to (38) and (39):

$$\frac{s_{\hat{R}}^2}{\hat{R}^2} \simeq \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}s_R^2 = E_R^2 \quad (38)$$

$$\frac{s_{\bar{\hat{Y}}}^2}{\bar{\hat{Y}}^2} \simeq \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}s_R^2 = E_{\bar{Y}}^2 \quad (39)$$

As $E_{\hat{R}}^2$ and $E_{\hat{Y}}^2$ result in equal values of relative variance, Hansen et al. (1951) propose changes to make it more generic $(cv)^2$, as shown in (40).

$$(cv)^2 = \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}\frac{\sum_{i=1}^{n}\left(y_i-\hat{R}x_i\right)^2}{n-1}$$

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}\frac{\sum_{i=1}^{n}\left(y_i-\bar{\hat{Y}}-\hat{R}x_i+\bar{\hat{Y}}\right)^2}{n-1} \qquad (40)$$

As $\bar{\hat{Y}} = \hat{R}_j\bar{\hat{X}}$, we can replace it in the above equation, resulting in (41):

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}\frac{\sum_{i=1}^{n}\left(y_i-\bar{\hat{Y}}-\hat{R}x_i+\hat{R}\bar{\hat{X}}\right)^2}{n-1}$$

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}\frac{\sum_{i=1}^{n}\left[\left(y_i-\bar{\hat{Y}}\right)-\hat{R}\left(x_i-\bar{\hat{X}}\right)\right]^2}{n-1}$$

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}$$

$$\frac{\sum_{i=1}^{n}\left[\left(y_i-\bar{\hat{Y}}\right)^2+\hat{R}^2\left(x_i-\bar{\hat{X}}\right)^2-2\hat{R}\left(y_i-\bar{\hat{Y}}\right)\left(x_i-\bar{\hat{X}}\right)\right]^2}{n-1}$$

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}$$

$$\frac{\left[\sum_{i=1}^{n}\left(y_i-\bar{\hat{Y}}\right)^2+\hat{R}^2\sum_{i=1}^{n}\left(x_i-\bar{\hat{X}}\right)^2-2\hat{R}\sum_{i=1}^{n}\left(y_i-\bar{\hat{Y}}\right)\left(x_i-\bar{\hat{X}}\right)\right]}{n-1}$$

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}\left[s_y^2+\hat{R}^2s_x^2-2\hat{R}\hat{\rho}s_xs_y\right]$$

$$= \frac{1-f}{n\bar{\hat{X}}^2\hat{R}^2}\left[s_y^2+\hat{R}^2s_x^2-2\hat{R}s_{xy}\right]$$

$$= \frac{1-f}{n}\left[\frac{s_y^2}{\bar{\hat{X}}^2\hat{R}^2}+\frac{\hat{R}^2s_x^2}{\bar{\hat{X}}^2\hat{R}^2}-2\frac{\hat{R}s_{xy}}{\bar{\hat{X}}^2\hat{R}^2}\right]$$

$$= \frac{1-f}{n}\left[\frac{s_y^2}{\bar{\hat{X}}^2\hat{R}^2}+\frac{s_x^2}{\bar{\hat{X}}^2}-2\frac{s_{xy}}{\bar{\hat{X}}^2\hat{R}}\right]$$

$$(cv)^2 = \frac{1-f}{n}\left[\frac{s_y^2}{\bar{\hat{Y}}^2}+\frac{s_x^2}{\bar{\hat{X}}^2}-2\frac{s_{xy}}{\bar{\hat{X}}\bar{\hat{Y}}}\right] = \frac{1-f}{n}\left(cv_y^2+cv_x^2-2cv_{xy}\right) \qquad (41)$$

WOODY DEBRIS VOLUME ESTIMATION

The ratio estimate ($\hat{R}$) was multiplied by the forest basal area (G) for obtaining the sum of woody debris cross-sectional areas (S) in each cluster. Subsequently, S was multiplied by the average length of pieces ($\bar{l}$) to estimate the wood debris volume per hectare (m^3ha^{-1}). Moreover, indices were applied to obtain the biomass (0.58) and carbon (0.48) stocks of deadwood (Cardoso et al. 2012).

RESULTS

In the mixed tropical forest remnant, 469 branches (82%) were sampled on the ground, followed by 57 dead standing trees (10%), 18 stumps (3%), and 28 fallen trees (5%), evidencing that the dead trees on the forest demand long time and require the acting of biotic and abiotic factors to decompose the wood. Thus, a total of 572 pieces were sampled, whose diameter distribution showed a negative exponential behavior (Figure 2), in which the woody debris was most abundant in the lowest diameter classes.

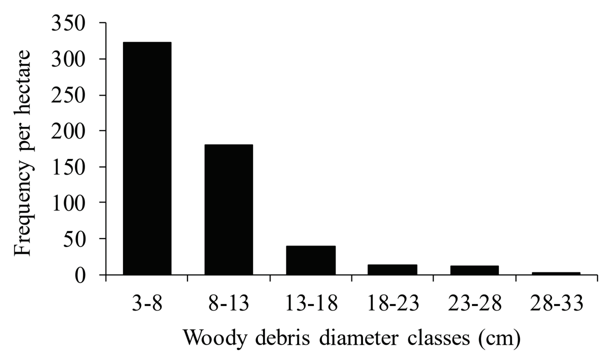

Figure 2 - Woody debris frequency by diameter classes in an urban mixed tropical forest.

The woody debris inventory has resulted in mean volumes equal to 9.24 m^3 ha^{-1} for branches, 10.99 m^3 ha^{-1} for dead standing trees, 25.19 m^3 ha^{-1} for stumps, and 17.87 m^3 ha^{-1} for fallen trees. In addition, we obtained a standard error ($s_{\bar{x}}$) of 1.32 m^3 ha^{-1}, and sampling absolute error (E_a) and relative error (E_r) equal to 2.66 m^3 ha^{-1} and 16.1%, respectively, by the Method of First Differences. These values were considered low, since the woody debris volume in the sample resulted from the survey of pieces with significant dimensional variation, where this variability requires high sampling intensity to achieve accurate estimates. Thus, the confidence interval (*CI*) for the mean woody debris volume ($\bar{X}$) resulted in:

$$CI\ [13.92\ m^3\ ha^{-1} \leq \bar{X} \leq 19.24\ m^3\ ha^{-1}] = 95\%.$$

It was observed the presence of pure nugget effect through the semivariograms fitted for the sum of woody debris cross-sectional areas (Figure 3a) and forest basal area (Figure 3b), confirming the first hypothesis of this study. These results indicated the absence of spatial correlation between the sampling units, which also showed the high complexity of woody debris spatial patterns to establish linear relationship with variables in natural forests. This was confirmed by the low linear correlation coefficient, equal to 0.08 between woody debris cross-sectional areas and forest basal area, noticeable close to zero.

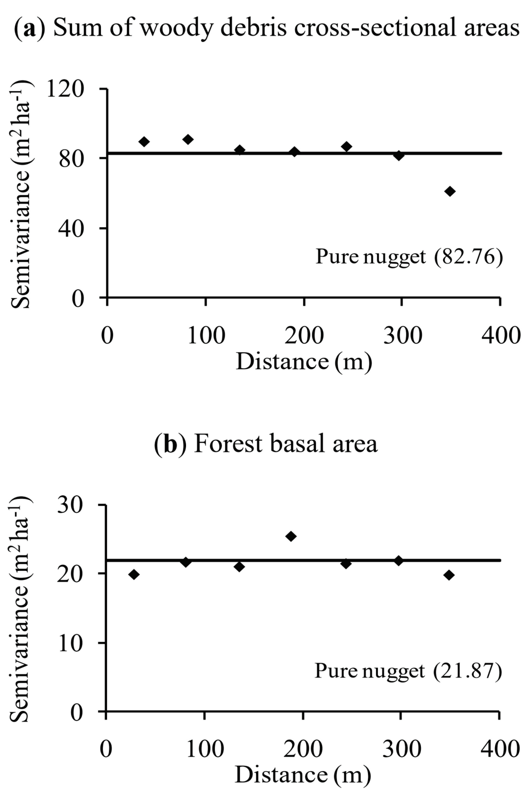

Figure 3 - Semivariograms fitted to the sum of woody debris cross-sectional areas (**a**) and forest basal area (**b**) in an urban mixed tropical forest.

In addition, the frequencies of woody debris cross-sectional areas (Figure 4a) and forest basal area (Figure 4b) have been identified as rectangular distribution. The appropriate probability distribution is the rectangular, where the coefficients *a* and *b* represent the minimum and maximum values, respectively. Thus, consistent estimates were obtained for the mean ($\bar{x}$) and standard deviation (ς), while the ratio between variables was constant.

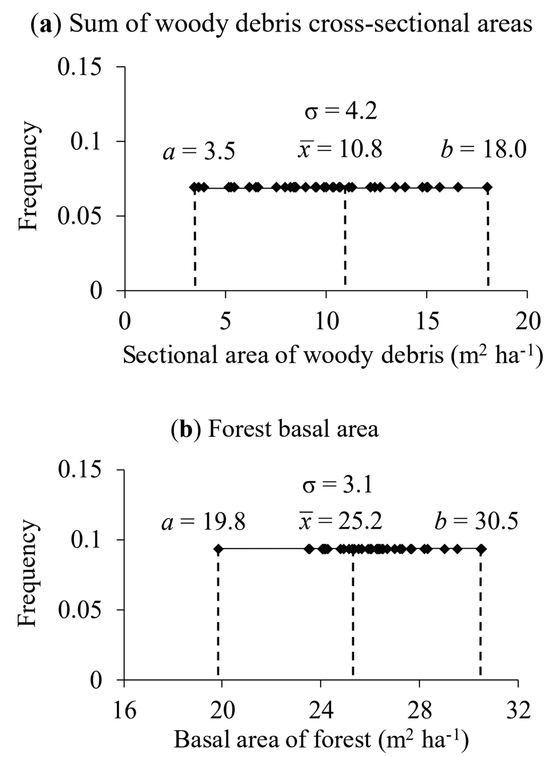

Figure 4 - Continuous rectangular distributions of the sum of woody debris cross-sectional areas (**a**) and forest basal area (**b**) in an urban mixed tropical forest.

This ratio estimate expressed the relationship between the woody debris spatial distribution and its stock on the forest, with sampling relative error (E_r) equal to 5.7% and confidence interval (*CI*) for the mean woody debris cross-sectional areas ($\bar{X}$) of $CI\ [9.43\ m^2\ ha^{-1} \leq \bar{X} \leq 10.69\ m^2\ ha^{-1}] = 95\%$. In addition, a slight tendency in the residuals was observed (Figure 5), in which was considered negligible (Cochran 1963) and statistically consistent, confirming the second hypothesis proposed in this study.

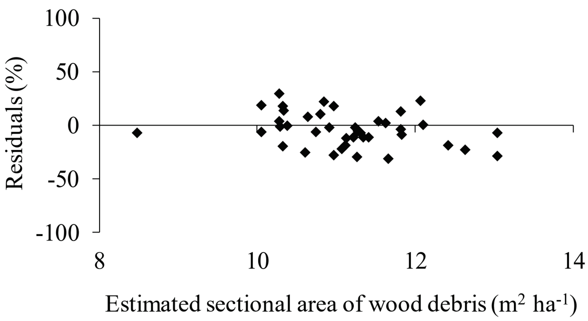

Figure 5 - Residuals of the sum of woody debris cross-sectional areas obtained by ratio estimate in an urban mixed tropical forest.

Subsequently, by multiplying the sum of woody debris cross-sectional area (*S*) of each cluster by the average length of pieces (Í) equal to 1.96 m, it was possible to estimate the confidence interval of the mean total woody debris estimated volume:

CI [18.49 m^3 ha^{-1} $\leq \bar{X} \leq$ 20.95 m^3 ha^{-1}] = 95%.

In addition, the confidence intervals for biomass and carbon stocks, after applied the respective indices, resulted in:
CI [10.72 Mg ha^{-1} $\leq \bar{X} \leq$ 12.15 Mg ha^{-1}] = 95% for biomass, and
CI [5.09 Mg ha^{-1} $\leq \bar{X} \leq$ 5.77 Mg ha^{-1}] = 95% for carbon.

DISCUSSION

The assessments of deadwood biomass are often concentrated in the litter component in mixed tropical forests (Schumacher et al. 2004, Backes et al. 2005, Watzlawick et al. 2012), since these studies are restricted to survey fine woody debris, such as leaves, flowers and seeds, in different methods that make it difficult to establish a comparison between studies and forest types. Notwithstanding, considering the quantification of branches for forest fire management (Waddell 2002, Donato et al. 2016) and the commercial use of coarse woody debris (Riffel et al. 2011), especially standing dead trees and fallen trees for fuel purpose, the sampling errors of 10% to 15% are most appropriate and, for this reason, further investigations should be carried out.

In an inventory of mixed tropical forest remnants in southern Brazil, Cardoso et al. (2012) have identified a woody debris carbon stock (5.80 Mg ha^{-1}) higher than that observed in this study (5.60 Mg ha^{-1}), due to the incorporation of other downed dead materials in different stages of decomposition. Also, these authors estimated carbon contents equal to 3.90 Mg ha^{-1} for deciduous forest and 4.40 Mg ha^{-1} for dense tropical forest, showing that the forest typologies contribute for different rates of deadwood biomass accumulation.

Despite the strong influence of tree mortality on the deadwood accumulation process (Castagneri et al. 2010), the climate, soil and topography conditions also affect the woody debris decomposition (Clark et al. 2002, Herrero et al. 2010). However, the difficulty for applying common methods to estimate the woody debris volume through the basal area of live trees, such as regression analysis, was also observed by Nordén et al. (2004) in temperate forests in southern Sweden. These authors identified that the forest basal area is also affected by the tree age, management activity, ecological succession and forest density, which makes it complex to establish its influence on the dynamics of woody debris stock on the forest.

On the other hand, the human activities in secondary forests, especially the harvesting of large trees that represent important sources of dead biomass in the ecosystems (Siitonen et al. 2000, Castagneri et al. 2010), affect the woody debris volume through changes on the forest structure, diversity and floristic composition, intraspecific competition, and tree mortality (Siitonen et al. 2000, Rouvinen et al. 2002, Debeljak 2006, Yan et al. 2007). Thus, the Strand and LIS sampling methods and the ratio estimate statistical tool proposed in this study are consistent to estimate the dynamics of the woody debris stock, aiming to prescribe conservation and management practices in natural forests.

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