The use of Natural Fallen Trees in Mature Tropical Amazonian Forest for Volumetric Regression Analysis and Volume Equations Adjustment

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The timber industry of the Amazon region faces several challenges. The lack of site-specific volume equations, for individual and stand volume stock estimation, is one of these challenges. Up to recent days, forest management plans in the Brazilian Rainforest are based on outdated volume equations, adjusted for a specific region. The cost effectiveness between the traditional regression analysis for volumetric studies and timber market values, associated to the bureaucracy needed for felling trees in the region, doesn’t create a friendly environment for forest managers in Amazonia.

Objective: Therefore, the main objective of this research is to present the sampling of natural fallen trees, as an alternative for the traditional method, for volume determination and volume equation adjustment, in mature upland Amazonian forests.

Results: The field survey conducted did not have a sampling area, considering every fallen tree as a single sample. Although some difficulties were identified, such as sampling small individuals, the method itself enabled a sample size large enough to compose two data sets, one for the regression analysis and the other for adjusted equations validation. Five volumetric models, available in classic forestry literature, were selected for the regression analysis. There was no distinction between botanical species due to scale constraints, where the number of individuals per species was very small. The regression statistics of representativeness (r square and precision (Mean Square Error – MSE; Standard Error of Estimate – SEE; Relative SEE – Syx%); and graphic of residual distribution) were estimated of each adjusted equation and compared with other volumetric studies in the literature in similar forests and even-aged forests. After adjusting the models, the statistics of the regression analysis, as well as the validation (R square, MSE, SEE, Syx% and the graphic of residual distribution) of all adjusted models showed robust and consistent results. Conclusion: Based on the results of this study, field procedures of sampling natural fallen trees still needs some improvement, but it fulfilled its objectives. Low costs involved, no bureaucracy and results as good as in any other circumstance, such as in planted forests. Now, there is no convenient excuse for not considering a site-specific volume equation for forest management plans in Brazilian Amazon forests.

INTRODUCTION

Precise estimation of the potential timber stock of a tropical mature Amazonian forest is indispensable for adequate and rational use the forest’s products (Barros and Silva Jr., 2009). According to Brazilian federal laws, any intent of using or exploiting forest’s products must be accompanied by a technical and scientific project, such as a Sustainable Forest Management Plan (SFMP). Especially for timber production, of which depends on specific and reliable information, with low uncertainty level. This makes the forestry sector continuously search for efficient methods of timber stock estimation (Thaines et al. 2010).

On the other hand, to estimate individual timber stock in Amazonian forests it is not a trivial job. Especially because of the shortage of site-specific volume equations available in the literature (Higuchi and Ramm, 1985; Rolim et al. 2006). Even when these equations are available, too often the independent variables of the equation are not compatible with the collected data in the forest inventory (Higuchi, 1992). Hence, it is most common
that forest managers have to depend on outdated and inappropriate data and volume equations (Higuchi and Ramm, 1985).

In the most recent complete forest management plan, available for consultation, based its production projections on outdated data and inadequate volume equations. According to the SFMP, proposed in 2008 by a logging company during the concession bidding step of a National Forest in Rondônia, Brazil, their estimates were calculated considering data from 1983 and the volume equation from Heinsdijk and Bastos (1963).

Ideally, for every region or site in a given country or state, should have a specific volume equation. Yet, given the traditional methods described in classic forestry literature (Husch et al. 1971; Loetsch et al. 1973), foresters usually tend to fell trees in order to determine the bole volume of a given number of individuals in order to perform a regression analysis and adjust a site-specific volume equation. In this case, due to the geographical characteristics of the Amazon region, the bureaucracy involved (license to cut down trees) and operation costs, forest managers tend to rely on literature equations.

Therefore, in this study, we present a method for volume determination and volumetric regression analysis in mature Amazon forests: sampling natural fallen trees. The main goal is to present this method as a reliable, replicable and auditable alternative for site-specific volume equation regression analysis, presenting the regression analysis statistics, comparing the results with other similar studies carried out in other areas and regions. Data was collected in a Conservation Unit (protected forest) in Central Amazon (57° 54’ 54"W and 4° 41’ 23”S), known as National Forest of Pau Rosa, in Amazonas State, Brazil.

MATERIAL AND METHODS

Study site and sampling methods:

For this study it was considered the areas of upland (terra firme) mature forests of a sustainable use Conservation Unit known as National Forest (FLONA) of Pau Rosa, located within the municipality limits of Maués, in Amazonas State (Central Amazon), Brazil. The FLONA is a well preserved 827 thousand hectares of tropical rainforest reserve. All field survey and data collection was carried out during a period of 25 (twenty five) days, with a team composed by one forester and two helpers. No specific materials were used: diameter and metric tapes, calipers, compass, clip board, pen and paper, machetes and individual protection equipment (boots, hard hats and gloves).

As for the sampling method, it wasn’t established a sample area or plot. Every individual (fallen tree) was considered as a single sample. In order to be sampled, each individual found in the forest had to present specific acceptable conditions, such as: exposed root (indicating that the entire tree was in the ground); stem in perfect conditions (without any severe damage or deformity, which would prevent the volume determination); and preferably, with the presence of fresh leaves in the crown of the tree (proving that the tree had recently fallen). The latter was often neglected due to availability constrains. Thus, the botanical identification of the sampled trees was impaired and therefore not accounted for.

Diameter, heights and volume determination:

Every sampled tree had their respective diameter at 1.3 m from the base (DBH), measured with a caliper or diameter tape depending on the conditions, and merchantable (Hf) and total heights (Ht), both measured with a metric tape. “Merchantable height” was considered as that point on the upper stem where branches, roughness or other defects render the remaining length unmerchantable (Higuchi and Ramm, 1985). The bole volume was calculated based on a combination of two traditional cubing methods: Smalian and Hohenadl, in which the stem was divided into 10 sections of equal lengths and each extremity measured (Husch et al. 1971). Every section was considered as a cylinder and its volume calculated individually, the total bole volume of each tree was the sum of all sections volume’s, as shown in Formula 1 and illustrated in Figure 1. The minimum DBH measured was 10 cm, given the standardization of other studies in the Amazon region (Baker et al. 2004; Asner et al. 2010; Feldpausch et al. 2011; Salimonet al. 2011; Lima et al. 2012).

\[ \text{Vol} = \frac{\pi}{40000} \times \left( \frac{D_1^2 + D_2^2}{2} + D_1^2 + D_1^2 + \ldots + D_i^2 \right) \times \frac{H_f}{10} \]

Where: Vol = volume, in m³; \( \pi = \) constant “pi”, equal to 3.14; \( D_i = \) diameter at “i” section, in cm; \( H_f = \) merchantable height, in m.

Volumetric models and regression analysis:

Five models were tested to evaluate the effectiveness of natural fallen trees sampling for volume equation adjustment (Table 1). These models were selected based on forestry literature (Couto and Bastos, 1987; Scoforo et al. 1994; Chichorro et al. 2003; Schneider and Tonini, 2003; Batista et al. 2004; Rolim et al. 2006; Barros and Silva Junior, 2009; Thaines et al. 2010; Silva et al. 2011). In which, three were linear models and two non-linear, considering only DBH and merchantable height (Hf). Because of the high botanical variability of the forest (Stege et al. 2013) and the scale (number of individuals per species and per area unit), there was no distinction of species or group of species, each volume equation was fit for all species combined. The regression statistics analyzed were: Coefficient of determination or r-squared (R²); Mean Square Error (MSE); Absolute and Relative Standard Error of
Estimate (SEE and Syx%, respectively); graphics of residual distribution; and uncertainty estimated in the validation process.

Fig. 1: Illustration of the combined method of volume determination.

Table 1: Volumetric models tested in this study.

<table>
<thead>
<tr>
<th>N</th>
<th>Model</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V = \beta_0 + \beta_1 \times DBH^2$</td>
<td>Kopecky-Gehrhardt</td>
</tr>
<tr>
<td>2</td>
<td>$V = \beta_0 + \beta_1 \times DBH^2 + \beta_2 \times (DBH^2 \times Hf)$ + $\beta_3 \times Hf$</td>
<td>Stoate</td>
</tr>
<tr>
<td>3</td>
<td>$V = \beta_0 + \beta_1 \times (DBH^2 + Hf)$</td>
<td>Spurr</td>
</tr>
<tr>
<td>4</td>
<td>$V = \beta_0 \times DBH^h \times Hf^g$</td>
<td>Berkhout</td>
</tr>
</tbody>
</table>

Where: $V =$ bole volume, in $m^3$; $\beta_0$, $\beta_1$ and $\beta_2$ = coefficients; DBH = diameter at 1.3 m from the base, in cm; Hf = stem height, in m.

The collected data was divided into two sets. The first was used for regression analysis (“Adjusted data”), where its diameter distribution followed the same tendency as the standing trees (inverted “J”). The second set was used to validate the adjusted equations. Hence, from the data archive of 259 trees, the first set counted with 144 individuals and the second with the remaining 115 trees. The adjusted equations were applied in the second data set and the Mean Square Error (MSE), the absolute and relative Standard Error of Estimate (SEE and Syx%, respectively) and the graphic of residual distribution were estimated based on the comparison between observed and estimated individual volume.

Results:

Descriptive results:

After a 40 day expedition period, 259 fallen trees were sampled. Average DBH was estimated in 33.9 cm ($\pm$ 2.7), varying from 10 cm to 126 cm. Comparing with the finding of Higuchi and Ramm (1985), the mean DBH estimated in our study was slightly smaller, but with a similar variation. Considering the standing forest, this average is considered high, due to large proportion of trees with DBH above 40 cm. The tallest sampled tree measured 44.8 m and the mean height was 24.0 ($\pm$ 0.8). As for merchantable height (Hf), mean value was 13.1 ($\pm$ 0.5), with a high variation, from 2 to 27 m. The mean determined volume was 1.59 $m^3$ ($\pm$ 0.34), varying from 0.02 to 18.82 $m^3$ (Table 2). The diameter distribution of the sampling did not follow a negative exponential distribution (Figure 2), justifying the need of dividing the data set into two: (i) one for regression analysis; and (ii) equations validation.

The largest sampled tree (DBH = 126.0 cm) had a total height (Ht) of 35.5 m and 23.8 m as merchantable height (Hf), with a volume of 16.3 $m^3$. The lowest value of Hf (2 m) was measured in a tree with DBH of 10.5 cm and Ht of 15.8 m. The tallest tree (44.8 m in total height) presented the highest timber volume (18.82 $m^3$), with 109.0 cm of DBH and 19.7 m of Hf. Overall, in average the merchantable height represented 55% ($\pm$ 1%) of the total height. However, of 54 “large” trees (with DBH > 50.0 cm) sampled in the study, 29 (53.7% of the individuals in that class) presented aHf x Ht proportion under the average, where two individuals presented Hf under 10 m.

Table 2: Basic distributional characteristics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Variance</th>
<th>C. V. (%)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBH (cm)</td>
<td>33.94</td>
<td>507.92</td>
<td>66.4%</td>
<td>10.00</td>
<td>126.00</td>
</tr>
<tr>
<td>Ht (m)</td>
<td>23.88</td>
<td>43.51</td>
<td>174.8%</td>
<td>11.00</td>
<td>44.80</td>
</tr>
<tr>
<td>Hf (m)</td>
<td>13.26</td>
<td>27.5%</td>
<td>10.00</td>
<td>1.00</td>
<td>18.82</td>
</tr>
<tr>
<td>V ($m^3$)</td>
<td>1.78</td>
<td>7.77</td>
<td>174.8%</td>
<td>0.02</td>
<td>18.82</td>
</tr>
</tbody>
</table>

Where: Ht = total height; Hf = stem height; V = cubed volume; C. V. = coefficient of variation.
The regression analysis of all five models resulted in good fit statistics (Table 3). The mean $R^2$ estimated among all five models was 0.96 ($\pm$ 0.01), thus, in average between 95 and 97% of all variation of the collected data was explained by the adjusted equations. In terms of precision, the Mean Square Error averaged 0.0784 ($\pm$ 0.0189); the SEE mean estimate was 0.0193 ($\pm$ 0.0023), which resulted in a mean Syx% of 2.93% ($\pm$ 0.35%).

Regression analysis results:

After the validation of the adjusted models, the graphic of residual distribution was elaborated as well as the uncertainty estimated. During the validation process, it was observed that Kopezky-Gehhardt’s (KG) model estimated negative values for individual with DBH between 10 and 12 cm. Therefore, indicating that a second equation should be adjusted for that DBH range. Nevertheless, even though the underestimation by KG’s model, all precision statistics of the validation process presented good estimates. The MSE, SEE and Syx% estimated mean values similar to the regression analysis, confirming the robustness of the method (Table 4). Average values for MSE, SEE, Syx% and uncertainty were, respectively: 0.0784 ($\pm$ 0.0189); 0.0193 ($\pm$ 0.0023); 2.93% ($\pm$ 0.35%); and 5.85% ($\pm$ 0.7%). As for the graphics of residual distribution, all models showed a similar uniformity, with Spurr’s model (Model 3) standing out as being the most irregular (Figure 3).

### Table 3: Regression analysis statistics.

<table>
<thead>
<tr>
<th>Model</th>
<th>$R^2$</th>
<th>MSE</th>
<th>SEE</th>
<th>Syx%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kopezky-Gehhardt</td>
<td>0.96</td>
<td>0.12456</td>
<td>0.3530</td>
<td>3.44%</td>
</tr>
<tr>
<td>Stoate</td>
<td>0.98</td>
<td>0.05949</td>
<td>0.2439</td>
<td>2.61%</td>
</tr>
<tr>
<td>Spurr</td>
<td>0.97</td>
<td>0.08233</td>
<td>0.2869</td>
<td>2.70%</td>
</tr>
<tr>
<td>Berkhout</td>
<td>0.97</td>
<td>0.11584</td>
<td>0.0280</td>
<td>3.69%</td>
</tr>
<tr>
<td>Schumacher-Hall</td>
<td>0.98</td>
<td>0.04669</td>
<td>0.0177</td>
<td>2.34%</td>
</tr>
<tr>
<td>Average</td>
<td>0.97 $\pm$ 0.01</td>
<td>0.0588 $\pm$ 0.0298</td>
<td>0.1859 $\pm$ 0.1349</td>
<td>2.96 $\pm$ 0.51</td>
</tr>
</tbody>
</table>

Where: $R^2$ = coefficient of determination; MSE = Mean Square Error; SEE = Standard Error of Estimate; Syx% = Standard Error of Estimate, in %.

### Table 4: Statistics of the validation process.

<table>
<thead>
<tr>
<th>Model</th>
<th>MSE</th>
<th>SEE</th>
<th>Syx%</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1070</td>
<td>0.0227</td>
<td>3.44%</td>
<td>6.89%</td>
</tr>
<tr>
<td>2</td>
<td>0.0612</td>
<td>0.0172</td>
<td>2.61%</td>
<td>3.21%</td>
</tr>
<tr>
<td>3</td>
<td>0.0657</td>
<td>0.0178</td>
<td>2.70%</td>
<td>5.40%</td>
</tr>
<tr>
<td>4</td>
<td>0.0962</td>
<td>0.0216</td>
<td>3.27%</td>
<td>6.53%</td>
</tr>
<tr>
<td>5</td>
<td>0.0618</td>
<td>0.0173</td>
<td>2.62%</td>
<td>5.24%</td>
</tr>
<tr>
<td>Mean</td>
<td>0.0784 $\pm$ 0.0189</td>
<td>0.0193 $\pm$ 0.0023</td>
<td>2.93% $\pm$ 0.35</td>
<td>5.85% $\pm$ 0.7</td>
</tr>
</tbody>
</table>
Discussion:

The procedures carried out during the field survey allowed a sampling large enough to divide the data set into two, one for regression analysis and another for equation validation. Indicating that the method showed great promises in terms of representativeness of the target forest. However, some aspects need to be improved, such as the determination of the merchantable height. This particular variable has an inherent subjectivity in its collection. For instance, as presented in Table 2, it was sampled a tree with only 2 m of stem height, where this individual measured 15.8 m of total height, resulting in a proportion of Hf to Ht is 12.7%, less than a quarter of the average. Thus, the definition of “merchantable height” must be revised and (possibly) substituted by “stem height”, which should be considered as: the length of the trunk, from base to the beginning of the crown (as suggested in Figure 1), in order to avoid these discrepancies.

Nevertheless, sampling natural fallen trees gathered a significant number of individuals. Although Higuchi and Ramm (1985) gathered almost 3x the number of samples as this study, the felling activity involves higher risks, power tools (chain saws) and specific human resources. Therefore, it is safe to say, given the differences between the regression statistics, that sampling natural fallen trees presented cost effectiveness higher than felling trees.

In terms of diameter distribution of the collected data, the field survey showed some difficulties to sample trees in lower diameter classes (under 30 cm). This can be explained by three hypothesis: (i) smaller trees usually are under storage individuals, with their crown located in the third or (at most) second store of the forest’s canopy, therefore not too much susceptible to natural forces that could knock down trees (such as: strong winds); (ii) given the first point, these individuals (DBH < 30 cm) tend to fall due to other larger trees. In this case, when it happens, usually the smaller trees are damaged (stems broken) invalidating it for sampling. At last, (iii) even when these trees actually fall in perfect conditions, their sizes collaborate for a quick decomposition, reducing its chances to be measured. This situation does not represent a drastic constrain itself, but it shows that the sampling effort, in the field, must be allocated in finding small trees (DBH < 30 cm).

As for the regression analysis, given the range of $R^2$ and Syx%, from 0.0 to 1.0 and 0 to 100% respectively, all adjusted models presented very good statistics. However, it is difficult to compare regression analysis results due to the reduced number of scientific papers published in the matter. Also, because of non-standardization of precision statistics, some studies present precision as Coefficient of Variation, others as MSE or the absolute value of the Standard Error of Estimate (SEE). The coefficient of determination (r-squared) is the only unanimous parameter. The graphics of residual distribution are very seldom presented, as well as the validation, due to data constrains.

Comparing our results with other studies, some performed in similar forest conditions and othersin planted forests, showed that this method it’s reliable and robust. For instance: Couto and Bastos (1987) published volumetric equations for an Eucalyptus sp. stand and the $R^2$ ranged from 0.80 to 0.96. In a caxeta (Tabebuia camarinoides (Lam.) DC.) forest, Batista et al. (2004) tested 16 different models and the estimated $R^2$ were all above 0.90, but the calculated SEE were very high (from 49.96 to 115.54). Machado et al. (2008), studying a plantation
of a Brazilian native species, bracatinga (*Mimosa scabrella*Benth.), adjusted ten models and resulted in high r-squared, but also high Syx% (ranging from 16.7 to 37.2%). In an even-aged forest stand, in Virginia State (USA), Jiang et al. (2005) adjusted volume equation and presented $R^2 > 0.90$ and SEE (absolute values) from 0.004 to 0.023.

In other tropical forests, Akindele and LeMay (2006) adjusted volume equations for specific group of species in Africa and presented similar results as ours ($R^2 > 0.86$ and SEE ranging from 0.21 to 1.17). In Porto Rico, Brandeis et al. (2006) adjusted volume equations for mixed dry forests species, the results were: $R^2$ between 0.56 and 0.99; MSE between 0.0001 and 0.003.

In the Brazilian Amazon, Higuchi and Ramm (1985) and Rolim et al. (2006) worked with regression analysis for volume equations. The first considered data from the same region, Central Amazon (Amazonas State), and the second in the State of Pará. Higuchi and Ramm (1985) felled 715 trees and tested five models, which resulted in ten equations, the results were: $R^2$ ranging from 0.89 to 0.98 and the SEE from 0.072 to 2.714. Rolim et al. (2006), after cubing only 55 (fifty five) trees, tested 12 models and the regression analysis resulted in $R^2$ between 0.82 and 0.99 and Syx% varying from 4.6 to 56.2%.

The mean estimates of the regression statistics of this study were considerably good, given that it showed better estimates than in even-aged forests. In terms of r-squared, the average was higher than the range of $R^2$ in Couto and Bastos (1987) study, which considered a single species, even-aged forest. The precision statistics also presented better estimates than found in more homogenous forests (Machado et al. 2008). Although, in comparison with Akindele and LeMay (2006) and Brandeis et al. (2006), our MSE were higher, but without a relative (in percentage) estimate, it is difficult to compare the actual effect of this Mean Square of Error. On the other hand, our estimated mean Syx% was almost half of Rolim et al. (2006) paper and estimated SEE within the variation range of Higuchi and Ramm (1985) estimate, both studies conducted in the Brazilian Amazon forests.

After the validation process, it is possible to point out that the method produced robust and reliable results. After applying the adjusted volume equations into a different data set, the estimated uncertainty of the equations was under the maximum acceptable in forestry studies (10%). This means that this method (natural fallen trees sampling) produces good quality and high representativeness volume equations. Considering the costs involved in the field survey, it is highly recommended that this method is conducted, rather than subjecting the estimates to inappropriate and outdated equations, such as proposed by Heinsdijk and Bastos (1963).

**Conclusion:**

Based on the findings of our study, the sampling of natural fallen trees in tropical forests represents an interesting alternative for site-specific volume equations adjustment. The results presented here, both descriptive and from the regression analysis, showed that it is not necessary to fell trees in order to determine merchantable volume for volumetric studies. The collected data produced robust equations, with regression statistics similar to studies conducted in homogeneous and even-aged forests. In future studies of timber volume stocks, based on primary field data, there is no apparent reason for not adjusting a site-specific equation.

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