INTRODUCTION

Obtaining accurate volumes of standing trees can be considered one of the greatest challenges in forestry. These volumes are usually estimated as a function of variables that can be obtained easily and with high precision, as the diameter at the breast height (DBH) - 1.30 m above the ground - and stem height of individuals (Rodriguez et al., 2013).

In this way, forest measurement is an important element of forest management, considering that the qualitative and quantitative estimates related to forest are dependent of precise measurements. It is from these estimates that the decision-making are carried out, therefore, gross errors can compromise viability of forestry projects, considering their robustness is dependent of accurate and efficient planning.

Thus, in order to increase the trustworthiness of forest inventories is pertinent that their error sources are known, with the aim to eliminate them, or at least reduce them. When considering the errors in height and DBH, there is a greater importance in errors for the second variable in the volume estimates, as it has greater impact on the volume (Couto and Bastos, 1988).

For individual volumes estimates is common to use empirical relations, where these volumes are obtained without felling the trees, using volumetric
equations. The use of these estimates, although valuable, is not yet, the more accurate solution, considering that for the development of empirical relations are required individual volumes data of trees, which can be estimated through destructive or non-destructive methodology. When the empirical relation is extrapolated from one region to another, where the individual volumes determination cannot be performed, there are problems inherent to representativeness of the empirical relation (Castro et al., 2008).

The destructive method for individual volume estimates of trees is traditionally used, providing accurate data for developing empirical relations. For this purpose, trees which volumes need to be measured are felled and diameter measurements are held along its stem at preset positions, for subsequent volumetric calculation.

According to Nicolaletti (2011), this fact renders this methodology improper for areas supported by legislation and fragile ecosystems, since trees cannot be felled in such areas and considering planted forests, the destructive method is, in most cases, more time consuming and more costly.

In this context, the use of non-destructive method is an alternative, which can be performed through measurements by climbing trees, or using optical instruments that provide indirect measurements of the diameters along the stems. On the use of optical equipment is important to consider the distance between the measurer and the target tree, as the diameters to be measured are directly proportional to these distances (Clark et al., 2000).

The aim of this study was to verify the accuracy of individual volume estimates through the use of dendrometer Criterion RD1000 using non-destructive methodology for individuals of Pinus taeda L. Different stands ages and different horizontal measuring distances (HD), between the measurer and the target tree were considered. The time spent in non-destructive individual volume estimates in each age and HD were also evaluated.

**MATERIAL AND METHODS**

**Study area:**

The study was conducted in Pinus taeda L. stands located in the municipality of Ponte Alta do Norte, Santa Catarina State, located at UTM coordinates approximate E: 553821, N: 7000262, zone 22 J.

According Köppen classification, the study area predominantly climate is of type “Cfb”, mesothermal, humid subtropical, with cool summers, without defined dry seasons and with occurrence of severe frosts. The mean annual precipitation is 1,740 mm and the mean annual temperature is 16.8 °C (Thomas et al., 2006).

Stands with 13 and 21 years were studied, both owned initial density of 1600 ind. ha⁻¹. The first, respectively had two thinnings, the first at 8, and the second at 11 years old, possessing as remnants approximately 600 ind. ha⁻¹. The second, in addition to those mentioned, was submitted to the third thinning at 15 years, owning around for 400 ind. ha⁻¹.

**Data collection:**

In the sampling were considered two stands ages (13 and 21 years), in which were sampled 40 individuals (20 individuals at each age). The individual volume estimates were carried out according to the non-destructive, destructive and xylometer methods. Destructive and non-destructive measurements were performed according to the methodology suggested by Holenadl that divides the tree into 10 sections, and the measurements are performed in relation to the stem: 5%; 15%; 25%; 35%; 45%; 55%; 65%; 75%; 85% and 95% (Machado and Figueiredo Filho, 2014).

For measurements in non-destructive methodology were used the Vertex IV hypsometer (individual total height measuring) and the Criterion RD1000 dendrometerixed at adapted monopod (diameters along the stem measurements) on HD of 10 m, 14 m and 18 m. Destructive volume estimates were performed with the aid of Stihl MS-361 chainsaw, caliper and measuring tape. The stems xylometry was conducted in xylometer designed for this study, measuring 3.20 m long, 0.90 m wide and 1.10 m high. The length of the logs for this procedure was 3.10 m.

In addition, were clocked the time required for the individual measurements according to the non-destructive methodology for different ages and HD studied.

**Data analysis:**

Absolute and relative errors for diameters, section volumes and individual volumes were evaluated. For the first two variables, it was taken as reference the data obtained by the destructive methodology, while for the third were considered the volumes provided by xylometer method. For these analysis was used descriptive statistics (mean and standard deviation) and graphic analysis of residuals. Negative values of absolute and relative errors indicate overestimation compared to reference value and positive values indicate an underestimation compared to them.

For the evaluation of the frequency distribution of volumes per individual and per area, it was used the Bootstrap resampling method, by generating 1000 simulations of 19 trees for each studied method, without considering any probability distribution. All analyzes were performed with R software (R Development Core Team, 2014). The time spent for non-destructive volume estimates were submitted to the Kolmogorov-Smirnov and Bartlett test. It was subsequently proceeded to analysis of variance (ANOVA) in
bifatorial design (ages and HD’s), followed by Tukey’s test at 95% of probability.

RESULTS AND DISCUSSION

Descriptive dendrometric data:

Data from the forest inventory are shown in Table 1, for the ages of 13 and 21 years, respectively.

Table 1: Summary of minimum (min), mean and maximum (max) data of diameter at breast height (DBH), total height (h) and individual volume (v) for two ages of *Pinus taeda* L.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>DBH (cm)</th>
<th>h (m)</th>
<th>v (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>mean</td>
<td>max</td>
</tr>
<tr>
<td>13</td>
<td>21.5</td>
<td>27.7</td>
<td>36.0</td>
</tr>
<tr>
<td>21</td>
<td>30.1</td>
<td>37.9</td>
<td>45.2</td>
</tr>
</tbody>
</table>

Errors in diameter along the stem:

In both ages, overestimation errors were observed in non-destructive measurements at the upper positions of the trees (smaller diameters) (Figure 1).

Larger errors in the higher positions of trees are associated with equipment band limitations, which in the smaller diameters positions were not able to frame the stem. Thus, especially in the position at 95% of the stem height, the observed diameters are smaller than the minimum diameter that can be measured by the device. It is also observed that, generally, with increasing HD and height position there is an increase in the minimum diameter which the equipment band is able to measure, implying greater diameters overestimations in positions at 85% and 95% for larger HD studied. This generates to the position at 95% of the stem height, overestimation error up to 350%.

It was noted based on the HD evaluated that the relative errors have similar behavior in the different stem positions, indicating tendency to overestimations in diameters smaller than 15 cm. For diameters larger than 15 cm the relative errors are concentrated near the zero axis, without apparent trend of underestimation or overestimation.

Considering that errors relating to diameters estimates in the highest stems positions are very discrepant, it was decided to demonstrate the errors related to measurements performed in the entire stem and also considering only 75% of it (Table 2).

Table 2: Mean absolute error (AEi) (cm) and mean relative error (REi) (%) (± standard deviation) in diameter, for different ages and HD, considering the entire tree height and 75% of it.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>HD (m)</th>
<th>Whoretree</th>
<th>75% offretree</th>
<th>AEi (%)</th>
<th>REi (%) (±)</th>
<th>AEi (%)</th>
<th>REi (%) (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>10</td>
<td>-1.60 (± 2.11)</td>
<td>-28.88 (± 54.75)</td>
<td>0.96 (± 1.67)</td>
<td>-7.34 (± 1.15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>-1.12 (± 2.23)</td>
<td>-28.60 (± 63.26)</td>
<td>0.25 (± 1.37)</td>
<td>-2.95 (± 10.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>18</td>
<td>-0.69 (± 2.71)</td>
<td>-28.47 (± 71.79)</td>
<td>0.40 (± 1.56)</td>
<td>-0.53 (± 10.65)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>10</td>
<td>-0.13 (± 2.99)</td>
<td>-19.31 (± 64.94)</td>
<td>0.92 (± 1.98)</td>
<td>-3.83 (± 8.72)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>14</td>
<td>-0.15 (± 3.26)</td>
<td>-22.74 (± 74.68)</td>
<td>1.08 (± 1.91)</td>
<td>-3.97 (± 7.82)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>18</td>
<td>-0.38 (± 3.37)</td>
<td>-25.39 (± 79.44)</td>
<td>-0.89 (± 1.93)</td>
<td>-3.19 (± 7.94)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Due to the larger errors in the last two stem positions (85% and 95%), it is noted that the errors are considerably lower for 75% of the stem compared to the full tree. The mean errors were lower than -7.34% and -3.97% for the ages of 13 and 21 years, respectively, both presenting overestimations, for all HD studied. However, when considering the whole stem, there are errors near 29% at the age of 13 years and up to 26% at the age of 21 years.

Differently from this study, Parker and Matney (1998) evaluating the accuracy of diameters measurements with dendrometer Criterion 400, observed underestimation mean errors of 0.13 cm, which indicate seven more accurate measurements. A similar trend was observed by Nicoletti (2011) performing measurements with the same device along the stems of *Eucalyptus grandis* Maiden up to 8 m high, who observed mean absolute error lower than 1 cm, which represents approximately 5% in relative terms. While Williams et al. (1999) also using the Criterion 400, reported similar trend as this study, with diameters overestimations of -0.12 cm, which indicates mean relative error of -0.40%.

Errors on volume by section:

Absolute errors of volume by section had different behavior in both studied ages. When considering only the age of 13 years, it is observed that the errors present different trends taking into account the HD, which does not happen at the age of 21 years (Figure 2).

At the age of 13 years it is noticed a trend of underestimation in the lower positions of the stem with increasing HD, however, there is overestimation in the upper positions. At the age of 21 years, there is underestimation of the volume up to 75% of the stem.
height and there is overestimations in the remaining sections (85% e 95%).

In both ages the mean absolute error of volume per section was \(-0.0006\ m^3\) for HD of 18 m, which represents the most accurate results from the HD studied. The HD of 10 m and 14 m showed respective values of \(-0.0061\ m^3\) and \(-0.0032\ m^3\) at the age of 13 years and \(-0.0048\ m^3\) and \(-0.0066\ m^3\) at the age of 21 years.

![Fig. 1: Diameter relative error (%) in relation to diameter measured by caliper (cm), considering different HD. Where: solid line indicates relative errors equal to zero and dotted lines demarcate the area in which the relative errors are less than or equal to 10%.](image)

Shorter HD makes it difficult to measure the upper positions of the stem, considering that the equipment is set at a monopod that has fixed height. In such situations, the measurer is often under a poor posture to be able to view the higher positions of the tree, which may result in larger errors of measurement.

Other factors that influence the non-destructive measurement errors are reported by Kalliovirta et al. (2005), mentioning as the main influential factors: very dense stands and with high branching, presence of lichens and partly loose bark on the stem. Williams et al. (1999) report that lighting conditions on stands are an aggravating of the errors in these measurements, and the author also mention that one of the major problems in the visualization of the stem with laser dendrometers is the landscape that lies behind the individual to be measured, especially when it comes to monocultures.

These reports assist in the explanation of larger errors occurring in higher positions of the stem, since in this tree portion there is an increase in the presence of branches and greater influence of the luminosity in the measurements (greater equipment inclination) than those observed for lower positions of the stem.
Fig. 2: Absolute error of volume per section (m³) in relation to relative position of the stem (%), considering different ages and HD.

Errors of individual volume and of volume per area:
The mean absolute and relative errors of individual volume, taking as reference the volumes obtained by xylometer, are presented in Table 3.

At the age of 13 years there was a decreasing trend in errors by increasing HD. However, at the age of 21 years no evident trend was observed, since the average error on the HD 14 m was larger when compared to the HD of 10 m. This denotes different behavior on the errors of estimates between the studied ages. However, both ages presented minor errors in individual volume estimates of trees in the HD of 18 m. Figure 3 shows the individual volume estimates according to the different methods, considering the procedure of Bootstrap resampling.

Table 3: Mean absolute and relative errors (±standard deviation) for destructive and non-destructive volume estimates taking as reference volumes obtained by xylometer. In methods for volume estimation: caliper refer to destructive method. Crit. 10 m, Crit. 14 m and Crit. 18 m refer to non-destructive method performed in HD of 10 m, 14 m and 18 m, respectively.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Method for volume estimation</th>
<th>Mean Absolute Error (m$^3$)</th>
<th>Mean Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Caliper</td>
<td>-0.0457 (± 0.0169)</td>
<td>-10.54 (± 3.92)</td>
</tr>
<tr>
<td>21</td>
<td>Caliper</td>
<td>-0.0776 (± 0.0268)</td>
<td>-11.92 (± 6.81)</td>
</tr>
<tr>
<td>13</td>
<td>Crit. 10 m</td>
<td>-0.1069 (± 0.0335)</td>
<td>-12.37 (± 7.04)</td>
</tr>
<tr>
<td>13</td>
<td>Crit. 14 m</td>
<td>-0.0519 (± 0.0274)</td>
<td>-11.86 (± 6.87)</td>
</tr>
<tr>
<td>21</td>
<td>Crit. 10 m</td>
<td>0.0025 (± 0.1196)</td>
<td>0.77 (± 7.78)</td>
</tr>
<tr>
<td>21</td>
<td>Crit. 14 m</td>
<td>0.0210 (± 0.1002)</td>
<td>1.67 (± 7.21)</td>
</tr>
<tr>
<td>21</td>
<td>Crit. 18 m</td>
<td>0.0013 (± 0.1053)</td>
<td>0.35 (± 7.02)</td>
</tr>
</tbody>
</table>

Fig. 3: Boxplot graph obtained by Bootstrap resampling method demonstrating the distribution of individual volumes, considering the xylometer method (Xylometer), destructive volume estimate method (Caliper) and non-destructive volume estimate method with Criterion RD1000 in HD of 10 m (Crit. 10m), 14 m (Crit. 14m) e 18 m (Crit. 18m). Where: solid lines are the mean individual volume (m$^3$.ind$^{-1}$) obtained by xylometer method (real volume).

Considering that the admitted error in forest inventories is at most 10%, not even destructive volumetric estimates presented acceptable error for the age of 13 years, which presented anmean value of -10.54%. For that age the non-destructive volume estimates presented largest errors for all HD compared to those obtained by destructive method. It can be assumed that the errors obtained from the non-destructive methodology considering a HD of 18 m were acceptable, since it was only 1.32% higher than those obtained by destructive volume estimates, both indicating volumes overestimation in relation to the xylometer method.

However, at the age of 21 years, results were within the acceptable error limit, presenting mean errors of -3.46% for the destructive volume estimates and 0.77%, 1.67% and 0.35% for non-destructive estimates in the HD of 10 m, 14 m and 18 m, respectively. The analysis of the errors indicates that the volumetric estimates are more accurate in larger trees, because absolute errors of volume presents smaller weights in relative terms when considering trees of larger volumes.

At both ages, the destructive methodology presented individual volumes overestimation, as well as non-destructive method at the age of 13 years, for all the HD. On the other hand, the non-destructive volume estimates at the age of 21 years presented small underestimation errors, which are lower than those obtained by destructive measurements for all the HD.

These low mean errors of estimate are attributed to the compensation of lower positions errors (volumes underestimations) and upper stem positions.
(volumes overestimations) (Figure 2). The individual volume calculation proposed by Hohenadl does not regard the upper tree portion as a cone, resulting in a higher share of that portion on the individual tree volume, thus, acts offsetting the underestimates of lower stem positions.

Castro et al. (2008) used Criterion 400 dendrometer in measurements for volumetric estimates and has observed similar behavior of errors as those obtained in this study, with overestimation for the smaller individuals and underestimates for intermediate size individuals. In the same context, Oliveira et al. (2013) has observed for individual volume estimates, mean relative errors of approximately 2.5%, employing the Criterion RD1000 in measurements. These results demonstrate no significant differences between non-destructive and destructive estimates.

Frequencies of volumes per hectare each volume estimation method, considering a confidence interval at level of 95%, is displayed in Figure 4.

![Fig. 4: Frequency curves obtained by Bootstrap resampling for different ages, representing the volume per hectare (m$^3$/ind$^{-1}$), obtained by xylometer method (black line); destructive volume estimate method (blue line); non-destructive volume estimate method in HD of 10 m (green line), 14 m (yellow line) and 18 m (red line).](image)

At the age of 13 years, the real volume (xylometer) ranged from approximately 241 to 303 m$^3$.ha$^{-1}$. The closest results were those from the destructive method, followed by the non-destructive method in the HD of 18 m, both overestimated, presenting estimated volume intervals of approximately 266 to 332 m$^3$.ha$^{-1}$ and 268 to 337 m$^3$.ha$^{-1}$, respectively.

However in the age of 21 years, less disparity between the curves was observed. The non-destructive estimates were more accurate than the destructive when compared to xylometer. The non-destructive volume estimate in the HD of 10, 14 and 18 m showed volumetric estimates intervals of 480 to 605 m$^3$.ha$^{-1}$; 481 to 597 m$^3$.ha$^{-1}$ and 487 to 607 m$^3$.ha$^{-1}$, respectively. The interval generated by the destructive method was 512 to 618 m$^3$.ha$^{-1}$, while the real volume obtained by xylometer was 496 to 600 m$^3$.ha$^{-1}$.

**Analysis of the time spent on non-destructive volume estimates:**

For the analysis of the time spent in volume estimate of each individual were considered the factors age and HD, and, there was not interaction between them at the significance level of 5% (p = 0.85). When evaluating the results of the HD factor, there were not significant differences at 5% probability by the analysis of variance (p = 0.19), with mean values of 294 s, 280 to 269 s, for HD of 10 m, 14 m and 18 m. Lower values of time spent in the larger DH were observed, although they are still not significant. That is because of the difficulty of measuring the highest tree positions in the smaller HD, which slows down the work.

However, times for non-destructive volume estimates are statistically different when considering the age factor, at a level of 1% probability (p < 0.01). Measurements at the age of 21 years had a mean time of 328 s, while at age of 13 years the mean time spent was 234 s per individual.

Such results are explained by the difficulty of measuring higher trees, as those at the age of 21 years, since most of the time spent is given to the diameters measurements at higher stem positions and, the higher are the individuals, longer the time spent on the measurements.

**Conclusion:**  
This study shows that:
• Non-destructive volumetric estimates are more accurate for individuals with 21 years compared to 13 years.
• At both ages, better results were obtained using the HD of 18 m, which can be stated, that among the tested HD, this must be the distance to be used in non-destructive measurements.
• The age factor had a greater influence on the time spent in measurements compared to HD, culminating in greater time spent on the measurements at age of 21 years.

REFERENCES


