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ESTIMATING THE VOLUME OF LOWER STEM-WOOD ON STANDING BEECH TREES USING TELEMETRY AND DENDROMETRIC TABLES: A COMPARISON

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Abstract: *Quite often the forest operators look for practical solutions to some of the current problems as specific to the wood supply chain, particularly those resting in the volume differences that occur between the volume estimates of standing trees and the volume estimates of felled trees. For this study three non-destructive methods were applied in order to estimate the volume of lower stem-wood on 32 standing trees from beech stands located between 600 and 1000 m above sea level, near Braşov, Romania. The results showed various total volumes of the lower stem-wood defined as the under-bark volume of wood contained in the stem, from the ground up to that height where the over-bark diameter of the stem decreased to 41 cm. We found an overestimation of volume by 53.95% when using the laser dendrometer compared to the tables developed by Giurgiu et al. in 2004 and an underestimation of volume by 14.16% compared to the tables developed by Popescu-Zeletin et al. in 1957. Based on the results of this study we recommend a careful use of Criterion RD 1000 to measure the stem diameter at considerable heights (more than 15 m) to avoid volume inaccuracy.*

Key words: *Upper stem diameters, standing trees, lower stem-wood, volume.*

1. Introduction

Nowadays, the volume of standing trees can be estimated using many non-destructive methods. For instance, a detailed reconstruction of the tree shape can be produced using LiDAR data as Heinzel and Huber (2017) showed for mature trees. In addition, low-resolution data captured by terrestrial laser scanning equipment can be effectively used for stem reconstruction as a novel technique [8]. Recently, Rodríguez-García et al. (2014) developed a tree measurement method based on stereoscopic hemispherical images. Other methods for

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the measurement of standing trees characteristics based on high-resolution photos have been used too [2-3]. At the same time, laser dendrometers are being increasingly used to collect the biometric data needed to estimate the volume of standing trees, in a non-destructive manner. As an example, Criterion RD 1000 (Laser Technology Inc.) is currently being used for various purposes such as producing taper models for buttressed trees [4], assessing the wood quality by measuring the knotty core taper and the form of standing trees [7], developing allometric equations that enable the estimation of the aboveground volume of trees [9, 23] or developing equations needed in prediction of biomass and carbon storage in urban forests [13]. Such a device was also used by Rutten et al. (2015) in forest inventory applications to analyze the stand structure of selectively harvested and non-harvested forests. When estimating the volume of standing trees, however, these methods are sometimes combined or used together to provide the means for data validation. To this end, laser dendrometers were used to check the accuracy of synthetic aperture radar data when estimating the above-ground biomass and other biophysical parameters of boreal forests [19] or to compare the results provided by space borne bistatic synthetic aperture radar data [10]. Non-destructive methods such as those using a laser dendrometer were also used in conjunction with terrestrial photogrammetry to model irregularly shaped tree trunks using as a predictor of biomass estimates the diameter at 13 m in height [1].

Taking into consideration the use of the laser dendrometers not only as a single non-destructive method to estimate the volume of standing trees but also as a tool to check the accuracy of data provided by satellites, terrestrial laser scanning or high-resolution images, this study aimed to test the accuracy of data collected by Criterion RD 1000 when used to measure diameters located on the lower stem. Therefore, the objectives of this study were set to: (i) produce estimates of the volume of lower stem-wood using three methods namely: based on laser technology (LT), tables developed by Giurgiu et al. in 2004 (T2004) and tables developed by Popescu-Zeletin et al. in 1957 (T1957); (ii) check the accuracy of results obtained by laser telemetry by comparing them to tables. Such research could provide practical solutions to some of the current problems as specific to the wood supply chain, particularly those resting in the volume differences that occur between the volume estimates of standing trees and the volume estimates of felled trees.

2. Material and Methods

Beech is one of the dominant species in Romanian forests [20]. In this study large-breast diameter individuals of beech (*Fagus sylvatica* L.) trees showing no visible stem defects (Figure 1) were chosen from a forest located between 600 and 1000 m above sea level, near Brasov, Romania. An important criterion when selecting each tree, consisted of a visual evaluation of the quality class, which was done according to the Romanian qualitative classification of the trees [5], resulting in the selection of those trees included in the first quality class, meaning that in broad-leaved trees, at least 50% of the stem height could be used by wood processing industry. The sample used in this study consisted of 32 beech trees with breast height diameter ranging between 40.8 and 69.75 cm and total tree height ranging between 25 and 34 m.

Fig. 1. An example of selected tree

In this study, the volume of lower stem-wood (hereafter V_{LSW}) was defined as the under-bark volume of wood contained in the stem, from the ground up to that height where the over-bark diameter of the stem decreased to 41 cm.

To estimate the volume of the stem in the near-ground segment, the over-bark diameter was measured on the standing trees at 2-m intervals using Criterion RD 1000 instrument (Laser Technology Inc., USA). The diameters were measured up to reaching 41 cm and the over-bark volume was estimated using the Huber's formula. Then, the under-bark volume of each segment was estimated by subtracting 5% from the over-bark volume, using the tables developed to estimate the bark proportion [5]. To improve the estimation by minimizing the effect caused by the shape irregularities on the cross-sectional area, the first section of 2 m in length located near the ground was further divided into two subsections of 1 m in length each. In this study, the selected trees exhibited the V_{LSW} on above-ground heights ranging from 1.8 m to 26.6 m, averaging 14.04 m. Distances needed to measure the diameters on the upper stem and total tree height were measured using an ultrasonic range finder (Haglöf Vertex IV Hypsometer, Langsele, Sweden). These distances ranged between 8 and 18.2 m (13.1 m on average) as they were adapted to the local visibility conditions. In many cases, the branches and smaller trees restricted the position of measurement.

An accuracy check was carried out by measuring two opposite diameters at several heights along each stem (0.8, 1.3 and 1.8 m from the ground level), using a caliper. These diameters were used as the "ground truth" in computing the method's bias which was defined and computed as the difference between the diameter measured by Criterion RD 1000 instrument and the diameter measured by caliper.

The V_{LSW} for the studied trees was also estimated using the estimation tables developed by Giurgiu et al. (2004) and the tables for estimating the upper stem diameters developed by Popescu-Zeletin et al. (1957).

3. Results

The studied beech trees were best characterized by the relationship between the total tree height (hereafter H), stem height up to that point at which the under-bark diameter is more than 40 cm(hereafter H_{LSW}) and the breast height diameter (hereafter DBH) (Figure 2).

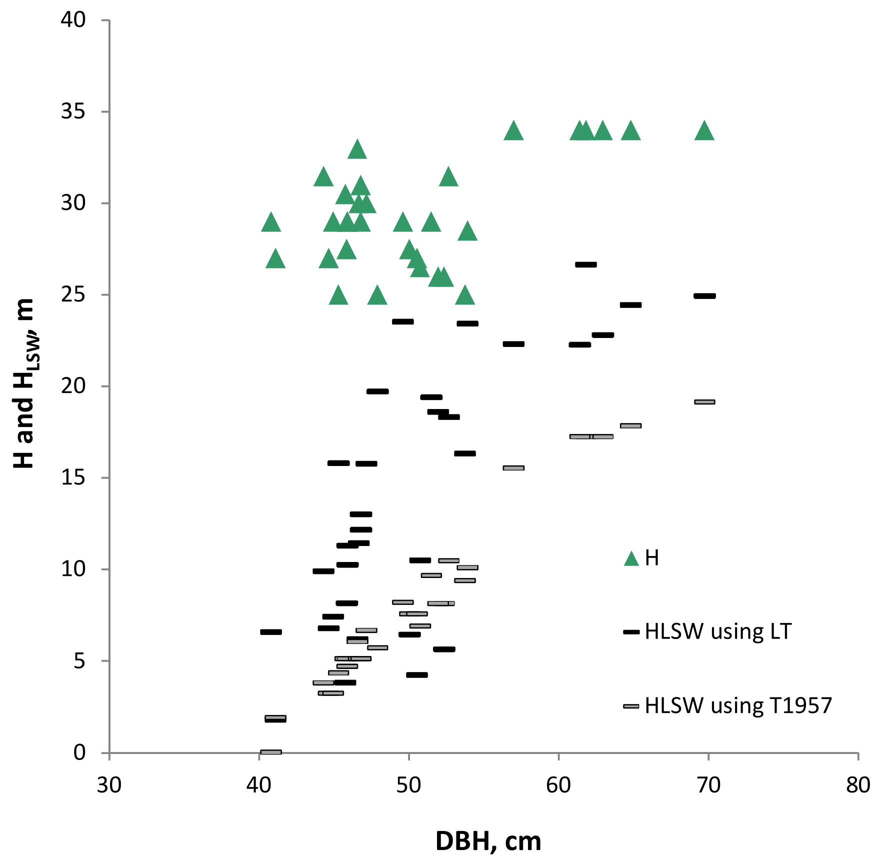

Fig. 2. Variation of the total tree height (H) and stem height up to that point at which the under-bark diameter is more than 40 cm(H_{LSW}) related to breast height diameter (DBH)

Based on the measurements carried out on the same direction at 0.8, 1.3 and 1.8 m aboveground, both, traditionally and by laser technology, the errors of the stem's diameter measured by Criterion RD 1000 were, in average, 0.95, 0.91 and 1.03 cm respectively. For individual trees, however, the errors were higher (Figure 3) depending on different factors. For instance, the eleventh tree was measured with a deviation of 25^0 from the standard direction of the study due to the field obstacles and to the cross-sectional area of this tree which was elliptical. After excluding the outliers, the bias was decreased at 0.73, 0.89 and 1.00 cm respectively.

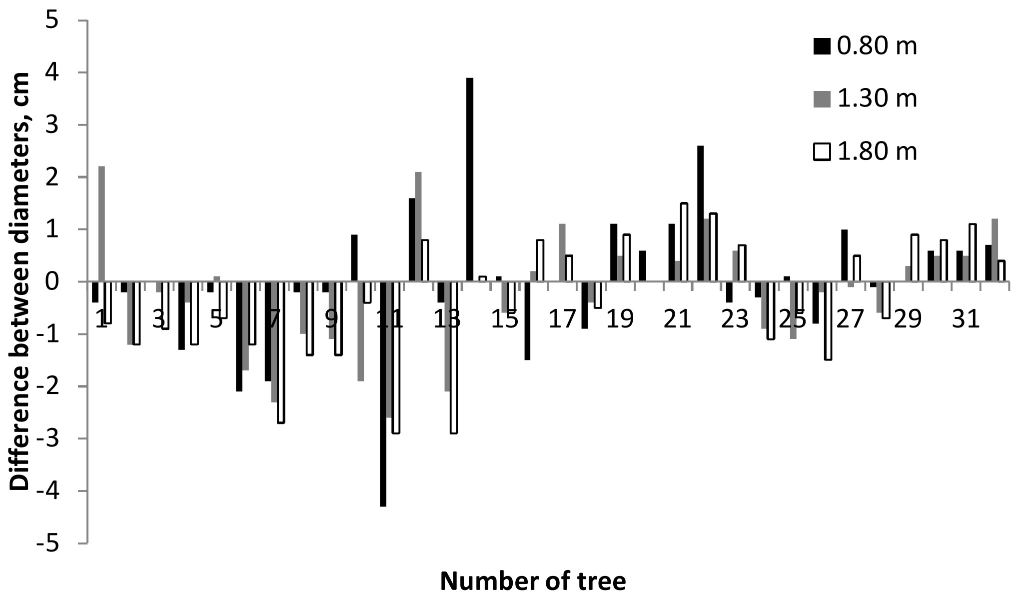

Fig. 3. Individual differences between diameters estimated with laser dendrometer and caliper

The errors of diameter measurement are actually higher when the tree ovality is taken into consideration, therefore when the diameter measured by Criterion is compared with the mean of the opposite diameters measured by caliper. In this case the mean error of the diameter measured by the laser dendrometer was of up to 1.61 cm, with the mean differences computed using the absolute values. If the differences are considered to be both positive and negative, the mean values of the bias were of -0.01, -0.23and -0.39 cm respectively.

The errors of the upper stem diameters affect directly the estimation of individual and total V_{LSW}. For instance, the total volume of wood contained in the segment of up to 40 cm under-bark was estimated at 79.236 m^3using the laser dendrometer measurements. The same variable accounted for 51.466 m^3 when using the estimation tables described by Giurgiu et al. (2004), and for 44.177 m^3 when using the tables developed by Popescu-Zeletin et al. (1957). This resulted in an overestimation of volume by 53.95% when using the Criterion compared to the tables developed by Giurgiu et al. (2004) and in an underestimation of volume by 14.16% compared to the tables developed by Popescu-Zeletin et al. (1957). Obviously, these differences require credible explanations. It is worth mentioning here that the differences in estimation at tree-level are to be expected (Figure 4) taking into account the concept behind the tables which were developed for estimations made at the scale of tree samples.

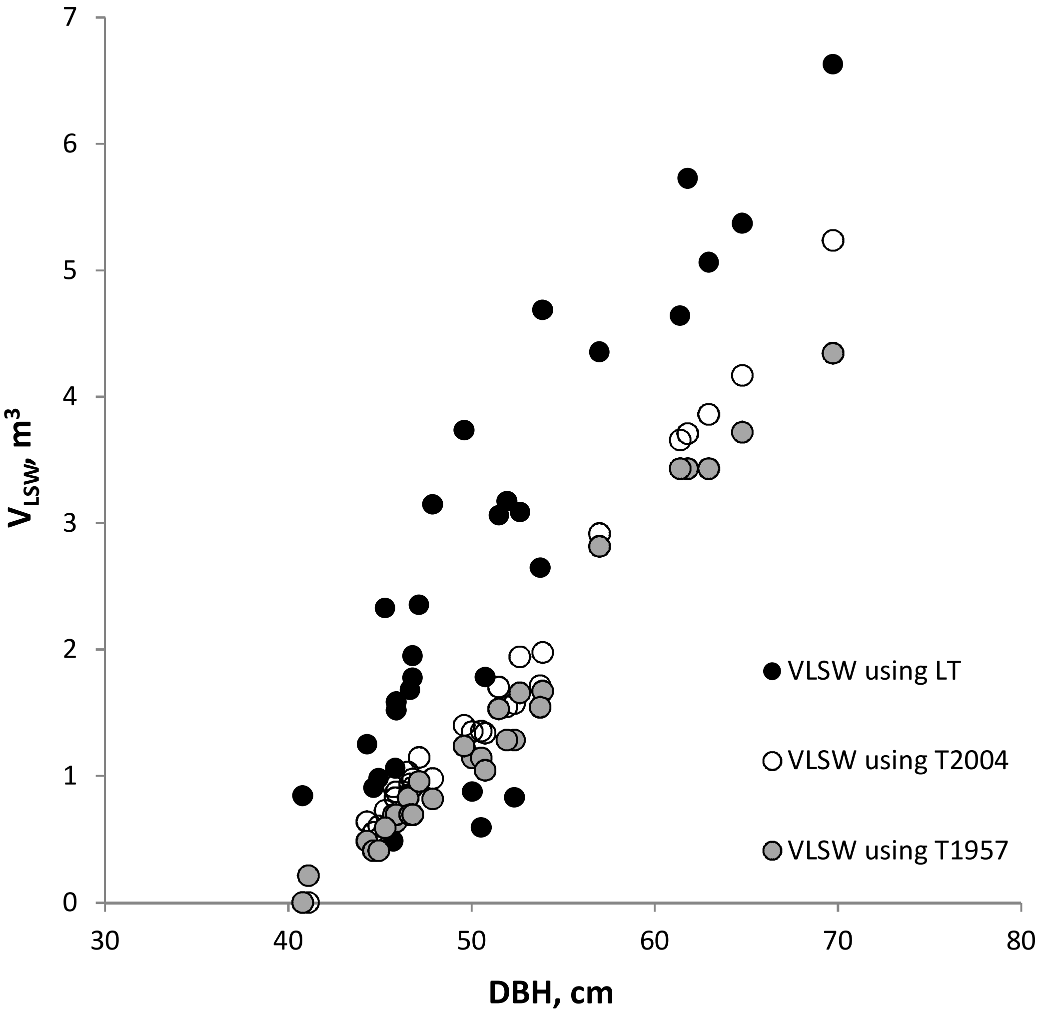

Fig. 4. Variation of the volume of lower stem-wood (V_{LSW}) on standing trees depending on breast height diameter (DBH)

4. Discussion

Can we really explain the differences between the total V_{LSW} resulted from using all of the three methods? On the one hand, the upper stem diameters measured with the laser dendrometer are affected by errors which result in volume differences. Based on the diameter controls, at 0.8, 1.3 and 1.8 m above ground, our study shows that the root mean square error of diameter was of 1.27 cm compared to the diameter values measured by caliper when keeping the direction of measurement, and of 1.79 cm when data was compared to the average of two opposite diameters. In the latter case, the error was higher because it included the deviation of the cross-sectional area from the circular shape when a single diameter was measured. Similar results were obtained by Nicoletti et al. (2015) who have shown that Criterion RD 1000 produced underestimated errors averaging approximately 1 cm, based on measurements of the stem diameters up to 8 m in height. Also, Cushman et al. (2014) mentioned an accuracy of approximately 1 cm when using the same laser dendrometer to measure upper stem diameters and to produce taper models. Compared to other tools, McCaffery et al. (2015) showed that Impulse Laser Rangefinder equipped with fixed scope and the True Pulse 360 R Laser Rangefinderequipped with adapted graduated scope obtained much better results compared to the Impulse Laser Rangefinder and Criterion RD 1000 dendrometer equipped with adjustable scope for diameter measurements on two lower and upper points.

On the one hand, the diameter errors are caused by other factors such as the height of measurement along the stem and the distance to the tree. For instance, Williams et al. (2017) found that Criterion 400 produced unbiased estimates of diameter and biased estimates of height measurements. Also, by using Criterion RD 1000 in their study, Westfall et al. (2016) suspected that the uncertainty of the diameter estimate would greatly increase as the height of the measurement level increases. Moreover, McCaffery et al. (2015) found that in the case of height measurement, the accuracy decreases at upper points when using Criterion RD 1000 instruments. According to Rodrigues et al. (2009), the distance is the most important factor controlling the accuracy when Criterion is used to measure diameters. As far as the distance to the tree is concerned, the accuracy of Criterion RD 1000 was evaluated by Rodriguez-Puerta et al. (2014). Measurements taken from the nearest distance (approximately equal to half of the tree height) showed a significant bias and a variance similar to that obtained from the furthest position (approximately equal to the tree height). In their study the latter was considered to describe an accurate position for estimating the standing tree volume as well as useful for developing more precise taper equations.

Therefore, the total V_{LSW} estimated on standing trees using Criterion RD 1000 might not be real in this study. An argument which could explain the overestimation of the total volume might rest in the H_{LSW}. These heights were higher in almost all the cases compared to the H_{LSW} provided by the used tables. Hence, an overestimation of the HLSW could be one of the causes contributing to the estimates of V_{LSW} shown in this study, when using Criterion.

On the other hand, the T1957 and T2004 based estimations produced as values much lower compared to the LT. However, these tables were developed based on field measurements carried on felled trees more than 6-7 decades ago, therefore it would be reasonable to question their actuality.

Last but not least, all of the methods are less accurate compared to destructive methods, but they are very useful when estimating V_{LSW} on standing trees and whole volume by assortments when there are restrictions for tree felling. The results of the methods tested in this study could be significantly improved in such circumstances in which sample trees would be available for measurement on the ground, after felling.

5. Conclusions

Our study demonstrated that when trees cannot be felled for volume estimation, the accurate estimation of the lower stem-wood on standing trees is still an issue that requires research in the field. Based on the results of this study we recommend a careful use of Criterion RD 1000 to measure the stem diameter at considerable heights (more than 15 m) to avoid volume inaccuracy. To solve the disputes between the harvesting operators when the standing tree volume estimation is different compared to the felled tree volume estimation, the method tested herein still needs improvements.

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