NON-DESTRUCTIVE MEASUREMENT TECHNIQUES FOR TAPER EQUATION DEVELOPMENT. A STUDY CASE FOR BLACK PINE (*Pinus nigra* Arn.) IN THE NORTHERN IBERIC RANGE (SPAIN)

Francisco RODRIGUEZ[1*]; Iñigo LIZARRALDE[1]
[1]*Castilla y León Wood & Forest Service Center (Cesefor)*
Pol. Ind. Las Casas calle C,Parcela 4, Soria, SPAIN
*corresponding author: paco.rodriguez@cesefor.com

Abstract:

Traditionally, tree volume prediction through volume tables or more modern taper equations, has required felling trees. Those destructive methods are not recommended in fragile ecosystems, such as Mediterranean areas, so alternative ones are needed. Even if tables from the National Forest Inventory (NFI) can be used, progress in telescopic and laser dendrometers now make possible non-destructive sampling techniques to measure diameters at different heights.

The use of these techniques can help harvesters and forest managers with the accuracy of their calculations, optimizing resources and time.

In this work, a new methodology based on non-destructive techniques is presented. Using Criterion™ RD1000, a laser dendrometer, a measure protocol has been developed in order to create taper models including product classification. The methodology is analyzed for black pine stands in Soria and Burgos (Northern Iberic Range). Variables representing observer and tree are randomized and influence of distance and position of the dendrometer are analyzed. Accuracy of the dendrometer in terms of bias and precision is analyzed for diameter and volume estimation. Furthermore, a comparison of two hypsometers is carried out in order to obtain the best results when using non-destructive data acquisition for taper equation development.

Successful results have been obtained. Total heights of stand trees, diameter at different heights and log and total volume can be estimated in a very precise and unbiased way.

Keywords: dendrometer, hypsometer, accuracy, forest management

1. INTRODUCTION

Nowadays, in the context of climate change, fragile ecosystems need even more care in their management. Nevertheless, this situation cannot be a handicap for forest research and increased efforts are needed to adapt forest research and management to this new status.

Diameter and volume estimation has always been based on felled tree measurements in order to obtain accuracy, above all, for large heights. Progress in telescopic and laser dendrometers allows forest managers and researchers to use non-destructive techniques without losing accuracy in their measurements.

Dendrometers have been widely used in forest measurement and several works have studied and compared their characteristics (WHEELER, 1952; AVERY AND BURKHART, 1983; BIGING AND WENSEL, 1988; JASUMBACK AND CARR, 1991; FAIRWEATHER, 1994; WILLIAMS et al., 1994; SKOVSGAARD et al., 1998; WILLIAMS et al., 1999; CLARK et al., 2000; MORAN AND WILLIAMS, 2002). Regarding precision in volume estimation with different dendrometers, relascope allows quite accurate volume estimation (bias less than 0.5%), existing no correlation between diameter at different heights and volume bias, and the size

of the tree (SALAS et al., 2005). CLARK et al. (2000) did not detect significant differences between the estimation of volume through a photographic camera or through an optic dendrometer (pentaprism) for diameters and an aluminum pole for heights. Besides, PARKET & MATNEY (1999) built unbiased taper equations using optic and laser dendrometers in comparison with equations obtained from felled trees.

Using laser dendrometer Criterion™ RD1000 and with an experimental design, accuracy is analyzed in terms of bias and precision for diameter and volume estimation. Furthermore, height measurement accuracy is assessed through the comparison of two hypsometers. Both dendrometer and hypsometer analysis are made for black pine (*Pinus nigra* Arn.) stands in the Northern Iberic Range (Spain).

The objective of this work is to assess the accuracy of two hypsometers and a dendrometer in order to prove if the results are valid and statistically unbiased compared to the results from felled trees. For the development of the present work, answers to these three questions are given:

- Can Vertex and Truepulse hypsometers measure in an accurate way the total height of a tree in typical forest conditions without felling the tree?
- Can Criterion RD1000 measure accurately diameters at different heights in typical conditions without felling the tree?
- Can we obtain unbiased estimation of individual tree volume based on the combination of measures of Criterion RD1000 dendrometer and Vertex or Truepulse hypsometers without felling trees?
- Has total height, diameter, and situation and distance a tree is measured from, effect on bias and precision of the measure?

Thus, the final aim of this work is to assess new measurement tools and techniques of non-destructive data acquisition for taper equation development.

2. DATA

Data for the development of the work was obtained from 13 black pine (*Pinus nigra* Arn.) plots in the Northern Iberic Range (Spain). 50 trees were felled covering a wide range of diameters, heights, stand structure, social class, density…etc. Table 1 shows descriptive variables of the data, both for individual trees and inventory plots. Figure 1 shows the study area.

Table 1: Descriptive data of felled trees and plots

	d (cm)	**h (m)**	**v (m^3)**	**N**	**G (m^2/ha)**	**Hdom (m)**
Mean	26.5	17.3	0.52	955	43.1	18.0
Max	46.4	26.0	1.68	1540	83.6	26.8
Min	12.1	6.05	0.04	353	16	6.8

d: diameter at breast height; h: total height; v: individual volume; G: basal area and Hdom: dominant height

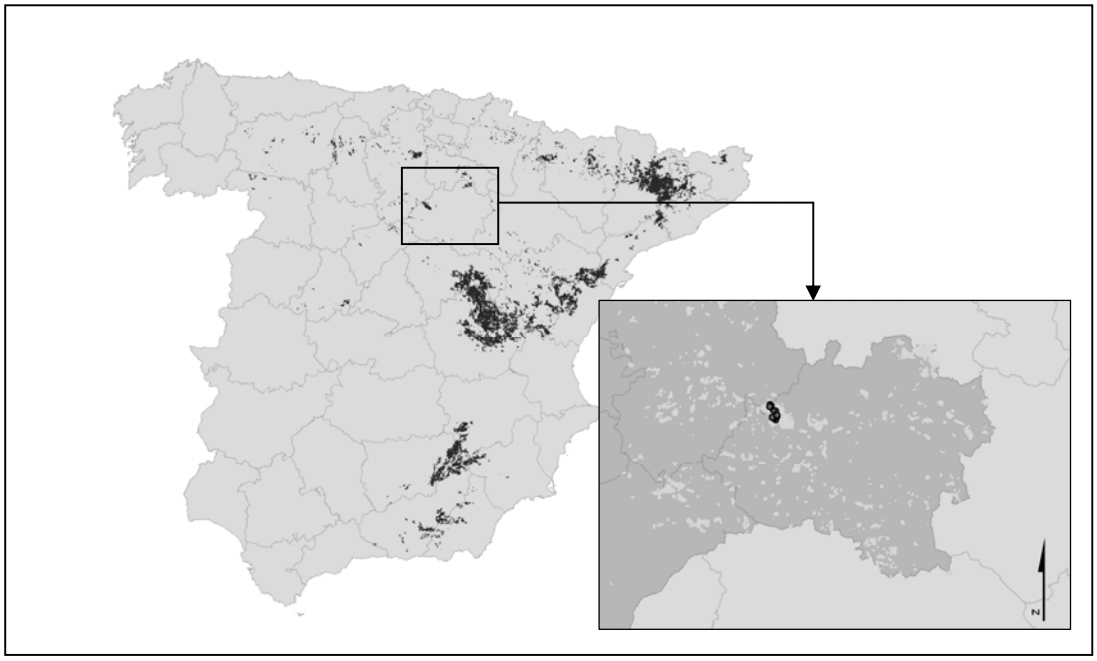

Figure 1: *Pinus nigra* Arn. distribution in Spain (left) and study area in Soria and Burgos provinces (right)

In each plot, 4 trees were selected from the different social strata (dominant, codominant and dominated). Diameter and height of the rest of the trees of the plot was measured. Plot size was big enough to contain 14 trees or the selected 4 trees. 38 of the 50 trees from 10 plots were measured with the three dendrometers.

In order to assess the accuracy of Criterion RD1000 for diameter and volume estimation, a factor analysis was designed, where "observer" factor was randomized using a coin. "height measurement device", "distance to the tree" and "visual position" factors were assessed. "Height measurement device" had three degrees of freedom; (i) Truepulse hypsometer, (ii) Vertex hypsometer, and (iii) Criterion RD1000 dendrometer. "Distance to the tree" had two degrees of freedom; (i) approximately equal to half of the height of the tree, and (ii) approximately equal to the height of the tree. Finally, "visual position" had also two degrees of freedom; (i) initial position or the position supposed to be the best for the measurement, usually in the same contour line, and (ii) 90º opposite to the first one, usually in maximum slope.

The measurement procedure was carried out following this scheme: (i) choice of the position of the dendrometer, (ii) check the distance to the tree (helped by Truepulse hypsometer), (iii) place the dendrometer over the tripod, (iv) randomization of the observer, using a coin, (v) measurement of diameters at heights of 30, 80, 130 and 180 cm, (vi) diameter measurements at different heights (8 to 16 measurements) along the stem, (vii) choice of a different position to place the dendrometer, (viii) measurement of the total height with the two hypsometers and the dendrometer from the 4 locations (near and far for each visual position), (ix) measurement of diameters at 30, 80, 130 and 180 cm using a caliper and from the two positions of the

dendrometer. For each combination of factors, log volume was calculated through Smalian's formula.

Finally, trees were felled for the "real" measurement, following these steps: (i) measurement of tree height with tape, (ii) measurement of two opposite (90º) diameters with caliper over several points along the stem (30, 80, 130, 180 cm from the ground and every meter to the top). In each case, diameter was considered as the arithmetic mean of two opposite diameters. Altogether, 907 diameters over 38 trees were measured. The "true" volume of each log was measured using Smalian's formula.

In a second phase, measurements were carried out for all the trees of the inventory, altogether, 207 trees in 10 plots. The variables measured were DBH, HT and using the optimal location in each case, two diameters along the stem at different heights, trying to represent the taper of the trees with less measurements over more trees.

3. METHODS

Analyzed factors were grouped in two new variables, OPTION and METHOD, as it is shown in table 2 and 3. Calibration was only done for Criterion RD1000 dendrometer and consisted in fitting, for each OPTION, a simple linear relationship between the diameter measured with caliper at 30, 80, 130, and 180 cm and the diameter measured with dendrometer in this way: $D_{caliper} = \alpha + \beta D_{criterion} + \varepsilon$. All the models were fitted by generalized least squares using the GLM procedure of SAS/STAT statistics software (SAS INSTITUTE INC., 2002).

Table 2: Disaggregation of variable OPTION in different factors of influence upon result accuracy

OPTION	HYPSOMETER	DIRECTION	DISTANCE
1	Vertex	Good (≈CL*)	Near (≈ 0.5xH***)
2	Vertex	Good (≈CL)	Far (≈ H)
3	Vertex	Bad (≈MSL**)	Near (≈ 0.5xH)
4	Vertex	Bad (≈MSL)	Far (≈ H)
5	TruePulse	Good (≈CL)	Near (≈ 0.5xH)
6	TruePulse	Good (≈CL)	Far (≈ H)
7	TruePulse	Bad (≈MSL)	Near (≈ 0.5xH)
8	TruePulse	Bad (≈MSL)	Far (≈ HT)
9	Criterion RD1000	Good (≈CL)	Near (≈ 0.5xHT)
10	Criterion RD1000	Good (≈CL)	Far (≈ HT)
11	Criterion RD1000	Bad (≈MSL)	Near (≈ 0.5xHT)
12	Criterion RD1000	Bad (≈MSL)	Far (≈ HT)

*CL: Contour Line

**MSL: Maximum Slope Line

***H: Total Height

Table 3: Disaggregation of variable METHOD in different factors of influence upon result accuracy

METHOD	METHODOLOGY	CALIBRATION
FELLED	TAPER_FELLED	NO
TREE_NO	TAPER_TREE	NO
TREE_YES	TAPER_TREE	YES
PLOT_NO	TAPER_PLOT	NO
PLOT_YES	TAPER_PLOT	YES

In order to calculate volume for each factor combination, taper equations were developed for each OPTION. A taper equation describes a mathematical relation between tree height and the stem diameter at that height. It is thus possible to calculate the stem diameter at any arbitrary height and conversely, to calculate the tree height for any arbitrary stem diameter. Consequently, the stem volume can be calculated for any log specification and it is possible to develop a volume equation for classified product dimensions (GADOW et al. 2001). Due to good results in other species (CASTEDO & ÁLVAREZ-GONZÁLEZ, 2000; ROJO et al., 2005), only a model described by HUI & GADOW (1997), based on the model by RIEMER et al. (1995) was analyzed, as it is shown in table 4. All the models were fitted by generalized least squares using the MODEL procedure of SAS/ETS statistics software (SAS INSTITUTE INC. 2002).

With the aim of refining the sample before the development of the taper equation, a local regression curve with a smoothing parameter of 0.35 was fitted using the LOESS procedure of SAS/STAT (SAS INSTITUTE INC. 2002). This approach, pioneered by CLEVELAND et al. (1988), is flexible because no assumptions about the parametric form of the regression model are needed. The residuals of the nonparametric curve were examined for detecting abnormal data points (BI, 2000).

Table 4: Mathematic formulation of the used taper equation

Model	Formulation
Hui & Gadow (1997)	$$d = 2*\left(\left(\frac{b_0}{\left(1-EXP\left(b_2*\left(1.30-\left(\frac{H}{100}\right)\right)\right)\right)}\right)+\left(\left(\left(\frac{D}{2}\right)-b_0\right)*\left(1-\frac{1}{1-EXP\left(\alpha_4*\left(1.3-\left(\frac{H}{100}\right)\right)\right)}\right)\right)+\left(\left(EXP^{(-\alpha_4*h)}\right)*\frac{\left(\left(\frac{D}{2}\right)-b_0\right)*EXP(1.3*\alpha_4)}{1-EXP\left(\alpha_4*\left(1.3-\left(\frac{H}{100}\right)\right)\right)}\right)-\left(\left(EXP(b_2*h)\right)*\frac{b_0*EXP\left(-b_2*\left(\frac{H}{100}\right)\right)}{1-EXP\left(b_2*\left(1.3-\left(\frac{H}{100}\right)\right)\right)}\right)\right)$$ *where* : D=Diameter at Breast Height H=Total Height h=mesured height $b_0=\alpha_1 \cdot D$ $b_2=\alpha_3 \cdot \left(\frac{H}{100}\right)^{\alpha_2}$ $b_1=\alpha_4$

First of all, possible differences between volume estimation using data of stand trees (METHODOLOGY=TREE or METHODOLOGY=PLOT) and the taper built from felled trees (METHODOLOGY=FELLED) were assessed. Subsequently, possible differences between "true" volume (Log volumes in cubic meters were calculated using Smalian's formula) and the volume obtained with the different METHODs were assessed.

Mixed effect models (VARJÖ et al., 2006) were used to explain volume differences between methodologies, where METHOD and OPTION factors were assumed to be fixed and the OBSERVERS and the TREES were treated as random variables. This type of model is very useful when an explanation of fixed factors is needed while random factors are controlled. In the case of variance heterogeneity, that is to say, when the explained variable (error in volume) depend on the real value of that variable (volume), a weighted regression was carried out. Besides, errors in relative terms were calculated to avoid variance heterogeneity, because errors in devices depend on the size of trees (WILLIAMS et al., 1998). All parameters were estimated applying MIXED procedure of SAS/STAT statistics software (SAS INSTITUTE INC. 2002). Model assessment variables (bias, relative bias, precision and relative precision) are shown in table 5.

Table 5: Model assessment variables

variable	**calculation**
bias (*b*)	$volume_{true} - volume_{observed}$
relative bias (*b%*)	$(volume_{true} - volume_{observed})/ volume_{true}$
precision (*p*)	$\lvert volume_{true} - volume_{observed} \rvert$
relative precision (*p%*)	$\lvert(volume_{true} - volume_{observed})/ volume_{true} \rvert$

4. RESULTS AND DISCUSSION

4.1. Accuracy of volume estimation with different taper equation methodologies

This first part of the analysis consisted in comparing results between different methodologies for taper equation development (METHODOLOGY=TREE or PLOT with FELLED METHODOLOGY).

Bias and precision (in absolute and relative terms) were assessed, being the real value the obtained from calculating the volume with the taper equation developed with felled trees. Thus, where residuals are positive, it means underestimation of volume by the equation developed with data from dendrometer measurements.

Results obtained with the mixed effect model are shown in table, where factors are those detailed in tables 2 and 3. Numeric values of accuracy (bias and precision) for each OPTION can be observed in figure 2.

Regarding bias, results from TAPER_TREE are always more similar to those obtained with TAPER_FELLED than the ones obtained with TAPER_PLOT. Besides, less biased results are obtained after calibrating the dendrometer. Unbiased results are obtained by always calibrating the dendrometer (TREE_YES), measuring from a distance similar to the height of the

tree, measuring from the best direction (usually, in the same contour line) and using either Vertex, Truepulse or Criterion to estimate heights (OPTION 2, 6 or 10). Analyzing results in relative terms, that is to say, taking into account tree's volume, ANOVA table shows significant differences in any case, although in terms of methodology, unbiased results are only obtained with TAPER_TREE. For the interaction of factors, unbiased results are only obtained using TREE_NO (without calibrating diameters), measuring height with Truepulse from a distance similar to the height and form a good direction (OPTION 6).

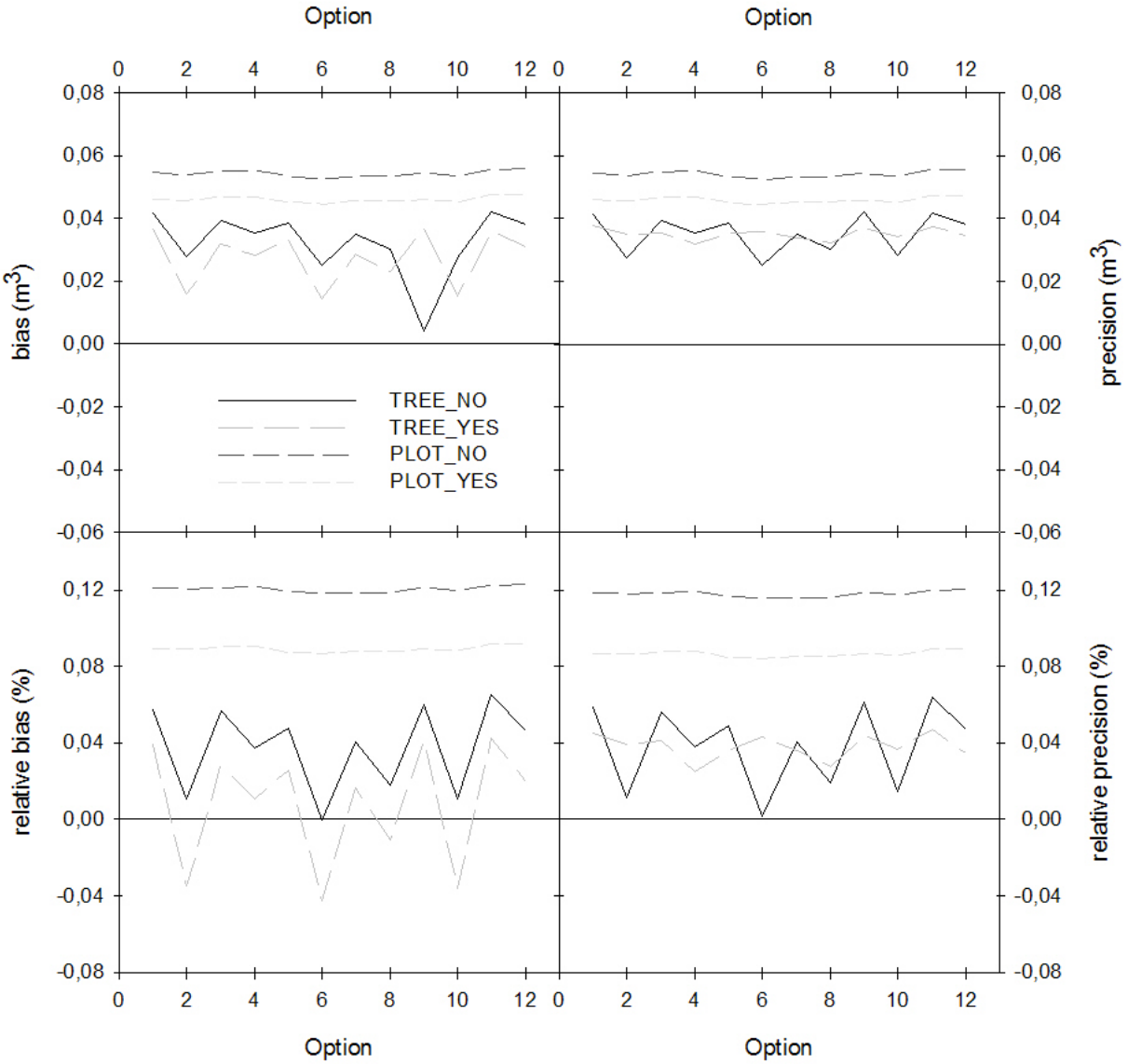

Figure 2: Representation of bias (up - left), precision (up - right), relative bias (down - left) and relative precision (down - right) through different METHOD x OPTION combinations assuming TAPER_FELLED is the "true" volume.

Table 6: F value of ANOVA to assess bias (b), precision (p), relative bias (b%) and relative precision (p%) of the comparison between results from developing a taper equation from felled trees and results from the taper equation developed with data from dendrometer measurements.

Effect	DF	Bias (b)	Precision (p)	Relative bias (b%)	Relative precision (p%)
Method	3	172.38*	106.49*	3015.42*	1276.70*
Option	11	10.05*	2.84*	115.10*	20.41*
Method X Option	33	2.55*	1.26	36.29*	13.15*

DF: Degrees of Freedom

About precision, results are similar, with better results using TREE_NO. In this case, ANOVA does not show differences between methods and locations (combinations of direction and distance), although the greater precision is obtained measuring from the "good" direction, at a distance similar to the height of the tree and measuring the height either with Vertex, Truepulse or Criterion (OPTION 2, 6 or 10). In relative terms, the better option is the same it was unbiased in the percent bias analysis.

4.2 Accuracy of volume estimation with different taper equation methodologies compared to volume as the sum of logs calculated through Smalian's formula

This second part of the analysis consisted in comparing the results with taper equations and the results of volume calculation by logs: three methodologies were considered in order to develop the taper equation; from felled trees (TAPER_FELLED), from several measurements with dendrometer over some stand trees (TAPER_TREE) and from some measurements with dendrometer over all the trees in the plot (TAPER_PLOT).

In all cases, bias and precision were assessed both in absolute and relative terms, assuming as true volume the one obtained calculating it by logs through Smalian's formula. Thus, where residuals are positive, the developed taper equation underestimates the volume of the tree. Analyzing the bias, ANOVA does not show significant differences in the interaction METHOD x OPTION (see Table 7). Bias only appears in TAPER_PLOT methodology, being unbiased for the other methodologies. The best results are obtained when developing the equation with felled trees (TAPER_FELLED). Calibration of diameter always enhance the results, being unbiased in all cases. If the calibration is not made, small bias is obtained only measuring near the tree. Otherwise, biased results are obtained. In relative terms, ANOVA shows significant differences in all cases. At a methodology level, bias appears only in TAPER_PLOT. Analyzing interaction of factors, most of the combinations reflect unbiased results.

Regarding the precision, ANOVA table shows significant differences only between methods, being TAPER_PLOT less precise than the other two (TAPER_FELLED y TAPER_TREE). There is no enhancement of results by calibrating diameters. Relative and absolute terms show similar results. Numeric values of accuracy (bias and precision) for each OPTION can be observed in figure 3.

Table 7: F value of ANOVA to assess bias (b), precision (p), relative bias (b%) and relative precision (p%) of the comparison between volume obtained with taper equation and the volume calculated by logs through Smalian's formula.

Effect	DF	Bias (b)	Precision (p)	Relative bias (b%)	Relative precision (p%)
Method	4	40.00*	15.41*	238.27*	35.83*
Option	11	3.19*	0.61	10.76*	1.24
Method X Option	44	0.61	0.50	2.12*	1.13

DF: Degrees of freedom

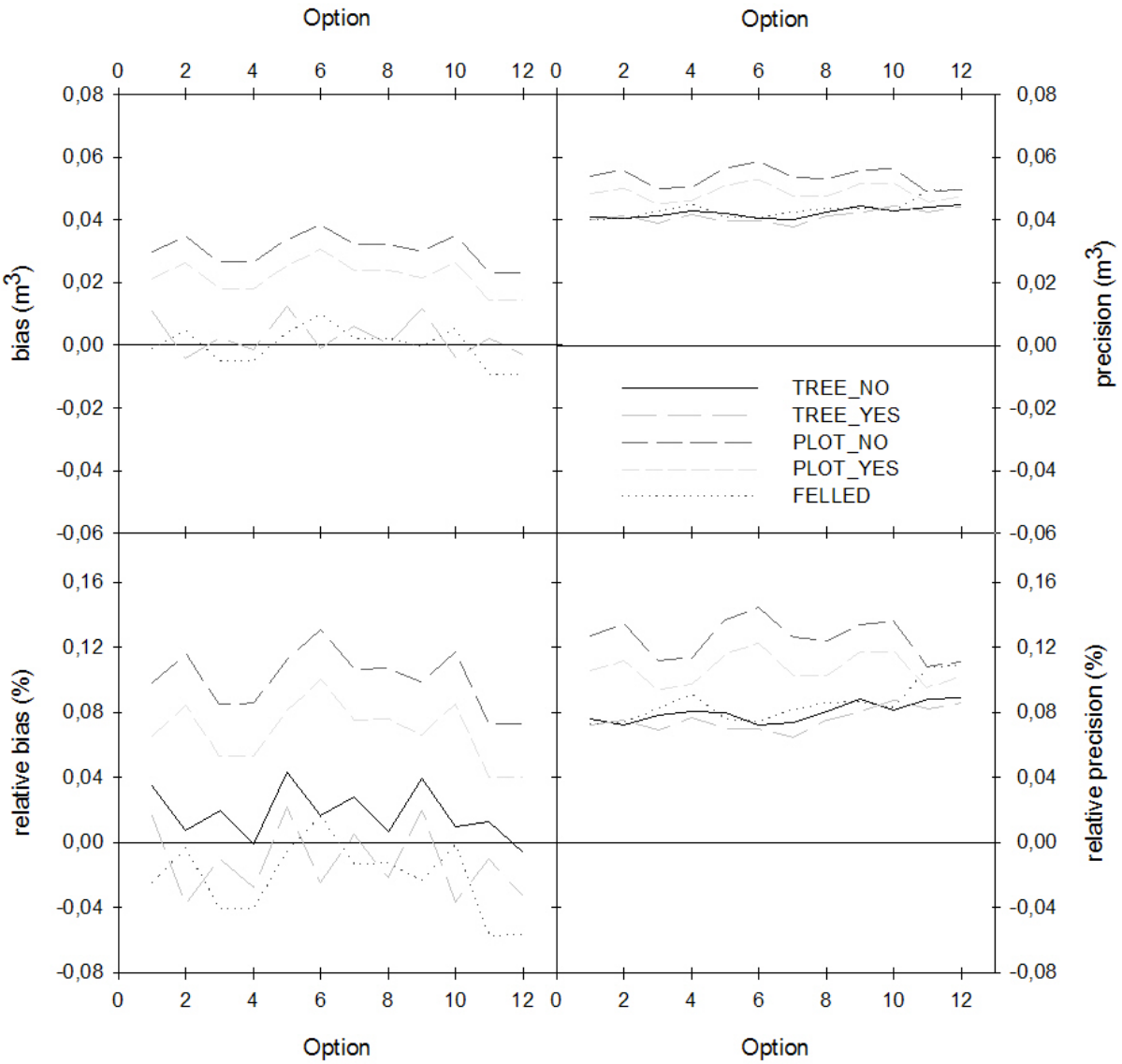

Figure 3: Representation of bias (up - left), precision (up - right), relative bias (down - left) and relative precision (down - right) through different METHOD x OPTION combinations assuming "true" volume as the one calculated with Smalian's formula

4.3. Calibration assessment

Finally, and only over the data measured with Criterion RD1000, the influence of calibration was assessed using caliper data. Bias and precision were calculated and compared with data for real volume. Results from the ANOVA are shown in table 8. Interaction of factors is never significant, while the effect of calibration is significant only for the bias, being positive (volume underestimation) without calibration, and negative (volume overestimation) with calibration. In general terms, there are no significant differences between calibrations or not for the same OPTION. Table 9 shows numeric values from the mixed effect model.

Table 8: F value of ANOVA to assess bias (b), precision (p), relative bias (b%) and relative precision (p%) of the CALIBRATION effect depending on the OPTION

Effect	DF	Bias (b)	Precision (p)	Relative bias (b%)	Relative precision (p%)
Calibration	1	19.92*	0.93	50.35*	1.91
Option	11	2.95*	0.77	7.02*	1.46
Calibration X Option	11	0.19	0.12	0.49	0.24

DF: Degrees of Freedom

Table 9: Model assessment variables (bias, precision, relative bias and relative precision) of the CALIBRATION effect

Effect	Bias (b)	Precision (p)	Relative bias (b%)	Relative precision (p%)
Calibration_NO	0.0043	0.0376	0.0178	0.0799
Calibration_YES	-0.0034	0.0365	-0.0112	0.0758

5. CONCLUSIONS

It seems likely that if the measurements are made at a distance similar to the height of the tree and using either Vertex or Truepulse, results are precise and unbiased. Some enhancement is obtained by calibrating, but does not seem compulsory since results in both bias and precision are good enough without calibration.

Comparing taper equation developed with both stand trees and felled trees, unbiased and precise results are only obtained if the measurements are taken from a distance similar to the height of the tree and in the best position (usually, contour line). Total height can be measured using either Vertex, Criterion or Truepulse, being preferred the latter.

Besides, volume estimation using taper equations developed with data from felled trees is unbiased and precise. When the equation is developed using measurements of the dendrometer over stand trees, that lack of bias and high level of precision is not always reached. Thus, TAPER_PLOT methodology is always biased and less precise than the others, while for the methodology by tree (TAPER_TREE) in most of the combinations, results are unbiased and precise, with no difference between calibrating or not the diameters.

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