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A Model to Estimate Tree Size when Trunk Girth Cannot be Used

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Abstract

Tree size measurements are usually taken to estimate the bearing potential of a tree, and also as a covariate to be used in the analysis of covariance in field experiments. The more simple measurement is trunk circumference, but in some cases this measure is not related to tree size, particularly in multi-trunk trees, in old trees with trunks showing geometry different to a cylinder, or in uncrowned trees. In such cases, the height and spread of the canopy is measured to calculate canopy volume, but this estimation is sometimes tedious and imprecise. In the present work, the relationship between trunk girth and the girth of the main branches (scaffold limbs) was determined in almond, walnut and olive trees to establish a model to estimate tree size. The experimental trees were trained in a vase-shape with trunks of 90 to 100 cm in height. The most accurate relationship between trunk girth and the girths of the main branches was $TC = 1.6, \overline{BC}$ where TC is the trunk circumference and $\overline{BC}$ the average branch circumference. This model was validated for the three species and was applied to estimate tree size in multi-trunk olive trees. In these trees, an imaginary single-trunk was calculated for each tree using the previous model combining the individual trunk girths by adding them and dividing the sum by the number of trunks per tree. The imaginary single-trunk circumference was highly and significantly correlated to canopy volume and linearly related to fruit yield, suggesting that it could be a more precise and easy measure that may be used as a substitute of canopy volume to estimate relative tree size.

Growth consists of an irreversible increase in size usually accompanied by an increase in dry weight. Fruit trees, as most woody species, grow by forming new shoots and extending the old ones, and by thickening those formed, and there is a need for some measure of each in order to define tree growth and/or size. Trunk girth is a simple measure that is easily practicable under field conditions and has been related to tree weight and fruit yield in many tree species (Westwood, 1993). Thus tree size can be estimated by the size of the trunk. In fact, trunk circumference is usually used as the measure of total tree size to estimate the bearing potential of a tree and is also used as a covariate in the analysis of covariance performed in field experiments. In some cases, trunk circumference is converted to trunk diameter or trunk cross-sectional area.

This measurement generally works better with young trees, where trunks are similar to a cylinder and where the trees are lightly pruned, although it also works with older trees that maintain these characteristics. Trunk circumference is generally measured at about 20 to 25 cm from both the graft union and the lowest branch, and the position is usually marked if it is to be recorded yearly. However, some fruit trees are trained with a short trunk that makes it difficult to get a precise measure of trunk circumference. Also, this measure is unrelated to tree size in old trunks showing protuberances or a geometry that is different from that of a cylinder; in trees subjected to severe, renewal pruning, sometimes uncrowned; or in multi-trunk trees. In such cases, a common alternative is to measure the height and spread of the canopy to calculate canopy volume. Depending on tree shape, this volume can be simulated using a spheroid or an ellipsoid form, but three to

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four measures per tree are required in order to achieve a good estimate. Such measurements can be tedious and sometimes imprecise, and may also depend on the person who takes the measurements. An estimation of tree size can also be obtained using devices such as ultrasonic sensors (Zaman et al., 2006) or by remote sensing images assessed by a computer program (García-Torres et al., 2008), but in field experiments this measurement is usually taken directly.

Accordingly, there is a need for more simple measurements of tree size in many situations such as in the cases mentioned above. In this context, Pearce (1976) suggested for apple trees that sometimes it is useful to measure branch girths and to combine them by adding the branch circumferences and dividing the sum by the square root of their number. Use of such tree measurements for different fruit trees might provide a good estimation of tree size.

The main objective of this work was to obtain a measure for estimating tree size that could be used as a covariate for the analysis of covariance instead of canopy volume. For this purpose, the first goal was to estimate trunk size from branch measurements on trees with several primary scaffold branches, and the second was to apply the model obtained in olive trees with multi-trunks.

Materials and Methods

Relationship between trunk girth and the girth of branches. In this study the objective was to obtain a possible model that expresses the relationship between trunk girth and the girths of main branches in trees trained in a vase-shape (open-center tree) where a single trunk is divided into two to four main branches, usually three. This training system is one of the most popular and is widely used in many different fruit tree species.

For this purpose, the following expression can be established:

$$TC = \frac{\sum BC}{k} \qquad [1]$$

where *TC* = trunk circumference, *BC* = branch circumference, and $k = f(n)$, being n = number of branches. These measurements, branch circumference and number of main branches per tree, are easily obtained under field conditions.

Two different approaches were conducted to solve this equation:

Approach 1:

$$k = n^{X1}$$

From Eq. [1]:

$$k = \frac{\sum BC}{TC} = n^{X1}$$

taking logarithms:

$$\log \sum BC - \log TC = X1 \log n$$

and

$$X1 = (\log \sum BC - \log TC)/\log n$$

Approach 2:

$$k = n\, X2$$

From Eq. [1]:

$$k = \frac{\sum BC}{TC} = n\, X2$$

and

$$X2 = (\sum BC/TC)/n$$

Plant material and measurements. The study was developed with three fruit tree species, almond (*Prunus dulcis* (Mill.) D.A. Webb), walnut (*Juglans regia* L.) and olive (*Olea europaea* L.), located at the Experimental Farm of Alameda del Obispo, in Córdoba, Southern Spain. Seventy five mature and 26 young almond trees spaced at 7 m x 6 m, 39 mature walnut trees spaced at 9 m x 9 m, and 73 mature olive trees spaced at 7 m x 7 m, were selected for measurement (Table 1). All these trees have a trunk of 90-100 cm in height because they are prepared for mechanical harvesting, and were trained in a vase-shape with 3±1 main branches. These trees are from different varieties of

Table 1. Characteristics of the three species evaluated in this study showing tree age and tree size.

Species	Age (years-old)	Average trunk circumference (cm)
Almond (mature)	12	70.8
Almond (young)	3-4	29.3
Walnut	28	120.3
Olive	14	61.7

each species because they are included in variety trials carried out in the Experimental Farm. Trunk and branch circumferences were measured directly with a tape at 20 to 25 cm from either the graft union or the branch insertion into the trunk.

Applying the model to multi-trunk olive trees. This study tried to apply the model developed in the above section to multi-trunk olive trees. The trees were selected from field experiments carried out in different localities of Granada Province, Southern Spain. Thirty-year-old 'Hojiblanca' olive trees spaced at 10 m x 10 m were selected from one locality. Two other localities included 40-year-old 'Picual' olive trees spaced at 10 m x 10 m, and the forth locality included 15-years-old 'Picual' trees spaced at 7 m x 7 m. All the trees were trained in the traditional form with a canopy formed from 2 to 4 trunks. Hence, across these locations, it was possible to select trees of two different varieties, of different age and under several environmental conditions.

Trunk circumferences were determined as indicated in the above section, and the measurements were combined to calculate an imaginary single-trunk of each tree according to the model developed above. The imaginary single-trunk is an estimation of tree size. Another measure of tree size was determined based on calculating the canopy volume using a simulated ellipsoid. The volume of an ellipsoid is given by the formula V=4/3 πabc, where a, b and c are the semi-axes of the ellipsoid, that were determined using a graduated surveying rod. Trees were harvested mechanically, and the individual yield per tree was recorded so that it could be related to the tree size measurements. Both the canopy volume and yield of each tree were obtained in 2010 and 2012.

Correlation and regression analyses were performed on the data using the statistical program Statistic Version 9.0 (Analytical Software, Tallahassee, FL, USA).

Results and Discussion

Mature and young almond trees were studied separately, but since no differences were found between them, all trees were combined into the same data set. Values of X1 and X2, which correspond to both approaches to the solution of Eq. [1] in the three species studied, are shown in Table 2. The results obtained were very similar among species. For the first approach to Eq. [1], the *k* values were:

Almond: $k = n^{0.61} \approx \sqrt[5]{n^3}$ and $TC = \dfrac{\sum BC}{\sqrt[5]{n^3}}$

Walnut: $k = n^{0.52} \approx \sqrt{n}$ and $TC = \dfrac{\sum BC}{\sqrt{n}}$

Olive: $k = n^{0.47} \approx \sqrt{n}$ and $TC = \dfrac{\sum BC}{\sqrt{n}}$

Walnut and olive gave the same model with this approach, and is the same suggested by Pearce (1976) for apple trees. However, the model for almond was different.

The second approach for Eq. [1] gave the following results:

Almond: $k = 0.66n$ and $TC = \frac{\sum BC}{0.66n} = 1.51\overline{BC}$

Walnut: $k = 0.60n$ and $TC = \frac{\sum BC}{0.60n} = 1.67\overline{BC}$

Olive: $k = 0.62n$ and $TC = \frac{\sum BC}{0.62n} = 1.61\overline{BC}$

where $\overline{BC}$ is the average branch circumference.

The results were, in this case, very similar among species and seem to be better than the first approach since both the SE of the means and the coefficients of variation (CV) were lower (Table 2). That means that there was less variability and, consequently, more precision in the estimate.

In comparison, the linear correlation between trunk circumference (TC) and the mean value of branch circumference ($\overline{BC}$) was highly significant, with coefficients of correlation of r = 0.98*** for almond, r = 0.90*** for walnut, and r = 0.81*** for olive. Hence, a regression model with TC as the dependent variable could be fitted. To gain precision, the regression model was forced through the origin, since such a constraint is plausible in this case. The results were almost the same as those obtained with the second approach (Table 3), suggesting that the regression relationship could be the more adequate model to express the relationship between trunk girth and branch girth in a number of different species. This assumption can be further tested by applying techniques to validate the regression models. Since the three species were trained in the same system, the data set of each one may serve to validate the model for the others. The r^2 values and other parameters were similar in all three species (Table 3) and also in the complete model developed by combining the data sets of the three species providing some assurance about the applicability of the model. Accordingly, a general model for these three species can be proposed as:

$$TC = 1.6\ \overline{BC}$$

Marini (1999) developed a model to estimate apple diameter from fruit mass using different techniques to validate models, which will be applied in the present work. The analysis of residuals, that is, the difference between the observed and

Table 2. Mean and dispersion values for X1 and X2, which correspond to both approaches to the solution of Eq. [1].

Values	Species					
	Almond		Walnut		Olive	
	X1	X2	X1	X2	X1	X2
Mean	0.61	0.66	0.52	0.60	0.47	0.62
SE[z] mean	0.006	0.005	0.016	0.008	0.010	0.009
CV (%)[y]	9.86	7.37	19.45	9.01	18.39	13.05
Minimum	0.36	0.50	0.24	0.50	0.23	0.45
Maximum	0.73	0.83	0.67	0.72	0.67	0.79

[z] Standard error
[y] Coefficient of variation

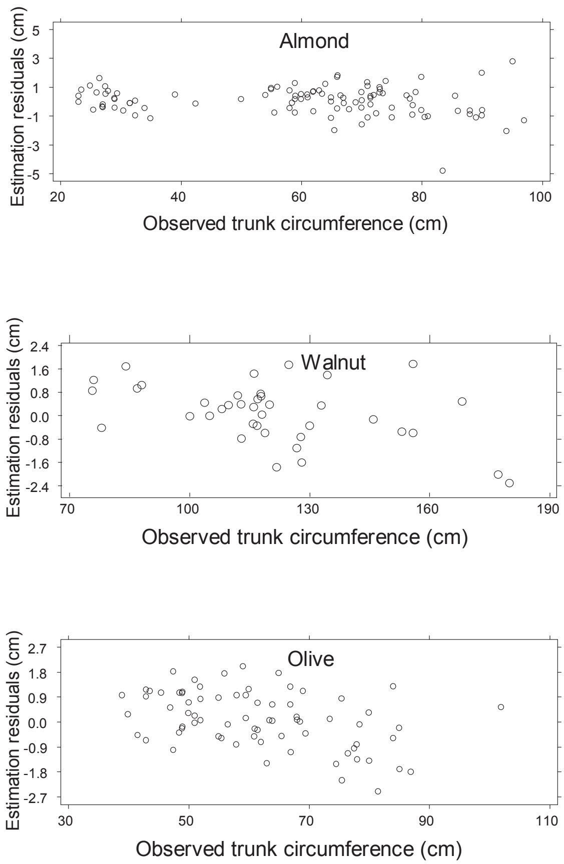

Fig. 1. Data distribution after estimated residuals were plotted against observed values.

fitted values, is an important technique for evaluating the fit of regression models, although may not be good for prediction. The residuals of the estimations were plotted against the observed trunk circumferences in the three species (Fig. 1), showing a random distribution in a horizontal band centered around zero and suggesting a good fit of the data to the model. Since the distribution of the data was similar in all three species, the model can be assumed to be a good predictor.

The PRESS (prediction sum of squares) criterion is a measure of how the fitted values can predict the observed ones. The PRESS value is always larger than the error sum of squares (SSE) and, in this work, relatively close to it (Table 3), suggesting the validity of the regression model for prediction. The PRESS residuals can be used to calculate an r^2-like statistic that indicates the prediction capabilities (Myers, 1990, cited by Marini, 1999). For the complete model data set this statistic was calculated as:

$$r^2_{pred} = 1 - (\text{PRESS/total sums of squares}) = 1 - (14078/1288286) = 0.9891$$

Thus the general model developed from the complete data set explains 98.9% of the variability. The value is very close to 0.9892, the r^2 value of the regression line shown in Table 3, suggesting again that the model is a

Table 3. Regression analysis of trunk girth (*TC*) vs. branch girths (*BC*) and parameters estimated from four data sets.

Statistic	Species			
	Almond	Walnut	Olive	Complete model[z]
Linear regression[y]	$TC = 1.52\ \overline{BC}$	$TC = 1.67\ \overline{BC}$	$TC = 1.62\ \overline{BC}$	$TC = 1.60\ \overline{BC}$
Standard error for $\overline{BC}$	0.01	0.024	0.024	0.01
Error sums of squares (SSE)	1855	4681	4766	13870
Prediction sum of squares (PRESS)	1902.1	4974.4	4905.1	14078
Mean square error (MSE)	18.54	123.19	66.20	65.42
Coefficient of determination (r^2)	0.995	0.992	0.984	0.9892
Significance[x]	***	***	***	***
Total degrees of freedom	101	39	73	213

[z] The complete model was developed by combining the data sets of the three species.
[y] Forced through the origin.
[x] ***Significant at $P \leq 0.001$.

good predictive model to predict trunk size from branch measurements.

Table 4 shows the correlations between actual and predicted trunk girth by the estimation model built on each species and the general model proposed. The correlations obtained were identical for each species. The data suggest that the conclusion drawn from these species is likely to hold true for other tree species trained in a vase-shape.

The results obtained with the three species studied served to define a simple model to explain the relationship between trunk girth and branch girths, with the aim of applying it to trees where trunk girth cannot be used to estimate tree size, as occurs in multi-trunk olive trees. This is a traditional training system for olive trees in many olive growing areas, where the usual estimation of tree size is canopy volume. In the multi-trunk olive trees in this study an imaginary single-trunk of each one was calculated using the general

Table 4. Correlations (*r*) between actual and predicted trunk girth in relation to the estimation model obtained for each species and the general model proposed.

Species	Estimation model[z]	General model[y]
Almond	0.978***	0.978***
Walnut	0.899***	0.899***
Olive	0.811***	0.811***

[z] Results of the regression analysis
[y] $TC = 1.6\ \overline{BC}$

Table 5. Mean and dispersion values for the imaginary single-trunk and canopy volumes in two years.

Values	Imaginary trunk circumference (cm)	Canopy volume 2010 (m^3)	Canopy volume 2012 (m^3)
Mean	103.3	58.14	47.97
SE[z] mean	4.7	4.2	3.8
CV (%)[y]	35.9	57.8	63.2
Minimum	44.3	13.0	9.0
Maximum	165.6	133.8	119.9

[z] Standard error
[y] Coefficient of variation

model developed above. Values obtained for these trunks and canopy volumes are shown in Table 5. These imaginary single-trunks were highly correlated to the canopy volume for both years (r = 0.82*** in 2010 and r = 0.74*** in 2012). Although highly and significantly correlated, there were differences in the r values between both years that could be due, at least in part, to the fact that the measure of canopy volume is more imprecise and may depend also on the person that takes the measurement. Differences in the correlation coefficients between years were also reported with canopy measures of olive trees using remote sensing images and direct measurements in the orchard (García-Torres et al., 2008), with the higher r values similar to those obtained in the present study. As shown in Table 5, the variability (CV) was higher for measurements of canopy volume than for the imaginary single-trunk. In fact, r = 0.87*** for the correlation between canopy volume in both years in trees that were not subjected to severe pruning during this period. Regardless, high correlations were obtained and data suggest that the imaginary single-trunk determined according to the model proposed could be used as a substitute for canopy volume to estimate relative tree size.

The measure of tree size is of great interest in estimating the bearing potential of a tree, and in field experimentation since it is usually used as a covariate in the analysis of covariance (Fernández-Escobar et al., 2010). For instance, the effect of treatments on fruit yield could be masked by tree size, since fruit yield and tree size are correlated. The use of tree size as a covariate allows the analysis of covariance to remove the effect of tree size and analyzes only the tree effect of treatments on yield. There are several requirements for the selection of a covariate, among which must be the independence of treatments (which is easy to check with an analysis of variance that shows that the F-test is not significant for treatments), and that the relationship between the dependent variable and the covariate must be linear (Snedecor and Cochran, 1967; Pearce, 1976). In our experimental trees, fruit yield was linearly related to both canopy volume and to the imaginary single-trunk girth (Table 6), showing a high significance and suggesting that both variables could be used as covariates in the analysis of covariance. This was the main objective of this work.

Fruit yield depends on many variables, among them tree size. According to the data presented here, tree size has an important role in fruit yield, but yield also depends on the effects of the other variables. Although the

Table 6. Regression analysis of fruit yield per tree vs. canopy volume or the imaginary single-trunk girth and parameters estimated for two years.

Statistic	Canopy volume	Trunk circumference
	2010	
Linear regression[z]	Yield = 1.24 canopy volume	Yield = 0.75 trunk circumference
SE[y] for independent variable	0.04	0.03
Error sums of squares (SSE)	35576	48376
Prediction sum of squares (PRESS)	37719	50710
Mean square error (MSE)	573.8	780.2
Coefficient of determination (r^2)	0.92	0.90
Significance[x]	***	***
r^2_{pred}[v]	0.91	0.89
AICc[u]	403.4	422.7
Total degrees of freedom	63	63
	2012	
Linear regression[z]	Yield = 0.61 canopy volume	Yield = 0.33 trunk circumference
SE[y] for independent variable	0.06	0.03
Error sums of squares (SSE)	53463	46966
Prediction sum of squares (PRESS)	55708	49056
Mean square error (MSE)	876.4	769.9
Coefficient of determination (r^2)	0.59	0.64
Significance[x]	***	***
r^2_{pred}[v]	0.57	0.62
AICc[u]	423.3	415.3
Total degrees of freedom	62	62

[z] Forced through the origin
[y] Standard error.
[x] ***Significant at $P<0.001$.
[v] r^2_{pred}=1- (PRESS/total sum of squares)
[u] Akaike's Information Criterion for small samples.

prediction of yield from canopy volume or trunk girth was not the objective of this work, the data presented in Table 6 showed that the PRESS value is close to SSE in all cases, and r^2_{pred} is also very close to r^2 of the linear regressions, indicating that both models could be good predictors of tree yield. Similar conclusions could be obtained with Akaike's Information Criterion (AIC) (Akaike, 1974). The AICc is the small-sample version of the AIC, which is useful for comparing models obtained with the same data set and calculated with the same dependent variable. The model with the lowest value is the best. The model could be built with canopy volume and the imaginary single-trunk as independent variables of a multiple regression, but since both variables were highly correlated, only the linear regression with each variable could be established. In this work, AICc values are similar in all cases (Table 6), being slightly lower for canopy volume in 2010 and for trunk circumference in 2012, indicating that both models had a similar precision. However, its accuracy depended on the year. The coefficient of determination was very similar with both variables and very high in 2010. In 2012 the results were identical, but r^2 was lower than in 2010. Also, fruit yield was different, and ranged between 63 and 83 kg per tree in 2010 and between 17 and 61 kg per tree in 2012. Regardless of the alternate bearing phenomenon that strongly affects olive trees, fruit yield in 2012 was characterised by high variability, with a coefficient of variation (CV) ranging from 57 to 63% in contrast to 2010 where the CV ranged from 2.2 to 6.3%. These differences were due to meteorological conditions, since 2010 was a normal year in the area with regard to temperatures but with higher rainfall than the average, and 2012 represented a year with a dry winter and a higher than average temperature during flowering. These two phenomena in 2012 directly affected olive flowering and fruit set. It is well known that dry winters provoke pistil abortion in olive (sometimes almost 100%) with a consequent reduction in yield (Uriu, 1960). In 2012, the percent of fertile flowers in our experimental trees was only about 18% in 'Picual' and 32% in 'Hojiblanca', although the incidence was different according to locality. Also, it is known that an increase in temperature during the flowering period may reduce fruit set because of a failure of pollination, and may provoke an increase of shotberries, which are small and partenocarpic fruits without commercial value (Fernández-Escobar and Gomez-Valledor, 1985). In our trees, shotberries increased in two localities in 2012 in comparison to normal years. These differences between years may explain the different r^2 obtained and the relative weighting given to tree size in predicting fruit yield. However, the results confirm that, independently of age, variety or environmental conditions, the imaginary single-trunk girth calculated according to the general model proposed in this work to estimate tree size based on the measure of multi-trunk girths, is a precise and easy measure that may replace canopy volume in field experiments with multi-trunk olive trees. Taking into account the validation of the model for different fruit tree species trained in a vase-shape, it can be concluded that it is likely that the results are applicable to other fruit tree species where trunk girth cannot be used to estimate tree size.

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