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STRUCTURE ANALYSIS AND BIOMASS MODELS FOR PLUM TREE (*Prunus domestica* L.) IN ECUADOR

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Summary

The development of dendrometric methodologies could allow accurate estimation of variables associated with the crown, such as primary production (fruit and timber) and tree vigor. The aim of this work was to develop a suitable method to estimate woody biomass in plum trees (*Prunus domestica* L.) in Imbabura, Ecuador by using an adapted dendrometry. Form factors and regression models were defined for branch volume calculation. From this, the distribution of woody biomass in the crown tree was characterized in every stratum. Occupation Factor and regression models were obtained in order to calculate the biomass in the crown tree, which can be used to estimate the CO2 captured in its structure during its development. Regression models for calculation of whole volume of the tree and pruned biomass were directly obtained from crown diameter and crown height with Rajustated^2 of 0.74 and 0.81. The average moisture content of green material was 51% and the average density of dry material was 0.66±0.07 g cm-3. Proximate analysis of plum wood showed at 79.8±9.2% volatiles and 2.1±0.3% ash. Elemental analysis of the wood pointed to 46.5±1.2% C, 6.1±0.5% H, 46.3±1.2% O, 0.6±0.3% N, 0.06±0.02% S, and 0.02±0.01% Cl. Cl, S and N contents are lower than the limits established by the standard EN 14691-part 4. With 46% of C, considering the relation 3.67 (44/12) between CO_2 and C content, the CO_2 sequestrated in the materials is 1.11 Mg m^{-3} wood material. Such method represents a tool to manage orchard resources and for assessing other parameters such as raw materials for cultivation, fruit production, CO_2 sink, and waste materials (residual wood) used for energy or industry.

Keywords: bioenergy, energy wood, logistics, yield prediction, residues

INTRODUCTION

The dendrometric characterization of individual forest trees has been an important issue to estimate wood volumes for industry and to perform forest inventories. However, dendrometric techniques have been poorly applied in agriculture due to the minimum use of wood up to now. New challenges in agriculture lead to the application of these techniques in order to calculate the wood in fruit trees and relate biomass to the amount of CO_2 captured from the atmosphere through photosynthesis during its growth (Francis, 2000). Evaluation of Life Cycles and waste materials can also be done with those techniques (Bessou et al., 2013). Volume of trees is necessary when applying remote sensing techniques, either spectral images or LiDAR (Persson et al., 2002; Andersen et al., 2006).

The hypothesis of this work is based on a reasonable proportionality between the different elements of natural systems, when they are in equilibrium. Therefore the amount of matter in the different structures of the plum trees will be related, maintaining a balanced proportionality which would be characteristic of the species, climatic conditions and cultivation practices (Velazquez et al., 2010). The study of methods to calculate the biomass would allow further analysis to establish the relations with useful information to manage the orchards, such as residual biomass predictions or inputs and yield estimations.

The difficulty in determining the direct volume in fruit trees leads to allometric relations (Olson and Rosell, 2013) and they were applied by Deckmyn et al. (2006) to model of wood development. Dendrometric parameters were related to the amount of residual material obtained from pruning in olive trees, almond trees, vineyards and citrus trees (Velázquez-Martí et al., 2011a,b,c; 2013). Velázquez-Martí et al. (2012; 2014) developed allometric equations to evaluate wood in whole trees of citrus and olive trees. Estornell et al. (2014) used allometric equations from dendrometry to relate wood volume and height of olive tree plantations and airborne discrete-return LiDAR data. All these studies were carried out in Europe; however, different varieties of plants, diversity among climates, and differentiated types of crop management increase the importance of carrying out studies with other species growing in other ecosystems.

Ecuadorian areas where plum tree is cultivated, with permanently warm weather (air temperature usually between 14ºC and 23ºC, rainfall ranging between 1500 and 2500 mm per year), dispersed ownership structures, small size of farms and small planting area per tree, require a specific analysis. The development of new methodologies could allow the accurate estimation of variables associated with the crown, such as primary production (fruit and timber) and tree vigor (Maltamo et al. 2004). Some studies reported the importance of knowing crown characteristics for predictions of growth, waste materials (residual wood), fertilizer inputs, irrigation or pesticides (Doruska et al., 1994; Garcia-Tejero et al., 2012). Knowledge of existing biomass and its relationship with crown sizes is needed for planning the plantations, as well as the logistics for fruit harvesting or pruning management. In addition, it would serve as a tool for characterizing and cataloguing plots in biomass surveys (Velázquez-Martí and Annevelink, 2009; Gracia et al., 2014; Perez-Arevalo et al., 2015).

This research was focused on the development of equations to predict actual volume and total biomass contained in plum trees (*Prunus domestica* L.) from an adapted dendrometry and the estimation of residual biomass coming from pruning of orchards cultivated in Imbabura, Ecuador.

MATERIALS AND METHODS

Study area

In the first stage, fifty trees were sampled in two areas of Imbabura, Ecuador to obtain mathematical models; 25 trees in the area “Antonio Ante” (UTM X: 810913, Y: 10039425 (WGS 84), 2400 AMSL); and other 25 trees in the area “Pimampiro” (UTM X: 172965, Y: 44442 (WGS 84) 2350 AMSL). Both areas have air temperature ranging between 11.3 ºC and 21.2 ºC and rainfall is about 1100 mm per year in both sectors.

In the second stage, 15 additional trees were selected in each location in different plots to test and validate the models obtained. Plants were between 4 and 12 years old. The rows of trees were separated 4 m and trees were spaced between 2.5 to 4 m. Therefore, each tree had on average 12 m^2 of growing area (4 x 3 m).

Dendrometric analysis of branches

The aim of first dendrometric analysis was to obtain methods to calculate the volume of branches based on easily measurable parameters; such as, basal diameter and length. In order to achieve this goal, two approaches were used: the determination of form factors, and regression functions.

Form factor (*f*) is defined by equation 1 as the ratio between the actual volume of the branch (V_{branch}) and the volume of revolution, taken as reference model (V_{model}) a cylinder, paraboloid, cone or neiloid. In principle, the form factor is a characteristic of the species and the diameter class. However, there was a statistical variability for each determination and the average, the standard deviation, kurtosis and skewness coefficients were determined.

$$f = \frac{V_{branch}}{V_{\text{model}}} \tag{1}$$

Thirty branches of each tree (ten of the first stratum, ten of the second stratum and ten of the third stratum) were sampled (Supplementary Material Figure S1). The diameter of each branch was measured every 10 cm and the actual volume of each portion of 10 cm length was calculated using equation 2, which is a truncated cone equation. The whole volume was calculated as the sum of each portion between two sections, using equation 3. The model of branch volume was performed by applying the equation 4 from the base diameter (d) and length (L) of the branch.

$$V_{\text{i}} = \frac{1}{3} \cdot \pi \cdot h \cdot \left(R^2 + r^2 + R \cdot r\right) \tag{2}$$

$$V_{branch} = \sum_{1}^{i} V_i \tag{3}$$

$$V_{\text{model}} = k \cdot \frac{\pi \cdot d^2}{4} \cdot L \tag{4}$$

Where *R* is the radius of the largest section, *r* is the radius of the lowest section, V_i is the volume of a portion of branch, V_{branch} is the actual volume of the branch, V_{model} is the volume of revolution, *k*=1 for the cylinder, *k* =1/2 for the paraboloid, *k*=1/3 for the cone, *k*=1/4 for the neiloid, *d* is the diameter of the base, and *L* the length of the branch.

Regression functions were proposed to relate volume of the branch (equation 3) from basal diameter and branch length. Then, other thirty branches were evaluated with the proposed models (equation 4 and regression model). Deviations between direct measures of volume (equation 3) and the estimated by the models were evaluated through paired samples test based on Student distribution. This was carried out with Statgraphics Centurion XVI software v.16.1.17 (32 bits) of StatPoint Technologies Inc (USA).

Models to quantify wood biomass of the whole tree

In order to calculate the volume of woody biomass in the whole plant two methods were developed. Firstly, occupation factor was analyzed, followed by the development of regression models for predicting the volume from crown diameter, stem diameter and plant height. Occupation factor is defined as the ratio between the actual volume of all branches of the crown and the apparent volume of the crown. Apparent volume is obtained as a volume of revolution calculated from crown diameter and crown height. Cylinder model was analyzed as a volume containing both the branches and the gaps between them. Palaboloid, cone and neiloid are proportional to the cylinder.

For estimating the actual volume of sampled plum trees crown, branches were measured by applying the equation of regression model obtained in the previous dendrometric analysis. Branch measures were carried out by layers (strata). The stratum 1 corresponds to the branches sprouted from the stem. The number of branches of this stratum is usually low (3-4 branches), with their diameters being the highest. The stratum 2 is formed by the branches originated in the stratum 1 and the following strata are formed by the branches sprouted from the previous layer. All the branches of the stratum 1 (layer) were measured. The volume of woody biomass of next strata was calculated, selecting a sample of several representative branches of each. The mean of the volume of sampled branches in each stratum was multiplied by the number of branches and the total volume of each stratum was calculated separately. In other words, the number of buds or ramifications in successive strata was counted.

Generally, the last stratum contains very small branches. For this reason, it was not possible to evaluate it with the method previously described. In this case, several external central branches and another from the top of the crown were cut of each sampled tree, and their volumes were determined by submerging them into water. Then, the obtained volume was multiplied by the number of branches of the external stratum. Regression functions were also calculated to relate crown volume from crown diameter (*Dc*) and tree height (*H*).

In order to validate occupation factor and volume crown function, other thirty trees were evaluated. Deviations between actual volume and the estimation by the models were evaluated by means of paired samples test based on Student distribution. This was carried out by means of Statgraphics CenturionXVI software.

Pruning residues calculation

Sixty trees were pruned and evaluated in both areas. Before pruning, measurements of stem diameter, crown diameter and tree height were taken. Subsequently, the pruning was carried out by removing branches to increase light availability inside the crown and induce new sprouting. The branches affected by diseases were also thinned. The weight of cut branches were measured doing bundles and using a dynamometer or scale. In addition, 22 representative branches were stripped, obtaining the percentage of the leaf mass. Leaves were weighted just after cutting and dry matter was estimated taking into account the relative water content. Subsequently, regression models were applied to relate the amount of residues and plant size. Then, 30 additional trees were evaluated to validate the model.

Characterization of biomass

Higher heating value, moisture content, elemental composition (C, H, N, O, S and Cl) were measured for each sample as well as the proximal analysis (%ash, %fixed carbon, and % volatile gases) was done. The calorific value was measured by a LECO AC-500 isoperibolic calorimeter. The weight percentage of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) was measured by a LECO TruSpec CHNS analyzer. Chloride was measured from water condensate in the calorimeter vessel by potentiometric titration using $AgNO_3$. %ash and %volatile evaluations were based on the weight difference after dry biomass heating in an oven at 550 ºC for 1 h (to evaluate ash) and 940 ºC for 4 min (to evaluate volatile). Fixed carbon is given by 100-(%ash-%volatile). The characterization of the biomass materials was conducted according to the standards shown in Supplementary Material Table S1.

RESULTS AND DISCUSSION

Dendrometric analysis of branches

Statistical description of the measured variables in branches is shown in Table S2. All parameters have a skewness and kurtosis coefficient between -2 and 2. This fact indicates that variables followed a Gaussian normal distribution, with mean and standard deviation being obtained. Therefore, they can be used in regression models without restrains. The volume model with form factor closer to one represents better the shape of the branch. It can be observed that the model closest to one is the paraboloid and the branch shape tends to this geometry.

In the variance analysis of the regression models, the p-value was less than 0.01 for all variables (Table 1), which means a significant relationship between variables (diameter and length of the branch) and the volume. The high standard deviation can be explained by the high data variability caused in part by the dissimilar diameter of measured branches. Both methodologies, form factor application and regression model allowed the calculation of the branch volume from its base diameter and length with enough accuracy (Table 1).

In the method validation, the deviations between predicted values using form factor and the volume measured from equation 3 were lower than 1.5%. The paired samples test showed no significant difference between actual volume (equation 3) and the calculated by form factor (p=0.56). On the other hand, the method by regression model gave differences lower than 0.8% (Table 1). The good fit of function to obtain branch volume allowed measuring easily the woody biomass in the crown by strata. These equations usually give very good fit and some examples can be found in Sajdak & Velázquez-Martí (2012) or Sajdak et al. (2014) for other tree species.

Wood volume in the crown

According to the values of skewness and kurtosis coefficients, all parameters related to crow structure follow a normal distribution (Table 2). Methods developed to predict biomass volume were obtained for trees with crown diameter ranging between

2.3 and 3.8 m and total height between 2.4 and 3.4 m. These are the usual sizes of productive trees and the obtained model is likely useful for bigger trees after validation. In smaller trees, biomass calculation is less interesting, and the proposed models can be less consistent.

The obtained average of occupation factor was 0.61 cm^3 dm^{-3} with 0.21 cm^3dm^{-3} of standard deviation. This parameter establishes the relationship between the apparent volume of the plant (woody materials and hollow contained therein) and actual biomass volume. Similar values were obtained previously for citrus trees (Velázquez-Martí et al., 2013) and olive trees (Velázquez-Martí et al., 2014).

A representative plum tree biomass distribution is shown in Figure S2. The stem volume only represents around 2% of the total biomass, and the crown volume around 98%. This is quite different when compared to olive trees, which have the biggest amount of biomass in the stem (Velázquez-Martí et al., 2014). Focusing on the crown volume, the highest percentage of biomass is concentrated in the stratum 3. There is a symmetric trend in the crown biomass distribution, which is the highest in the centre, and then decreases towards the strata 1 and 5. This fact was already observed in citrus trees (Velázquez-Martí et al., 2013). It should be noticed from the analysis that the stratum 5 located in the periphery of the crown contains small branches. Although their number is high, it does not represent a significant biomass.

A regression model was directly obtained from crown diameter and crown height to obtain the whole volume of the tree (Table 1); the variance analysis provided p-values for independent variables lesser than 0.01. It is observed that the best model provided a R^2=0.74, which means that it explained 74% of the variability of the volume of woody biomass contained in the plant. For this model the standard deviation of differences between observed and predicted values was 3115 cm^3 and the mean absolute error was 2328 cm^3. Regarding the model validation, deviations between the volume predicted by regression model and the actual volume measured in each tree were lower than 5.8% (Table 1).

The average moisture content of green material was 51% and the average density of dry material was 0.66±0.07 g cm^{-3}. With 46% of C, considering the relation 3.67 (44/12) between CO_2 and C content, the CO_2 sequestrated in the materials is 1.11 Mg m^{-3} wood material

Pruning residues calculation

The average weight of the dry woody residues without leaves obtained from pruning reached 2.34±0.97 kg per tree, which means around 2.0±0.8 Mg biomass per hectare every year. High dispersion in this measure can be caused by pruning style, area per tree, irrigation, light, temperature and others. To fit the best regression model that describes the relationship between residual biomass from pruning, simple and quadratic equations from combinations of crown and stem diameter and tree height were tested as explanatory variables. The best fit was obtained with crown diameter and stem diameter, with p-value lower than 0.01 for all variables and $R_{adjusted}^2$ of 0.81 (Table 1). Estimations of the amount of pruned woody biomass had maximum deviations of 6.7% and the average percentage of leaves in the residues was 15% biomass.

Characterization of biomass

The characterization of the biomass revealed a calorific power of 18.13 MJ kg^{-1} dry matter, which means that the available energy per hectare is about 35 MJ every year and serves as a reference for energy balance studies. Proximate analysis of plum wood showed at 79.8±9.2% volatiles and 2.1±0.3% ash. Elemental analysis of the wood pointed to 46.5±1.2% C, 6.1±0.5% H, 46.3±1.2% O, 0.6±0.3% N, 0.06±0.02% S, and 0.02±0.01% Cl. Cl, S and N contents are lower than the limits established by the standard EN 14691-part 4, which fix the conditions for chips used as biofuels in %Ash<3%, %N<1%, %Cl<0.05%, %S<0.1%.

CONCLUSIONS

Two methods were developed for calculating the branch biomass of plum trees from simple measurements such as base diameter and length. Branch volume can be calculated from volume of a cylinder of reference, multiplying by a form factor, or by the application of the regression models, which provide better fit. Biomass was then calculated by using density. In addition, two approaches can be also followed for estimating the wood biomass of whole tree from crown diameter, stem diameter, and tree height. Firstly, a regression model was calculated; secondly, the actual volume of a tree was calculated considering the volume of a solid of revolution and an occupation factor. Applying the density to this volume, the total biomass of a tree was obtained.

Most of biomass was concentrated in the plum crown (98%) and biomass stem accounted 2% of total. Considering crown strata, the central one had the highest percentage of biomass (40%). According to the thermochemical characterization of plum wood, the residual biomass from pruning can be used as chips for bioenergy. The results obtained in this study are the first step of a new research line in which these data can be correlated to LiDAR (Light Detection and Ranging) and lead to a simple, fast, and accurate way of predicting biomass. LiDAR technology is an active remote sensing system that registers ground elevation measurements and vertical vegetation structures.

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Table 1. Models for calculation biomass of Plum tree

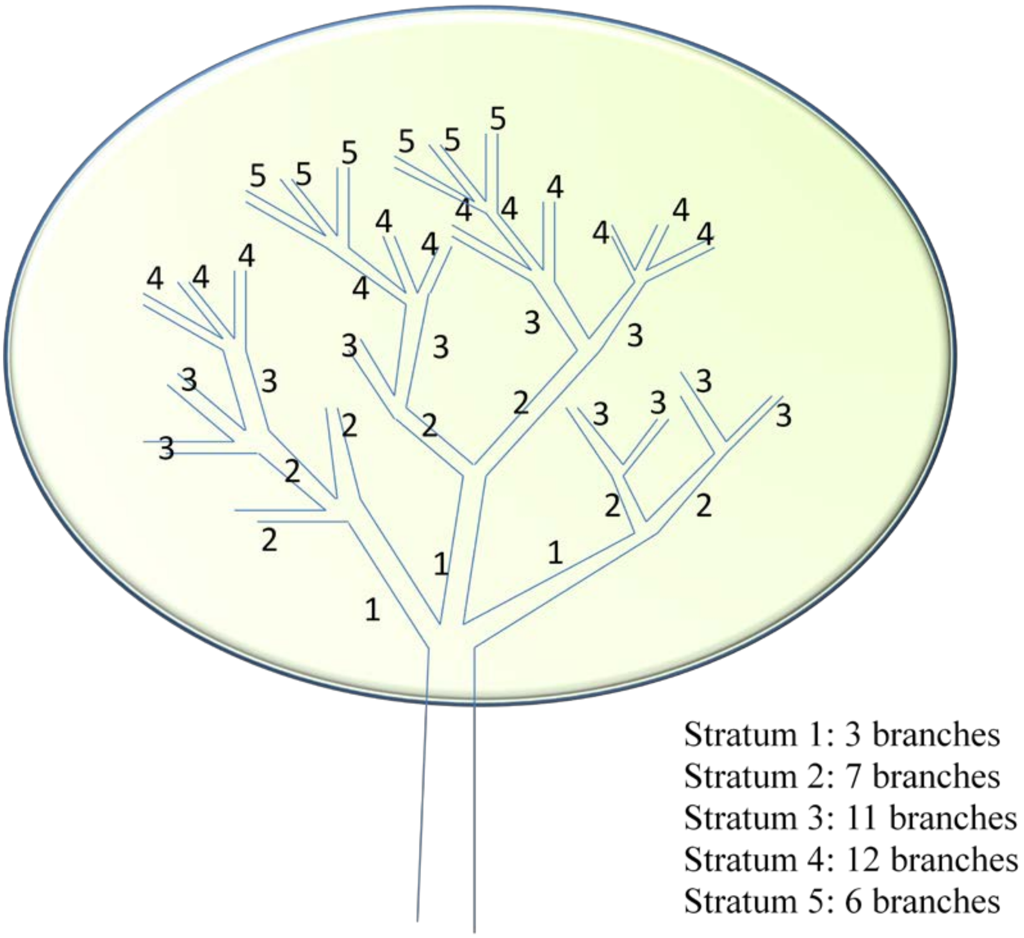
Volume equations	$R_{adjusted}^2$	σ_X	MAE	p-value
$V_{branch} = -6.914 + 0.449 \cdot d_{branch} \cdot L_{branch}$	0.91	7.99	5.43	<0.01
$V_{tree} = 15637.8 - 75.65 \cdot H + 0.23 \cdot D_c^2$	0.71	2327.94	3115.01	<0.01
$B_{residues} = -2.576 - 0.092 \cdot D_t + 0.021 \cdot D_c$	0.81	0.33	0.45	<0.01

V_{branch} is the wood volume of the branch (cm^3); d_{branch} is the diameter of the base (cm); L_{branch} is its length (cm); V_{tree} is the wood volume of the tree (cm^3); D_c is the diameter of the crown (cm); H is its tree height (cm); B_{residue} is the dry weight of residues per tree obtained from pruning (kg); D_t is the stem diameter (cm); R^2 is the determination coefficient; MAE is the mean absolute error; σ_x is the standard deviation of the error.

Table 2. Statistical summary of the parameters studied in the whole plant

Variables	Mean	Std. Deviation	Coef. Skewness	Coef. Kurtosis	Min.	Max.
Actual volume of whole plant (cm³)	12133.7	5515.6	0.30	1.75	3226.1	26118.5
Crown apparent volume (cylinder model) (cm³)	43542.8	9126.17	-0.41	1.21	29281.5	63468.0
Crown diameter (cm)	289.06	41.24	-0.29	1.35	227.0	384.0
Stem diameter (cm)	13.29	2.37	0.55	-0.53	8.02	18.41
Total height (cm)	298.9	24.49	-0.67	-0.41	241.0	344.0
Stem height (cm)	35.96	9.15	-0.02	0.63	19.0	57.0
Occupation Factor (Cylinder)	0.61	0.21	-0.24	0.14	1.09	0.16

Supplementary Material



Stratum 1: 3 branches
Stratum 2: 7 branches
Stratum 3: 11 branches
Stratum 4: 12 branches
Stratum 5: 6 branches

Figure S1. Scheme to define the strata and number of branches in each

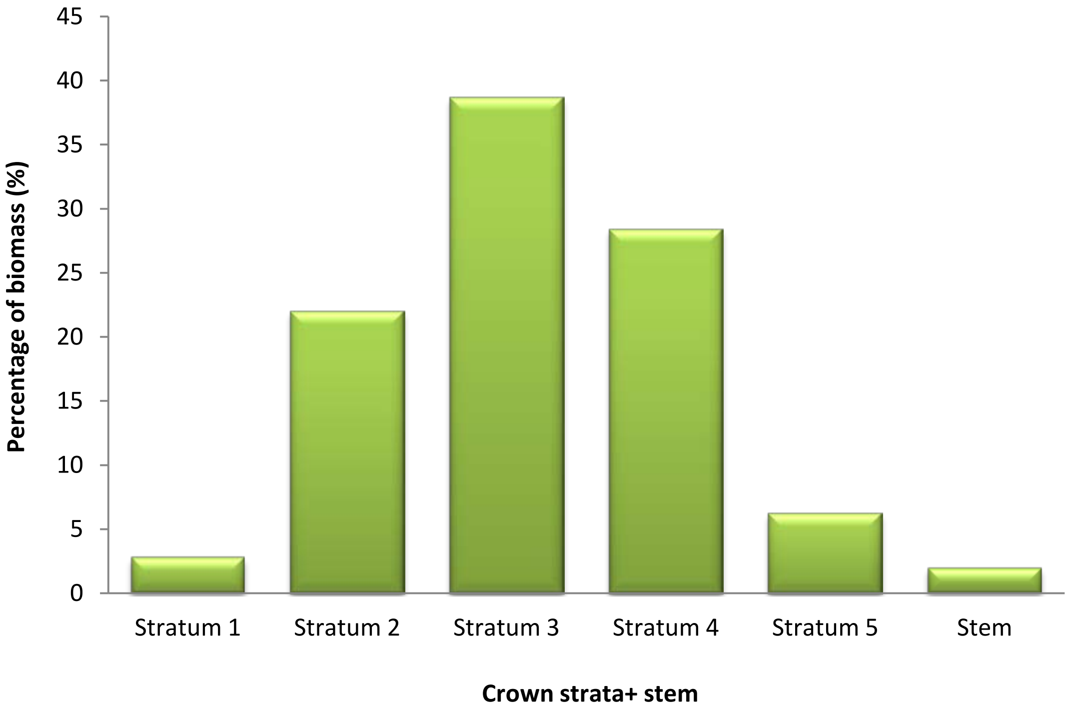


Figure S2. Biomass distribution in the plum crown.

Table S1. Standards used in the characterization of biomass

Standard	Title
CEN/ S 14778-1	Solid biofuels - Sampling - Part 1: Sampling Methods
CEN/TS 14779	Solid biofuels - Sampling - Methods for preparing sampling plans and sampling certificates
CEN/TS 14780	Solid biofuels - Methods for sample preparation
EN 14774-2	Solid biofuels - Determination of moisture content - oven drying method. Part 2. Simplified Method: Total moisture
EN 14918	Solid biofuels - Determination of calorific value
EN 15148	Solid biofuels - Determination of volatile matter
EN 14775	Solid biofuels - Determination of ash
CEN/TS 15104	Solid biofuels - Determination of total carbon, hydrogen and nitrogen - Instrumental Methods
CEN/TS 15289	Solid biofuels - Determination of total sulfur and chlorine
CEN/ TS 15105	Solid biofuels - Methods for determining the water-soluble content of chloride, sodium and potassium

Table S2. Statistical description of branch parameters

Variables	Mean	Std. Deviation	Coef. Skewness	Coef. Kurtosis	Minimum	Maximum
V_{branch} (cm^3)	84.3	25.57	-0.90	1.83	52.51	133.15
d (cm)	1.28	0.15	-0.25	0.40	1.00	1.61
L (cm)	156.03	25.38	-1.13	1.01	122.0	203.0
Form factor cylinder	0.41	0.06	-0.010	1.47	0.32	0.57
Form factor paraboloid	0.83	0.13	0.659	-0.097	0.65	1.14
Form factor cone	1.25	0.19	0.659	-0.097	0.97	1.71
Form factor neiloid	1.66	0.25	0.659	-0.097	1.29	2.27