# Quantification of Potential Lignocellulosic Biomass in Fruit Trees Grown in Mediterranean Regions

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This research was based on three species: *Citrus sinensis* (orange), *Olea europaea* (olive), and *Prunus amygdalus* (almond). The biomass was determined for a complete tree without roots, but including stem, branches, and canopy or crown. The obtained results demonstrate that the stem volume is slightly higher for almond trees (0.035 $m^3$/tree) than for olive trees (0.027 $m^3$/tree). In comparison, the average stem volume of orange trees is lower (0.006 $m^3$/tree). On the other hand, the total biomass volume including canopy branches is similar in all three species: 0.043 $m^3$/tree for orange tree, 0.066 $m^3$/tree for olive tree, and 0.040 $m^3$/tree for almond tree. The new practical quantification model for these Mediterranean agricultural crops is based on total biomass calculations normally used in forestry stands. So, the obtained values were used to develop models for biomass of the stem, branches, and canopy, relating them with the diameter and volume stem. The regression analysis shows a significant correlation with minimized estimation errors. This allows a practical use of this model in biomass calculation in standing trees, both for total tree biomass and also for pruning material.

*Keywords: Biomass; Quantification; Orange trees; Olive trees; Almond trees*

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## INTRODUCTION

The use of lignocellulosic biomass for energy use or for material purposes (wood-based panels, especially particle boards) in Mediterranean regions is strongly conditioned by the harvesting costs and supply logistics to industrial plants (Gomez 2008). Thus, current projects in agro-forestry biomass valorization and management are limited to local or subregional areas (PATFOR 2011). There is a large amount of usable lignocellulosic biomass, which could be extracted from various tree species in Mediterranean regions, *e.g.* in Spain (IDAE 2007; Frías 1985). This includes management and quantification of lignocellulosic fruit orchards or plantations, through residual biomass from pruning and replacement of plantations in a specific area (CIRCE 2006; Esteban *et al*. 2008). So far, these options have not been extensively studied for bioenergetic purposes, especially the estimation of total available biomass of fruit trees in any region with Mediterranean climate.

The multiple use of these orchards as fruit production and as biomass for either energetic or wood material uses can provide additional benefits to the orchards owner. In addition, biomass from pruning operations is generally burned in fields, which generates $CO_2$ emissions and increases fire risks. Such disposal practices of pruning operations lead to 25% of the total wildfires in Spain (WWF 2005).

Fernández (2009) and Perpiña *et al.* (2009) developed equations for biomass estimation in fruit trees; however, these equations are limited to the determination of the weight of biomass (in kilograms and tonnes) possible from pruning operations only. The current research has developed a new practical approach for the quantification of lignocellulosic agricultural biomass (*e.g.*, fruit trees) that is based on total biomass calculations normally used in forestry stands. So, the obtained values were used to develop models for the biomass of stem, branches, and canopy or crown, relating them to morphological parameters that can be easily measured in the field: $D_0$ (referential diameter), $D_{fm}$ (average diameter stem), and $L$ (length). This allows a practical use of this model in biomass calculation in standing trees, both for total tree biomass and also for pruning material in cubic meters.

Our research principally aimed at analyzing the lignocellulosic agricultural biomass grown in Mediterranean regions using the example of Spain. *Citrus sinensis* (orange), *Olea europaea* (olive), and *Prunus amygdalus* (almond) were selected for study as the most significant fruit species in this country. Thus, the main goals were to determine the amount of biomass contained in the studied species and to develop practical prediction models based on simple measurements of dendrological parameters. To achieve these goals, the research also included as specific objectives the dendrometric analysis of the stem and branches, the identification of morphological coefficients, the determination and evaluation of stem volume functions, and the biomass analysis of canopy and branches structural parameters.

## MATERIALS AND METHODS

### Selection of Species

The area of study includes the coast and interior territory of the Mediterranean area of Spain. The lignocellulosic fruit crops chosen for this research represent the largest area in these regions: orange, olive, and almond (ESYRCE 2010).

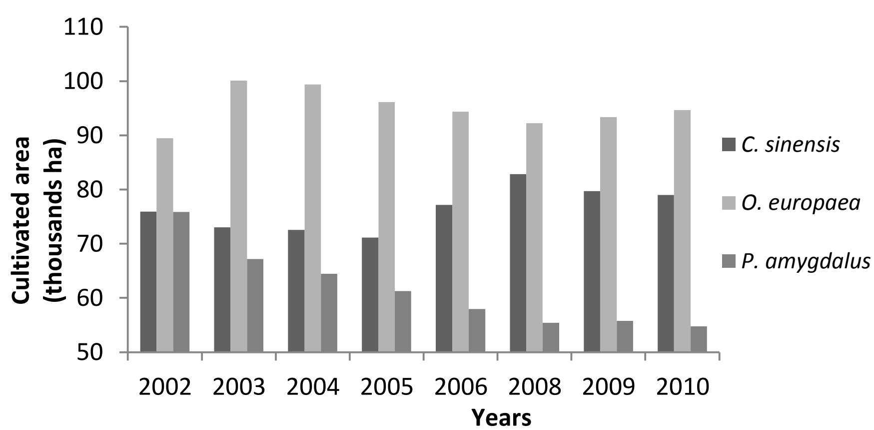


**Fig. 1.** Acreage of orange, olive, and almond trees of the Comunidad Valenciana 2002-2010. Source: Data obtained from MARM (2010). Prepared by the authors.

Figure 1 shows the cultivated area in the "Comunidad Valenciana" during the past eight years. For practical purposes of measurement and homogenization of the data, varieties of species were not considered in selecting sampling crops. Instead we opted to focus on aspects such as their representativeness, availability, and accessibility.

## Design Sample Areas and Data Collection

Species sampling was carried out in the Comunidad Valenciana. The method consisted of the selection of field crops, by species, in the same geographical area and production age.

*Selection of plots*

Plots were selected from among currently productive groves. Four to six representative plots were selected per species, taking into consideration the following selection criteria: even-aged crops, representative crop density, similar and representative water and soil conditions, representative irrigation systems (generally drip irrigation), similar weather conditions, and similar altitude above sea level typical for each species. *C. sinensis* was sampled in the Province of Valencia in the districts of La Safor (110 AMSL) and Ribera Alta (70 AMSL). *O. europae*a and *P. amygdalus* were sampled in the Province of Castellón in the districts of Alto Palencia (620 AMSL). The minimum plot size was 0.5 ha. All the tested orchards were in productive age (from 20 to 40 years old).

The plantation density varied from one plot to another, so the average was obtained trees/ha for each species (*C. sinensis*: 448 trees/ha; *O. europaea*: 159 trees/ha; *P. amygdalus*: 222 trees/ha). Despite not considering the type of soil in the selection of plots, the dominant and most common soil type in the region is clay-type.

*Selection of individual trees*

In a preliminary statistical study to determine the minimum sample size, the method developed by Hapla and Saborowski (1984) was applied. In a bioenergy-related study such as this, density can be used as a key variable that links the wood structure with the calorific power of the biomass. Density values were documented on 10 randomly selected trees. Following Hapla and Saborowski (1984), the following pre-test was carried out,

$$N_{\mathrm{min}} > (\mathrm{z}^2 * \mathrm{s}^2) / \mathrm{l}^2 \quad (1)$$

where $N_{\mathrm{min}}$ is the minimum sample (trees per plot), $z$ (1.96) is the critical value for standard normal distribution for significance at the 2.5% level (Sachs 1984), $s$ is the maximal standard deviation, and $l$ is the desired absolute accuracy, which is defined as

$$l = 0.01 * d * x_{\mathrm{min}} \quad (2)$$

where $d$ is the given relative accuracy of 95%. So $d$ equaled 5 and $x_{\mathrm{min}}$ was the lowest average value of all samples, in these case of all 10 trees. Results have shown that for an accuracy level of 95%, a minimum of three density (energetic) values in a minimum sample of 15 trees per plot have to be taken.

If the sample size is adequately large, the results obtained will guarantee homogeneous groups (Argibay 2009). For economic reasons, following the method of Hapla and Saborowski (1984) for even-aged plots, an acceptable number for this study was determined to be 15 trees per plot, having a total sample of a minimum of 60 trees per species. Being even-aged trees under the same site conditions, this total sample can be considered as representative for the research purposes. Malformed and border trees were dismissed, since they are not representative for the selected plots.

Representative individuals of the plot were identified according to the normal distribution analysis of the main dendrometric parameters: stem diameter and tree height. To do this, the following statistical variables were documented for the total collective of each selected plot: average, standard deviation, minimum, and maximum for variables $D_m$ (mean diameter of stem) and ($H$) total tree height. All individual trees being inside the simple confidence interval both for $D_m$ and $H$ were considered for the selection. From this collective, 15 trees were finally selected on a random basis in the sampling plots.

*Data collection*

Data of morphological parameters were gathered for stem and for branches, since pruning operations are carried out annually or biennially in the selected species. Consequently, this biomass source has to be considered in the quantitative and qualitative analysis.

Dendrometric measurements were performed on standing trees with a forest caliper for diameters larger than 15 cm (Mantax model Haglöf brand) and with a digital caliper (Vernier brand: 6"-150 mm) for stems with diameter less than 15 cm; tree height was measured with a SUUNTO hypsometer. The distance between trees was measured with metric tape in order to determine the crop density.

All branches were counted in the entire canopy of each selected tree for total quantification based on the morphologic data recorded for selected representative branches. The branches in the canopy were subdivided in two diametrical classes:

1. Diameter $\geq$1.0 cm to $\leq$ 7.0 cm: three representative branches were selected.
2. Diameter $\geq$ 7.0 cm: one representative branch was selected.

These two categories were selected because the branches that are usually pruned are below 7.0 cm in diameter at the base of the branch, so after determining the diameter classes, one will know the percentage of branches susceptible of pruning.

Branches were selected starting at a minimum of 1 cm in diameter, because in lower diameters the branches are not completely lignified. Representative branches measuring greater than 7.0 cm generally correspond to the first-order branches, and their number varies between two and four per tree. With this method it is not necessary to cut the branches in order to calculate the volume.

## Mass and Volumetric Biomass Characterization

*Relationship between diameter and stem volume*

Due to the fact that stem dimensions in fruit trees are dissimilar to forest trees, the normal diameter at a fixed breast height (DBH at 1.3 m) method cannot be used for estimating their stem volumes. Therefore, the diameter was determined at the half length (0.5$L$) of each stem. The total stem volume for each tree was calculated following the Huber (1828) equation,

$$V_f = g_m L \tag{3}$$

where $V_f$ is the volume ($m^3$), $g_m$ is the basal area ($m^2$) in the mid-section, and $L$ is the considered length of the stem (m).

The relationship between stem diameter (in the mid-section) and volume were determined with regression and correlation analysis.

*Diametric classes*

(a) Stem: The diametric classes of the stem were determined, since it is an important variable for fruit trees when it is decided to harvest or remove whole tree orchards. The selected trees were classified in diametric classes of ≥ 22.0 cm and < 22.0 cm. The latter class was divided into two subclasses (7.0 to 15.0 cm and 15.0 to 22.0 cm).

The descriptive statistics of the average stem diameter of all sampled species are shown in Table 1.

**Table 1.** Stem Diameter per Species (cm)

| Species | N | Min | μ -σ | **Mean μ** | μ +σ | Max | CV (%) |
|---|---|---|---|---|---|---|---|
| *Citrus sinensis* | 90 | 6.3 | 9.7 | **14.9** | 20.1 | 25.6 | 34.9 |
| *Olea europaea* | 75 | 11.8 | 16.6 | **26.9** | 37.2 | 52.4 | 38.3 |
| *Prunus amygdalus* | 60 | 14.7 | 18.4 | **23.0** | 27.5 | 31.2 | 19.7 |

The widest diameter ($D_m$) corresponds to olive trees with a mean value of 26.9 cm, followed by almond trees with 23.0 cm and orange trees with 14.9 cm (See the detail in Fig. 3). The descriptive statistical analysis of the total sample showed a relatively high coefficient of variation (CV) for olive and orange trees (38.3% and 34.9%), while the total almond collective showed a lower CV (19.7%). This can be explained due to the fact that olive as well as orange trees vary in dependence of the age of each individual plot. So, the coefficients of variation of the individual plots are significantly lower. On the other hand, the sampled plots of almond trees were of very similar age (around 30 years), so that the stem diameter variation was significantly lower both for the total collective and for the individual plots. Independently of the different ages, an important factor that determines the variation of the diametric distribution is the natural variability between individuals of the same species (Donoso 1995).

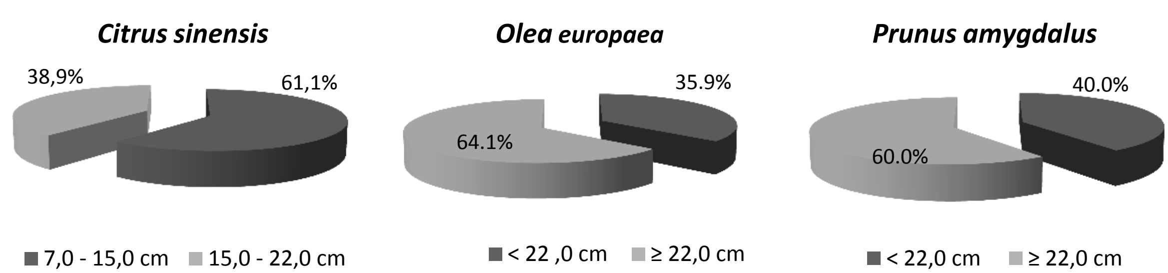


**Fig. 2.** Distribution diametric percentage of stems; Source: Prepared by the authors.

In general, taking into account the different conditions to which each orchard had been subjected, the variability of the $D_m$ was low, indicating homogeneity in the stem diameters for each species in a given age.

A quantitative description of the biomass is important when assessing the orchard conditions (stocking density, age, and tree volume, *etc*.) and implementing management decisions (cultural treatments like pruning, removal of trees, *etc*.). This is possible to obtain from the diameter data, due to the strong relationship between this variable and the information gathered from the inventory (Prodan *et al.* 1997). For this reason, the stem diameter is the most important tree dimensional parameter directly measurable in the field. The stem diameter constitutes a basic input in calculating the basal area, stem volume, and even the canopy characteristics (coverage and canopy biomass volume) (Brown 1997).

In this study, according to characteristics of each species, mainly referring to the dimensions (length and diameter), $D_m$ was determined for the analysis. For this reason, it is not possible to indicate a specific diameter interval for the entire range of the Mediterranean fruit species, since several other variables must be considered. However, in agreement with Merino *et al.* (2005), it is considered that 7.0 cm is a minimum diameter for using the lignocellulosic biomass for bioenergy purposes.

(b) Branches: The diametric classes of selected braches in each tree were determined. These were classified into two diametric classes (< 7.0 cm and ≥ 7.0 cm).

Table 2 shows the descriptive statistics of the general diameter average of all branches sampled for each species. The parameter *n* is the average number of woody branches per tree.

**Table 2.** Descriptive Statistics of Diametric Classes' Distribution of Branches (cm)

| Species | *N* | Min | $\mu - \sigma$ | **Mean** $\mu$ | $\mu + \sigma$ | Max | CV (%) |
|---|---|---|---|---|---|---|---|
| *Citrus sinensis* | 130 | 2.0 | 2.5 | 5.6 | 8.6 | 12.7 | 54.3 |
| *Olea europaea* | 39 | 2.8 | 3.3 | 8.4 | 13.6 | 22.9 | 61.2 |
| *Prunus amygdalus* | 49 | 2.2 | 5.5 | 9.3 | 13.2 | 19.9 | 41.5 |

The normal distribution interval for orange branches was 2.5 to 8.6 cm. The corresponding value in olive branches was 1.9 to 16.4 cm, and for almond branches it was 5.5 to 13.8 cm. According to these results, olive and almond trees have larger average diameter branches (8.4 and 9.3 cm, respectively), while orange trees have the lowest average diameter with 5.6 cm and greater number of branches per tree. Therefore, olive and almond trees were found to have higher averages values for diameters and thicknesses and fewer branches per canopy. High CV was expected in all fruit orchards, since branches with varying thickness have been sampled from different aged trees.

Figure 3 shows the percentage distribution of branches diameters based on diametric classes. Branches classification into smaller and greater than 7.0 cm is based on their limited use in wood manufacturing processes (FAO 1998). The figure shows olive and orange trees with a greater percentile of diameters less than 7.0 cm compared to diameters more than 7.0 cm. Almond trees show a different trend, where 67.9% of their branches have diameters larger than 7.0 cm.

These results will influence the final destination of this raw material, and will help to identify and plan the different products that can be obtained from them.

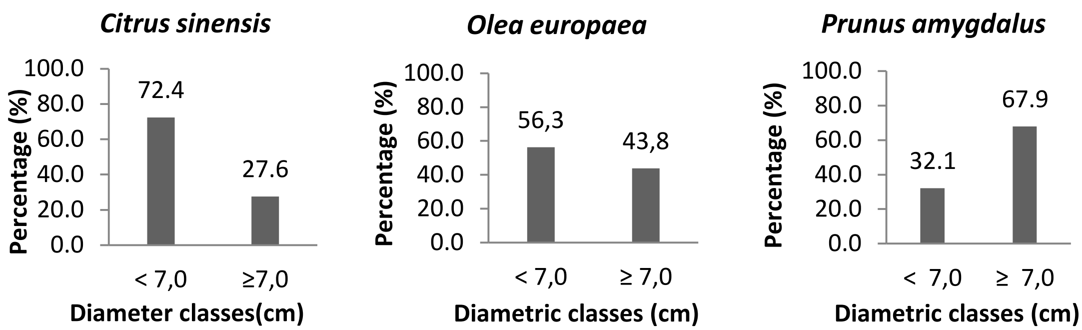


**Fig. 3**. Percentile of diametric distribution of studied fruit branches
Source: Prepared by the authors.

Several studies have proposed different referential diameters for wood biomass, especially for forest-based bioenergetic raw material. For example, Merino *et al.* (2005) proposed using referential diameters greater than 7.0 cm, whereas Brañas *et al.* (2000) suggested diameters greater than 4.0 cm for the same purpose. Similarly, Tolosana (2009) noted that biomass fraction for energy purposes were branches up to 14 cm in diameter. These diameters correspond to the residual forest biomass that is destined to chip production, since these diameters are similar to the maximum values found in the studied branches of the fruit trees analyzed. PATFOR (2011) stated that trees with less than 23 cm diameter can be considered as potential bioenergetic resources. In other words, all canopy biomass can be considered as residual biomass for bioenergy purposes.

*Morphology of stem and branches*

For the calculation of the stem volume of each individual tree, the shape factor $f$ was determined. This shape factor is a morphic coefficient arising from the relation between real volume and cylinder volume.

$$f = \frac{\text{real volume}}{\text{cylinder volume}} \quad (4)$$

The shape factor is a characteristic of the species and diametric type referred to the stem. However, due to their statistical variability, the average and dispersion is determined for each case. This factor can be normalized by Huber´s equation that defines the *real form factor* ($f_v$).

In addition, the following data were calculated for each plot:

*Total tree stem*

The average diameter ($D_m$) in the mid-section was registered by establishing a caliper in the maximum diameter and turning it 22.5° clockwise, obtaining the most representative diameter according to Siostrzonek (1959). Stem height was measured with a metric tape or a hypsometer, depending on the tree height.

*Canopy*

The branches were assessed according to the methodology described by Hohenadl (1936), since the branch conicity was not linear or continuous due to shape irregularities. Finally, the total number of branches was recorded for the calculation of the total canopy biomass volume.

*Determination of branches volume and canopy biomass*

Following Hohendahl (1936), each analyzed branch was divided into at least five equal parts, and then the equatorial diameter of each section was measured so that an initial and end diameter for each interval was obtained (Fig. 4).

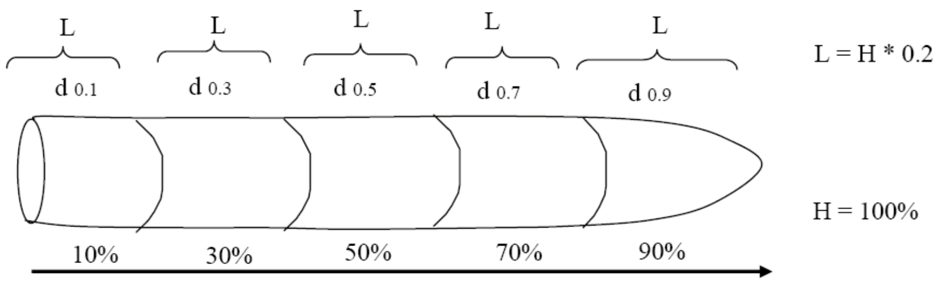


**Fig. 4.** Stem Division in five equal parts; Source: Prodan *et al.* (1997)

Hence, branch volume has been calculated as follows,

$$V= \frac{\pi}{4}\cdot L\cdot\left[\frac{\left(d_{i0.1}^2+d_{s0.1}^2\right)}{2}+\frac{\left(d_{i0.3}^2+d_{s0.3}^2\right)}{2}+\frac{\left(d_{i0.5}^2+d_{s0.5}^2\right)}{2}+\frac{\left(d_{i0.7}^2+d_{s0.7}^2\right)}{2}+\frac{\left(d_{i0.9}^2+d_{s0.9}^2\right)}{2}\right. \tag{5}$$

where $V$ is the total branch volume ($m^3$), $L$ is the length of the section (m), and $d_i$ is the diameter at the lower and upper part of each section (cm).

The total canopy biomass and/or pruned volume could be estimated with the volume of the measured branches, extrapolating this value to either the total branches of the tree or to the estimated number of the branches to be pruned.

*Relationship between stem volume and canopy biomass*

Once the stem volume and the canopy biomass volume were determined, a regression analysis was used to establish the relationship between both variables for each species.

*Development of a prediction model for branches volume*

In order to estimate the total volume of the branches obtained in a pruning operation, a practical prediction model for the branches volume was developed. The variables $D_0$ (diameter of the lowest section, also called *reference branch diameter*) and $L$ (total branch length) were used. Then, using Statgraphics software, multiple regression models were analyzed for defining total branch volume functions in accordance with the mathematical models proposed by Prodan *et al.* (1997), Näslund (1936/1937), Spurr (1952), and Schumacher and Hall (1933).

## RESULTS AND DISCUSSION

### Stem

Stem volume was estimated using Huber´s equation to obtain the total biomass per tree of a certain number of sampled trees (N) per species (Table 3).

**Table 3.** Stem Volume by Species ($m^3$/tree)

| Species | N | Min | μ -σ | **Mean μ** | μ +σ | Max | CV (%) |
|---|---|---|---|---|---|---|---|
| *Citrus sinensis* | 90 | 0.001 | 0.003 | **0.006** | 0.010 | 0.013 | 59.3 |
| *Olea europaea* | 75 | 0.006 | 0.007 | **0.024** | 0.042 | 0.074 | 70.3 |
| *Prunus amygdalus* | 60 | 0.011 | 0.029 | **0.035** | 0.048 | 0.060 | 35.2 |

The stem volume is not consistent in olive and orange trees, especially in olive, as can be observed by the high value of CV. There were orange trees with very small stems showing the lower volume in average (0.006 $m^3$/tree). On the other hand, almond and olive species exhibited clearly defined stems with higher and regular dimensions. They also had larger volumes, with values of 0.035 $m^3$/tree (almond) and 0.024 $m^3$/tree (olive). Almond trees showed the lowest CV with 35.2%; therefore, they presented a lower variability in stem volume in contrast with orange (59.3%) and olive trees (70.3%). The high variability was visually appreciated in the sampling plots, since different tree ages were documented in olive and orange orchards. Moreover, these values are also influenced by the natural variability shown in orchards with these species (Cubero 2003).

*Relationship between stem diameter and volume*

The regression equations relating stem volume to stem diameter are given in Table 4.

**Table 4.** Volume Equation of the Various Species

| **Species** | **Equation for stem volume** ($m^3$) | $R^2$ | $\sigma V_f$ |
|---|---|---|---|
| *Citrus sinensis* | $V_f$ = - 0.00698 + 0.00107 $D_{fm}$ | 0.749*** | 0.001 |
| *Olea europaea* | $V_f$ =-0.03642 + 0.00324 $D_{fm}$ | 0.788*** | 0.012 |
| *Prunus amygdalus* | $V_f$ =0.0001 $D_{fm}^{\ 2}$ – 0.0036$D_{fm}$ + 0.0418 | 0.816*** | 0.013 |

In Table 4, $V_f$ is the stem volume ($m^3$), $D_{fm}$ is the average stem diameter (cm), $R^2$ is the determination coefficient, and $\sigma V_f$ is the standard deviation of $V_f$. These equations achieved acceptable $R^2$ results (significant at $p < 0.01$). The lowest determination level was achieved in the case of orange trees ($R^2$ = 0.749), followed by olive trees ($R^2$= 0.788), and almond trees ($R^2$ = 0.816). Therefore, the resulting regression equations for all species are recommended for their application. Moreover, this conclusion is supported by the fact that all obtained values of $\sigma V_f$ were very acceptable.

One should be aware that these equations are local functions, which consider only the diameter and pertain to a limited geographical area. Thus, these equations must be used in the geographical area where the data were gathered (Prodan *et al.* 1997). In case they are applied to other areas, preliminary validation field studies should be conducted in order to determine if they are applicable.

*Stem shape factor*

Resulting shape factors were determined by the average volume of a certain number of sampled trees ($N$) per species (Table 5).

**Table 5.** Descriptive Statistics of the Shape Factor ($f$V) in the Studied Species

| Species | N | Min | - $\sigma d$ | Prom. | + $\sigma d$ | Max | CV (%) |
|---|---|---|---|---|---|---|---|
| *Citrus sinensis* | 90 | 0.69 | 0.81 | 0.88 | 0.98 | 0.98 | 10.0 |
| *Olea europaea* | 75 | 0.32 | 0.53 | 0.71 | 0.90 | 0.99 | 26.2 |
| *Prunus amygdalus* | 60 | 0.25 | 0.39 | 0.45 | 0.52 | 0.55 | 14.3 |

An average shape factor of 0.88 was found in orange trees, since that is the species having a shape close to that of a cylinder, followed by olive trees with 0.71. In contrast, almond trees were close to 0.45, similar to the results found for conifers, which are recognized by their conical shape and shape values between 0.4 and 0.6 (Rebottaro and Cabrelli 2007; Grosse and Kannegiesser 1988). The CV is low in all fruit species, indicating a high homogeneity within each plot.

In general, the dispersed results of shape factors for the different species are attributed to two causes. The first is the fact that each one has different tree morphological characteristics. This is corroborated by Donoso (1995), who points out that variation will depend on the tree species and environmental conditions. The second refers to the planting distance variable (trees per ha, basal area), which strongly affects the shape factor. As plantation distance increases, it decreases competition for light, water, and nutrients. Trees grow with many branches. They are short in height and do not need natural pruning. This translates into a diameter and height growth that affect shape factor significantly.

These results are very important for agricultural activity planning (pruning and/or final harvesting) in fruit orchards. They make it possible to determine in advance the amount of biomass removed from the orchard with a good approximation, either for energy purposes or as raw material for wood-based panels.

## Branches

Pruning is a typical agricultural treatment for fruit species. Branches are very abundant as the result of annual or biannual pruning operations. They represent a significant lignocellulosic biomass source that should be quantified annually or each two years depending of the orchard, on a per hectare and per tree basis.

*Equations for branch volume in fruit trees*

Branch volume prediction models are very important since they serve as a basic tool for agricultural treatments and operations (Clutter *et al.* 1983; Méndez *et al.* 2006). Especially in forestry, several mathematical models for forest species (Akindele and LeMay 2006; Zianis *et al.* 2005; Pillsbury and Kikley 1984) have been developed, but not for fruit trees.

Table 6 shows the best models obtained after the regression analysis.

**Table 6.** Develop of Volume Models per Species

| Species | Author | Model (cm)$^3$) | $R^2$ |
|---|---|---|---|
| *Citrus sinensis* | Spurr | $V_R = -23.0003 + 0.69923 D_0 H$ | $0.910^{***}$ |
| *Olea europaea* | Spurr | $V_R = 397.94 + 0.50193 D_0 H$ | $0.946^{***}$ |
| *Prunus amygdalus* | Spurr | $V_R = 109.164 + 1.4575 D_0 H$ | $0.871^{***}$ |

In Table 6, $V_R$ is the branch volume (cm$^3$), $R^2$ is the determination level, $D_0$ is the referential diameter (cm), and $H$ is the length (cm).

Comparing the mathematical models mentioned in the methodology, the Spurr (1952) function presented the best fit, with high $R^2$ values (significance at $p < 0.01$).

The development of these models is an important tool for measuring the branch volume of these species. They provide the volume directly, allowing determination of the biomass removed per tree in pruning (m$^3$). The results can be extrapolated to the hectare by multiplying by the average number of branches pruned per tree. In order to obtain the pruned biomass waste in tonnes (1.000 kg) per tree, the equations should be multiplied by the density of each species. Moreover, knowing the calorific power of each species, it is possible to estimate the MJ/ha obtained in pruning.

These equations provide the available biomass from pruning of these fruit trees. According to FAO (1998), this allows one to define a range of possible end products given the biomass residues specification (diameters and lengths, minimum, and maximum), such as pulp, chips, and pellets, among others.

## Canopy

Stem volume was estimated from the volume of canopy mainly to calculate the average total volume of a tree.

*Canopy biomass volume in fruit trees*

According to Table 7, olive trees exhibited the largest canopy biomass volume, 0.042 m$^3$/tree, followed by orange trees with 0.037 m$^3$/tree, and finally almond trees with 0.017 m$^3$/tree.

**Table 7.** Descriptive Statistics of the Canopy Biomass Volume Distribution (m$^3$)

| Species | N | Min | $- \sigma v$ | Prom. | $+ \sigma v$ | Max | CV (%) |
|---|---|---|---|---|---|---|---|
| *Citrus sinensis* | 90 | 0.010 | 0.010 | 0.037 | 0.064 | 0.103 | 71.7 |
| *Olea europaea* | 75 | 0.012 | 0.021 | 0.042 | 0.062 | 0.096 | 49.0 |
| *Prunus amygdalus* | 60 | 0.002 | 0.003 | 0.005 | 0.007 | 0.009 | 38.2 |

The amplitude between $\sigma v$ ranges (olive [0.021 to 0.062 m$^3$], orange [0.010 to 0.064 m$^3$], and almond trees [0.003 to 0.007 m$^3$]) showed that the canopy volume varies significantly depending on the species.

The highest canopy variation was shown by orange, with a CV equal to 71.7%, mainly due to its own variability of individuals, since samples were taken from different aged trees and different cultivated geographical areas in the region. Olive and almond trees showed a lower canopy volume variation due to the more homogeneous sampling plots.

Besides the possibility to obtain wood biomass, the estimation of the canopy biomass volume is important for determining its primary production (fruits), since its canopy dimensions reflect the vigor of the tree (Schomaker *et al.* 1999). Several researchers mention the importance of knowing their characteristics for predicting their growing rate, fruit production, and biomass waste in pruning, among other variables (Doruska and Burkhart 1994; Brunner 1998).

Table 8 includes the sum of total values obtained from stem and canopy biomass volume.

**Table 8.** Total Biomass in the Canopy of the Studied Species ($m^3$/tree)

| Species | N | Min | - $\sigma d$ | Prom. | + $\sigma d$ | Max | CV (%) |
|---|---|---|---|---|---|---|---|
| *Citrus sinensis* | 90 | 0.013 | 0.014 | 0.043 | 0.072 | 0.112 | 66.7 |
| *Olea europaea* | 75 | 0.020 | 0.033 | 0.066 | 0.099 | 0.136 | 50.3 |
| *Prunus amygdalus* | 60 | 0.001 | 0.023 | 0.040 | 0.057 | 0.065 | 41.8 |

Table 8 shows that olive trees provide the greatest amount of biomass (0.066 $m^3$/tree), which was expected since olive trees present the largest average size, followed by orange (0.043 $m^3$/tree), and almond trees (0.040 $m^3$/tree). So, knowing the density of the plantation, the biomass per cultivated hectare can be estimated.

*Relationship between the stem and canopy biomass volumes in fruit trees*

The relationship between the amount of photosynthetic tissue and the production of non-photosynthetic tissue (Waring 1983) can be used for predicting the volume of trees. Along this line, some models estimate the stem volume of the tree by quantifying its canopy (Vanclay 1994). However, it has been considered as very useful to provide the reverse process. So, Table 9 includes a regression analysis for determining the actual canopy biomass volume from the already quantified stem volume.

**Table 9.** Regression Analysis for a Model of Canopy Biomass Volume in Dependence of the Stem Volume

| **Species** | **Equation** ($m^3$) | $R^2$ |
|---|---|---|
| *Citrus sinensis* | $V_C=0.0047 - 13.298\ V_f^2 + 5.1103\ V_f$ | $0.759^{***}$ |
| *Olea europaea* | $V_C=0.008 - 18.646\ V_f^2 + 2.155\ V_f$ | $0.731^{***}$ |
| *Prunus amygdalus* | $V_C=0.0017 + 1.0785\ V_f^2 + 0.0681\ V_f$ | $0.733^{***}$ |

In Table 9, $V_c$ is the real volume ($m^3$) and $V_f$ is the stem volume ($m^3$). As can be observed in Table 9, the lowest $R^2$ (significant at $\alpha = 0.01$) was 0.731 for olive trees, followed by orange trees with 0.759, and almond trees with 0.733. These functions are acceptable for their practical application. However, the fact that the $R^2$ values were not very high can be explained by the high variation of the stem volume for these fruit species.

Finally, based on all the previous estimates, Table 10 summarizes the amount of biomass that can be obtained from the pruning and a whole tree per hectare of each species.

**Table 10.** Total Biomass in Pruning and Whole Tree ($m^3$/ha)

| Species | Plantation density (tree/ha) | Pruning ($m^3$/ha) | Whole tree ($m^3$/ha) |
|---|---|---|---|
| *Citrus sinensis* | 450 | 1.80 | 19.4 |
| *Olea europaea* | 160 | 0.16 | 12.1 |
| *Prunus amygdalus* | 230 | 0.23 | 17.1 |

Table 10 shows that the pruned orange tree had the greatest amount of material extracted with 1.8 $m^3$/ha. The corresponding values for olive trees and almond trees were just 0.16 $m^3$/ha and 0.23 $m^3$/ha, respectively. However, when considering the volume of the entire tree, olive trees with 12.1 $m^3$/ha and almond trees with 17.1 $m^3$/ha reduce this difference; the corresponding value for orange trees was 19.4 $m^3$/ha. These relationships are consistent with the larger stems in comparison to orange trees.

According to these results (Table 10), these fruit trees contain a large amount of material per tree. Therefore, the whole tree mass should be considered as a potential source of raw material. In addition, pruning will depend on the density of plantation and the number of hectares dedicated to these crops in the different Mediterranean regions.

## CONCLUSIONS

The unused biomass produced in the fruit tree orchards in the Mediterranean region presents a huge potential use. The fruit has to be considered as the main product, while the biomass is a by-product. Nevertheless, agricultural treatments such as pruning or tree replacements offer a good source of raw material, especially for bioenergy. Annual or biannual pruning operations enable a sustained supply and a possibility for energy plants at the local or regional level. This agricultural material can be a very interesting complement to the forest-based biomass produced at a larger scale.

Results of this research show a high variation of the main dendrometric parameters (stem architecture and volume, branches, and canopy) due to the strong anthropogenic influence in these orchards manifested by the agricultural treatments. The high statistical significances obtained in the mathematical models represent a useful prediction tool for the amount and the quality of the produced biomass, which can be used both for the material from branches as well as for the stem material. Nevertheless, the observed variation of the dendrometric parameters in dependence of agricultural treatments and geographical area implies a limit in the applicability of the presented prediction models. Consequently, the developed methodology in this research can be used with the specific data for these fruit species in other geographical areas for biomass estimation.

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