QUANTIFICATION BASED ON DIMENSIONLESS DENDROMETRY AND DRYING OF THE RESIDUAL BIOMASS FROM PRUNING OF ORANGE TREES IN BOLIVAR PROVINCE (ECUADOR)

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Abstract

In this work a new approach to evaluate the amount of residual biomass obtained from orange trees based on normalization of variables is proposed for Bolivar province (Ecuador). So far, several models to quantify the amount of residues obtained from pruning had been proposed from dendrometric and cultivation variables; such as: height, crown diameter, stem diameter, area per plant, yield and age. However, the high dispersion of their values, caused by uncontrolled conditions, gave models with low-medium coefficient of determination. The aim of this work has been to develop several models in order to predict wet available biomass using dimensionless dendrometric parameters from height, diameter and height of the crown and the stem height. They

improved coefficients of determination to 0.94 for the global mathematical model. The drying process of pruned materials has also been analyzed. Residual biomass with 50% initial moisture content was dried outdoor on cement and ground until they reached constant moisture content. Models used to describe the drying process of agricultural products were employed to fit the observed data of the drying process of orange tree chips. Among the tested models, the Midili and Page were those that best fitted the observed data in the drying process. The information offered by these equations is of vital importance because they help estimating the amount of biomass that is generated in a given area, and the implementation GIS maps. In addition, logistic algorithms can be applied.

INTRODUCTION

Recently, the Ecuadorian government has launched a reform to the country's productive matrix which aims to exploit efficiently all available resources in order to achieve better life levels in the current social context within the globalized economy of the world [1]. The use of agricultural biomass as raw material for energy is being a challenge for the Ecuadorian government. However, there is lack of information about surveying systems and processing under Ecuadorian climatic conditions and in the height where its plots are located (0-3500 m above sea level). A lot of residual biomass for energy can be used from the management of the Ecuadorian agriculture, especially in pruning operations, renewing plantations or cropping residues. So far, this source of biomass has not been used, because it presents various technical difficulties, lack of sufficient information;

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such as: the amount and processing of these wastes. Citrus is one of the most important cultivated and consumed fruits in Ecuador and in the world. Annual pruning is a necessary operation in these fruit trees for a physiological control and continual production [2]. This study is focused on the quantification of the residues obtained in the pruning of orange trees, and on studying its drying process. The amount of available biomass as well as the drying process before transportation leads to a more adequate logistical planning.

Every year, those branches which are badly formed or damaged should be eliminated because they are going to produce defective fruit. Pruning in the inner part of the tree allows a better illumination. When the number of branches decreases, the number of fruits per plant is lower; the nutrients and the weight on the main branches are better distributed; the quality of production generally improves; and reduces the alternate bearing [3-4]. It means that a great amount of biomass can be obtained from this process. This work continues previous studies presented by Velazquez and Fernandez (2010) [5], Velazquez et al. (2011) [6] and Velázquez et al. (2011) [7], where equations to predict residual biomass from pruning of several fruit trees were shown. These researches showed that these wood residues depend on many variables, some of them related to dendrometric parameters, cultivation factors such as: irrigation, and climatology. Velázquez and Fernandez (2010) [5], Velázquez et al. (2013) [8] developed models to quantify residual biomass from citrus trees. These models used dendrometric variables and cultivation parameters; such as: height, crown diameter, stem diameter, area per plant, yield and age. However, uncontrolled conditions caused high dispersion of their values. Many factors can influence the tree growing, yield and pruning, and cause different relations between the residual biomass and geometrical

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parameters of the tree. This causes lower coefficient of determination in predictions models.

The aim of this work has been developing equations to predict wet available biomass obtained in the pruning of orange trees using normalized and dimensionless dendrometric parameters obtained from tree height, diameter and height of the crown and the stem height. Some factors that influence the amount of biomass obtained are also evaluated. Also, drying models were analyzed; this analysis allowed knowing drying kinetics, and minimum moisture content achievable in determined conditions. Several models have been applied to different agricultural products to determine the speed drying and the moisture gradient between the material and environment [9-12]. The application to chips obtained from citrus tree pruning was analyzed in this work.

The information offered by these equations is of vital importance in order to estimate the amount of biomass that is generated in a given area, and for implementing GIS maps. In addition, logistic algorithms can be applied; such as, *borvemar model*, which locates biomass concentration points for its distribution from GIS digital maps [13]. This algorithm is based on searching points with a minimum amount of available biomass in a limited area. Therefore, the amount of biomass in every plot in an area must be studied in order to apply the method. Another possible model is *bioloco model* (Biomass Logistics Computer Optimization) developed by Annevelink and Mol (2007) [14], and Diekema, et al., (2005) [15]. This algorithm provides a logistic model based on graphs where the source nodes (sources of biomass) and destination nodes (biomass processing plants) exist, connected by arcs that represent costs or distances. This model calculates the optimal nodes which must supply the destination nodes at a given time

depending on the seasonality of the sources. Bioloco can use borvemar model to determine the nodes and then select which ones are the best at all times. The implementation of these models is only possible if the amount of biomass can be calculated. Many studies have been carried out in forest areas [16-17], but few tools have been studied in agricultural systems, especially in fruit trees [18-20], some of them were carried out by Di Blasi et al. (1997)[21]. These studies are also necessary to relate biomass with Lidar data [22-23] or vegetation index from multiespectral images [24-25]. They open a new tool to plant management. These studies will allow to perform measurement, inventory and evaluation of the requirements for planning the use of this resource in rural communities in the Andean region [5][13].

MATERIALS AND METHODS

Study Area

The study was conducted in the province of Bolivar (Ecuador) (Figure 1); Bolivar is a province located in the center of Ecuador at western Andes. It is characterized by a deep valley in the high Andes, serving a vast hinterland of agricultural settlements. Its climate is subtropical, with a long dry season (May - October) where temperature ranges are between 6 and 18°C, and 18-22 °C in the warm months (November-April). There is an approximate rainfall ranging between 1000 and 2000 m. In this area pruning of oranges trees is realized between May and July. Up to now, residues are not being used, but they could be dried as energy biomass. Sampling of these residues was carried out in three locations near the city of Guaranda: Guavito (X_{UTM}=684908.4, Y_{UTM}=9859929.8), Las Mercedes (X_{UTM}=685324.8, Y_{UTM}=9859201.2); and San Pedro

(X_{UTM}=684320.9, Y_{UTM}=9857641.8). The measurements were carried out in Valencia variety trees which is the most used in this area. Age of trees was about 15 years old.

Figure 1. Location of Bolivar Province

Dendrometric Analysis

Before pruning, the main dendrometric variables were taken out of 50 trees in each location to characterize the plots. For each tree following variables were reported: Total wet pruned biomass (kg per tree) that consists of branches and leaves collected from each tree; tree height (H in m); crown diameter (Dc in m), crown height (Hc in m), and height of stem (Ht in cm). Separation of orange trees in studied plots is shown in Table 1.

Table 1. Orange trees distribution per canton studied

	Guavito	Las Mercedes	San Pedro
Distance between trees per rows (*DF* in m)	6.6	5.8	6
Distance between trees per columns (*DC* in m)	5.8	5.8	5.5
Number of trees per rows (*NF*)	15	20	15
Number of trees per columns (*NC*)	20	20	30
Trees per m^2 (*TA*)	7.84	11.89	13.64

After pruning, bundles of the residual materials were weighed by means of a dynamometer. Mass measurement in the field was carried out with moist materials. All branches of each tree were defoliated and weighed to determine the mass percentage of leaves and wood.

In Table 2, the average and standard deviation of the parameters of the measured trees are described. According to the skewness and kurtosis coefficients all of them followed gauss distribution in all studied variables.

Table 2. Characteristics of measured trees in each canton where sampling was carried out .

	Guavito		Las Mercedes		San Pedro	
	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation
Diameter of crown (m)	3.89	0.59	4.73	0.89	4.89	0.88
Height of the crown (m)	3.32	0.54	3.45	0.64	4.13	0.54
Height of the tree (m)	4.47	0.49	4.93	0.63	5.75	0.55
Height of the stem (cm)	32.8	9.02	49.04	7.20	63.64	17.35

Number of trees per area

Based on the distance between the trees in each row (*DR*), the distance between the trees in each column (*DC*), and the number of trees per rows (*NR*) and columns (*NC*), the number of trees per area (*TA*) (tree/m^2) was calculated using the following equation (1). The values of *DR*, *DC*, *NR*, *NC* and *TA* are shown in Table 1.

$$TA = \frac{NR \cdot NC}{DR \cdot DC} \qquad (\text{tree/m}^2) \qquad (1)$$

To determine the wet biomass to be harvested per area (**BIOSUP)** (kg biomass/m^2), the mass of pruned biomass per tree (Wet biomass) and the number of trees per area were used (*TA*).

$$BIOSUP = \text{wet biomass} \cdot TA \qquad (2)$$

From the dendrometric variables available *H*, *Dc*, *Hc* and *Ht*, new normalized variables are proposed with values between 0 and 1, by mean of the following equations:

$$H_{a\,\dim} = \frac{H - H_{min}}{H_{max} - H_{min}} \qquad (3)$$

$$Dc_{a\,\dim} = \frac{Dc - Dc_{min}}{Dc_{max} - Dc_{min}} \qquad (4)$$

$$Hc_{a\,\dim} = \frac{Hc - Hc_{min}}{Hc_{max} - Hc_{min}} \qquad (5)$$

$$Dt_{a\,\dim} = \frac{Dt - Dt_{min}}{Dt_{max} - Dt_{min}} \qquad (6)$$

Where *min* and *max* correspond to the minimum and maximum values measured in each tree population respectively. Also, the amount of wet biomass per specific area according to the dimensionless variables obtained from tree height, crown diameter, crown height and height of stem respectively were defined as dependent variables.

$$BIOSUPDc = \frac{BIOSUP}{Dc_{asim}} \qquad (7)$$

$$BIOSUPH = \frac{BIOSUP}{H_{asim}} \qquad (8)$$

$$BIOSUPHc = \frac{BIOSUP}{Hc_{asim}} \qquad (9)$$

$$BIOSUPHt = \frac{BIOSUP}{Ht_{asim}} \qquad (10)$$

Determination and modeling of drying curves

Samples of residual branches and leaves were collected after pruning orange trees, which was carried out between July 1st and July 20th of 2014. Then, they were chipped and extended on the ground and they were summited to a natural outdoor drying on two different ground surfaces: concrete and agricultural soil without vegetation. Chips' average size was 15 cm with a standard deviation of 2 cm. chip's thickness layer extended on the soil was between 4 and 5 cm. During the drying period, the maximum and minimum temperatures observed were $22.5^{o}C$ and $8.8^{o}C$ respectively, the mean relative humidity in the air was 53%, and the average monthly rainfall was 14.3 mm.

Range of initial moisture content was between 50% and 65% wet basis both on cement and ground. To model drying, chips were dried in open natural conditions until constant moisture content was reached. To measure the evolution moisture content, five samples of chips were randomly chosen and dried in an oven at $105 \pm 1°C$ during 24 hours. The

dried branches had diameters between 1 and 6 cm, being the average diameter 3.9 cm. The experimental data of the drying process was fitted to mathematical models expressed by equations indicated in Table 5. These models are frequently used to describe the drying phenomenon in agricultural products [24]. Moisture ratio (*MR*) was estimated through equation (11), where: ω_t, ω_o and ω_e are the moisture content at any time, initial moisture content and equilibrium moisture content, respectively.

$$MR = \frac{\omega_t - \omega_e}{\omega_o - \omega_e} \qquad (11)$$

RESULTS AND DISCUSSION

Dendrometric analysis

Figures 2, 3 and 4 represent the behavior of the dimensionless variables which define specific residual biomass from different studied dendrometric variables, for the three locations where pruning of orange trees was sampled. Mathematical behavior is similar in all considered variables. Adjustments of regression were performed in each case. To determine the characteristic pattern TABLECURVE 2D software was used, obtaining the following general model:

$$Y = \frac{A + C \cdot X^2}{1 + B \cdot X^2} \qquad (12)$$
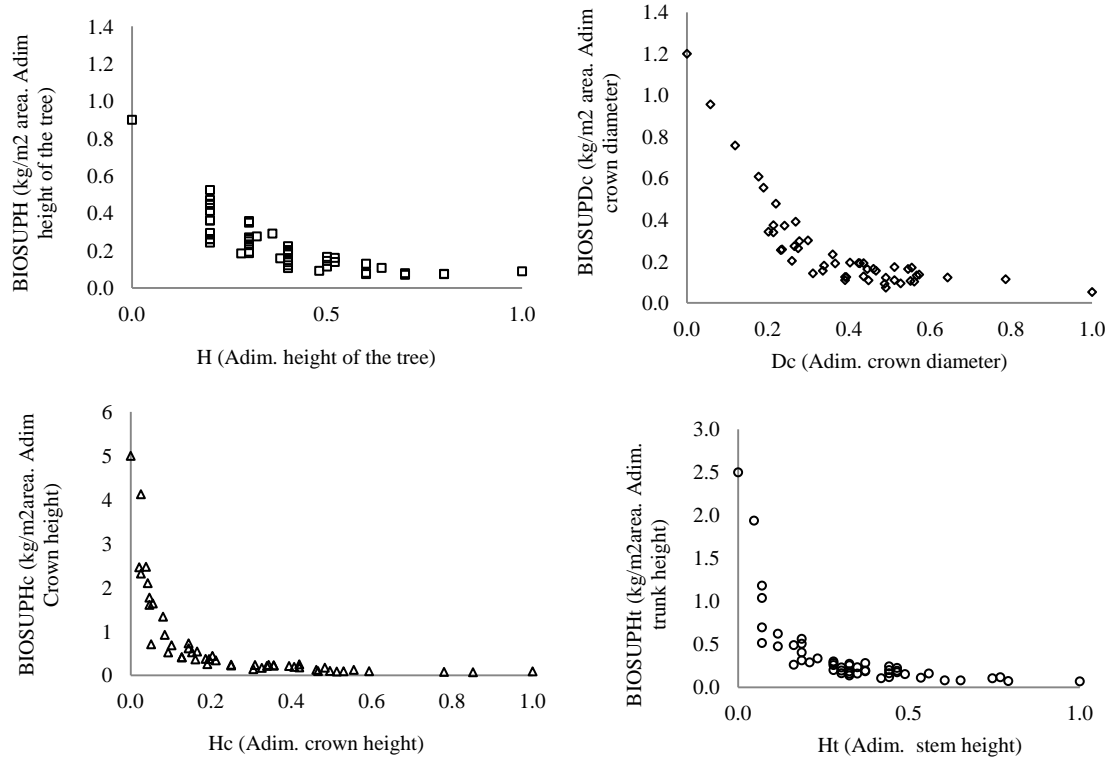
Figure 2. Specific biomass vs dimensionless dendrometric parameters for Guavito location
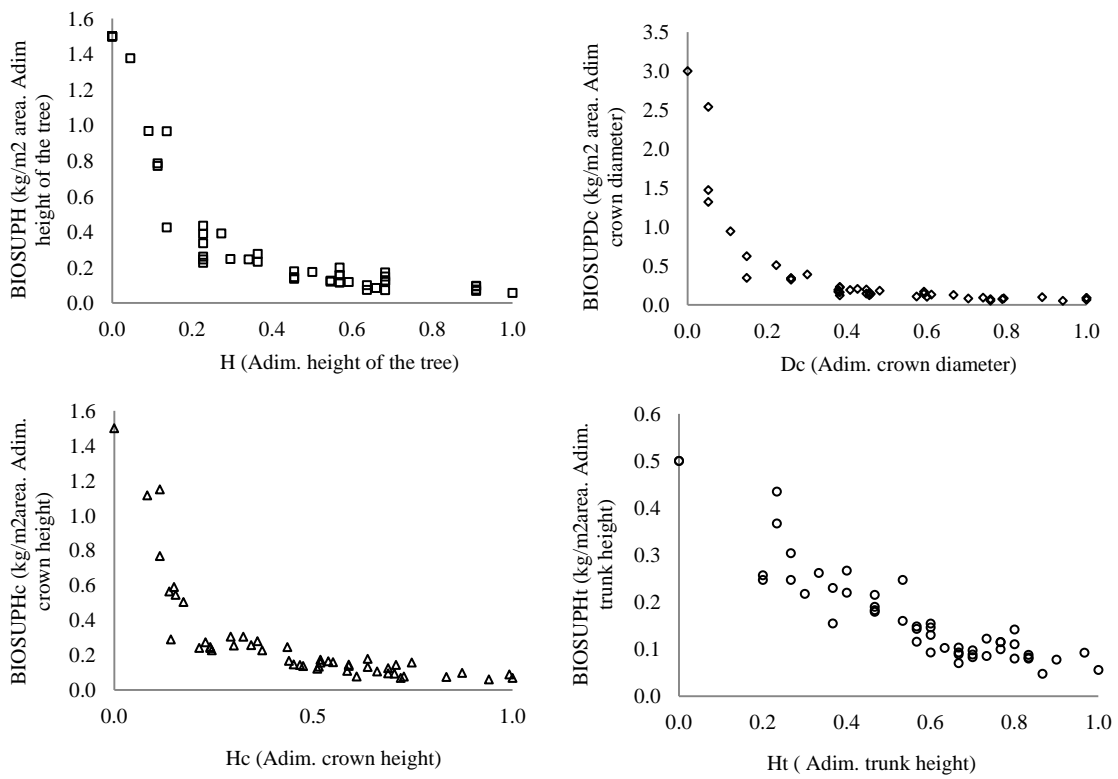

Figure 3. Specific biomass vs dimensionless dendrometric parameters for Las Mercedes location
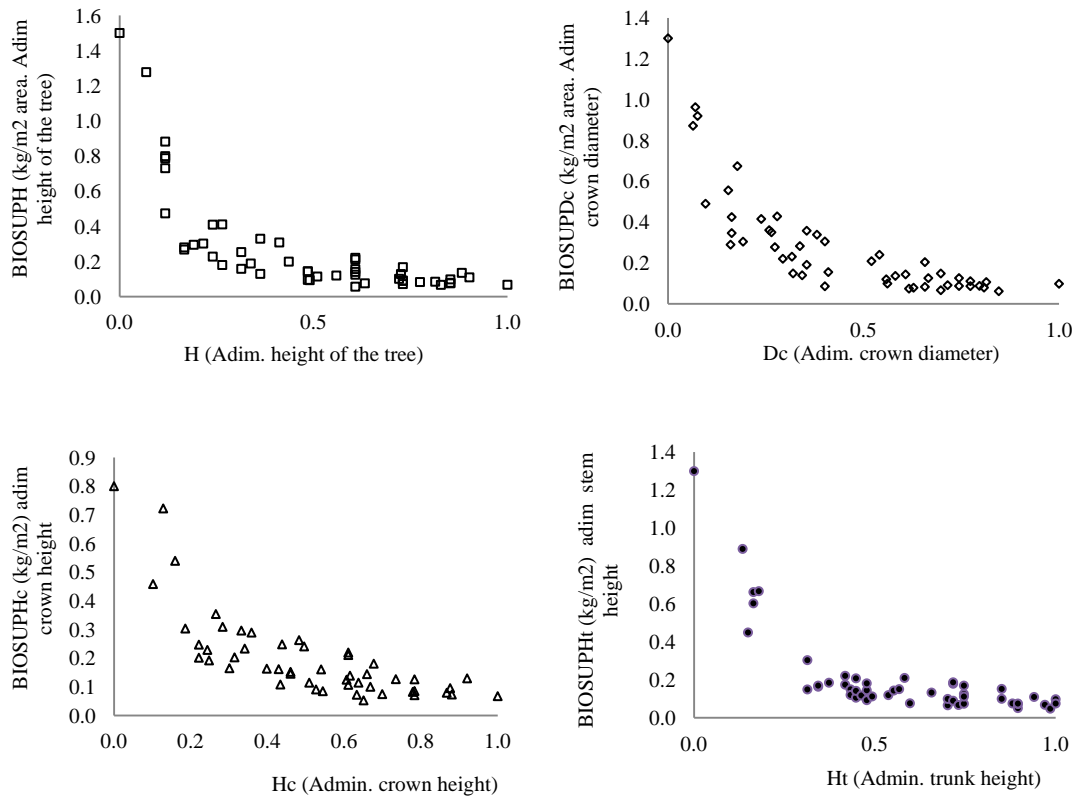
Figure 4. Specific biomass vs dimensionless dendrometric parameters for San Pedro location

Table 3 contains the specific parameters obtained for quantifying the biomass associated to each canton where the model was analyzed. Coefficients of determination of the four possible models are significantly high, between 0.87 and 0.98. These models were validated with independent samples different to the ones used at the model. Predicted values were checked with new observed values by paired sample test, which is based on t-student distribution.

Table 3. Model parameter for the specific biomass in function of the dimensionless

	Canton	Y (kg biomass/m^2)	Parameters			
			A	B	C	R^2
Height tree $X=H_{adim}$	Guavito	0.0295	0.89	38.08	2.10	0.85
	Las Mercedes	0.0329	1.50	77.16	5.68	0.98
	San Pedro	0.0336	1.58	101.54	8.21	0.92
Diameter crown $X=Dc_{adim}$	Guavito	0.0295	1.82	50.10	2.12	0.94
	Las Mercedes	0.0329	2.95	241.43	23.14	0.93
	San Pedro	0.0336	1.24	86.18	9.34	0.88
Height crown $X=Hc_{adim}$	Guavito	0.0295	4.73	918.67	165.90	0.92
	Las Mercedes	0.0329	1.56	87.35	6.70	0.91
	San Pedro	0.0336	0.80	40.47	3.35	0.81
Trunk height $X=Ht_{adim}$	Guavito	0.0295	2.56	361.87	52.03	0.92
	Las Mercedes	0.0329	0.48	10.03	0.33	0.87
	San Pedro	0.0336	1.32	49.33	2.51	0.93

In order to define a global model to calculate biomass coming from orange trees pruning, regardless to the location, the best fit was based on independent variable *BIOSUPDc*. Table 4 shows the parameters of the global mathematical model.

Global mathematical model:

$$BIOSUPDc = \frac{A + C \cdot Dc_{a\,dim}^{2}}{1 + B \cdot Dc_{a\,dim}^{2}} \qquad (13)$$

Table 4. Parameter for global model in function of the dimensionless diameter crown

	A	B	C	R^2
$BIOSUPDc = \dfrac{A + C \cdot Dc_{a\,dim}^{2}}{1 + B \cdot Dc_{a\,dim}^{2}}$	2.19	223.66	27.00	0.94

These models improve the prediction given by Velazquez et al (2013) [7] which had a R^2 between 0.5 and 0.65. They did not use normalized and dimensionless variables. The models presented in this work have 0.81 and 0.97. This ratio expresses the variability explained by the model. On the other hand, previous studies; such as: Velazquez et al (2013) [7] or Estornell et al., (2015) [26] used polynomial equations; however, the proposed model with normalized variables gave better predictions. It is important to

point out that the model had a good fit in orchards of three different cities. As it can be seen in Table 3, the coefficients A, B or C of equation (12) change for each city, nevertheless the global model had an unusual high R^2.

The use of standardized variables involves knowing the maximum and minimum values of the parameters used in every orchard. Therefore, applying these predictive equations is more difficult than applying models with non-normalized variables, but accuracy significantly increases.

Determination and modeling of drying curves

Drying samples of orange pruning from the three previous mentioned localities (Guavito, Las Mercedes and San Pedro) was conducted outdoors, using two different surfaces: concrete and agricultural ground. Figures 5 and 6 show the drying curves for the different surfaces used. The results didn't point the location factor as significant in the curves; all of them showed similar trend. This was checked by paired sample test, which is based on t-student distribution. As it can be seen, the initial moisture content was about 50% and 65% for both drying: cement and ground, and it reached constant value at day 15 at 15%. Figure 7 shows the variation of average moisture content (ω) versus time.
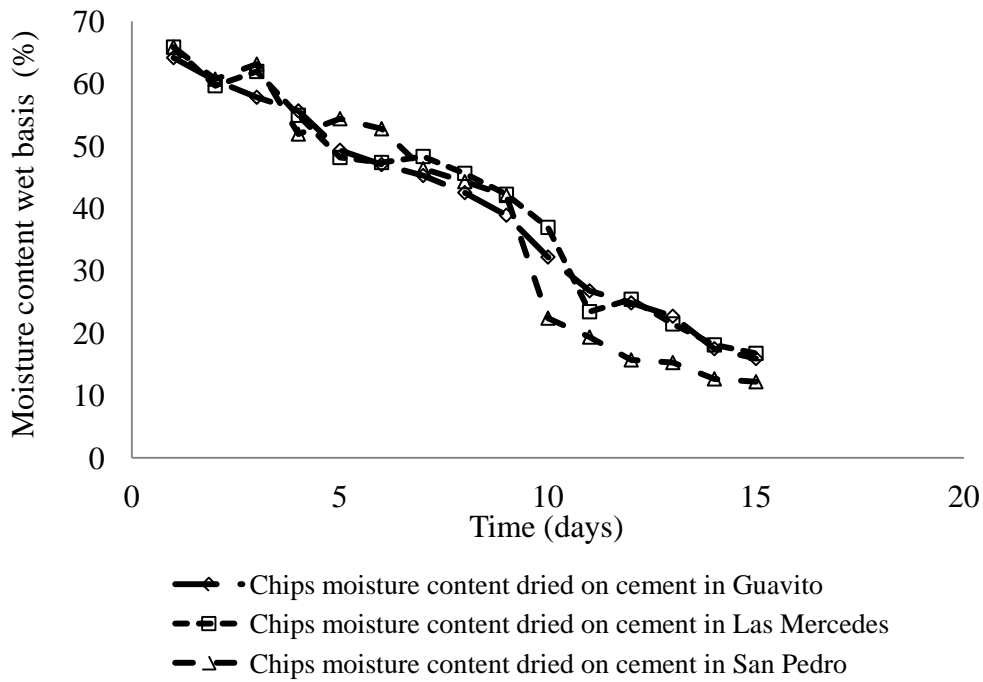
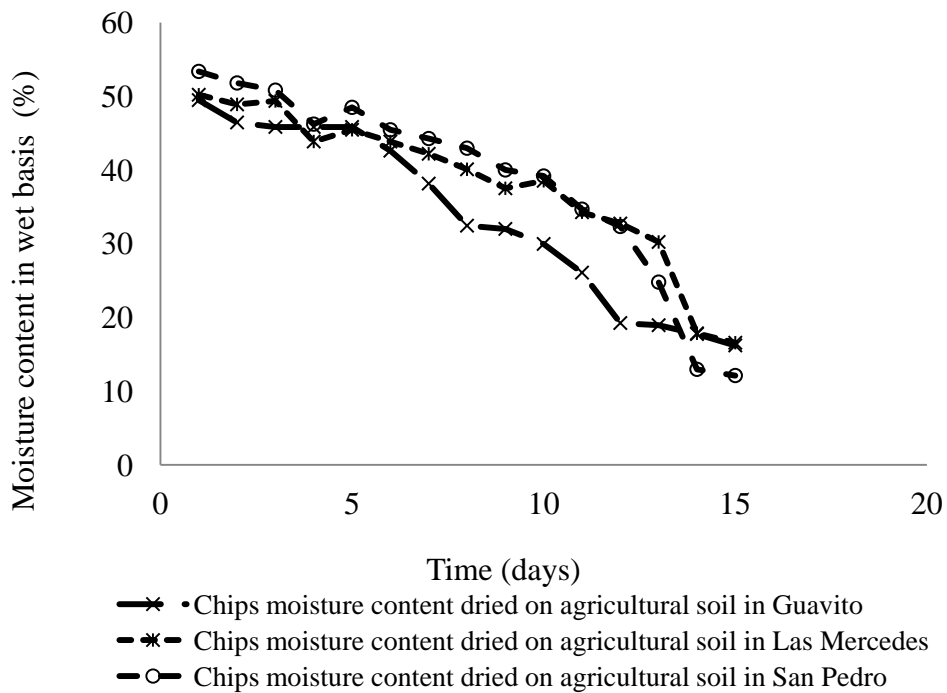Figure 5. Comparison of drying curves for three location on concrete in natural outdoor drying.

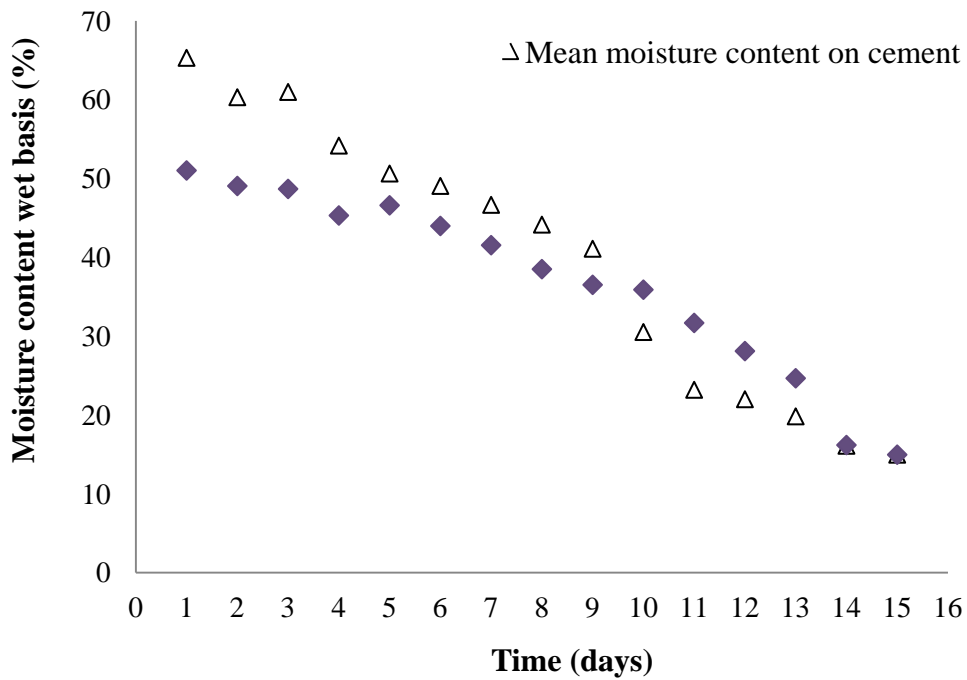Figure 6. Comparison of drying curves for three location on ground in natural outdoor drying

Figure 7. Average moisture content on cement and ground in natural outdoor drying

Table 5 shows drying models to define moisture ratio versus time. All of them had a high fit. The best models were Midili and Page.

Drying models allow to determine the operation variables in dryers. If the wood biomass to be dried is m with initial moisture content ω_1, and it is uniformly aired at constant wet-bulb temperature, after drying time its moisture content is ω_2, being $\omega_1 > \omega_2$, water to be removed can be calculated by equation (14).

$$m_{water} = m \cdot (\omega_1 - \omega_2) \qquad (14)$$

For calculating the drying time, kinetics models such as the ones shown in Table 5 should be used. For example, if the model of Henderson and Pabis is applied, the drying time is given by equation (15).

$$t = -\frac{1}{k} \ln \frac{MR}{a} \qquad (15)$$

The air flow to dry the material ($\dot{m}_{air}$) can be determined by equation (16), which represents the matter balance in the drying process. The removed water in the wood material is absorbed by the air flow which has an initial absolute humidity (ω_{air1}), and then it goes out with ω_{air2} absolute humidity. It should be verified in psychometric diagram that the relative humidity in the air is lower than 100%.

$$\dot{m}_{water} = \frac{m \cdot (\omega_1 - \omega_2)}{t} = \dot{m}_{air} \cdot (\omega_{air2} - \omega_{air1}) \qquad (16)$$

As example, drying process is depicted in Figure 8. The air flow goes into dryer in the condition pointed with number 1 (50°C and absolute humidity 0.004 kg water/kg dry air). The drying process is occurred at constant wet-bulb temperature (line 1-3). The moisture content in the air after biomass drying is fixed at 0.014 kg water/kg dry air; therefore, the temperature of the air at withdraw of dryer is 25°C. The maximum permissible absolute humidity for ω_{air2} would be given by point 3 at 0.0165 kg water/kg dry air.

Table 5. Drying models and parameters tested for determine drying kinetics on cement and ground

| Model name and equation	Cement		Ground	
	Parameters model	Statistics	Parameters model	Statistics
Newton $MR = e^{-k \cdot t}$	k=0.0901	$R^2 = 0.834$ RMS = 0.0320	k=0.0622	$R^2 = 0.765$ RMS = 0.0343
Page $MR = e^{-k \cdot t^n}$	$k = 0.0076$ $n = 2.1088$	$R^2 = 0.975$ RMS = 0.0125	$k = 0.0015$ $n = 2.5862$	$R^2 = 0.966$ RMS = 0.0131
Henderson and Pabis $MR = a \cdot e^{-k \cdot t}$	$k = 0.1173$ $a = 1.2404$	$R^2 = 0.902$ RMS = 0.0246	$k = 0.0841$ $a = 1.2118$	$R^2 = 0.846$ RMS = 0.0277
Logaritmic $MR = a \cdot e^{-k \cdot t^n} + b$	$k = 0.0282$ $a = 3.0360$ $b = -1.8985$	$R^2 = 0.966$ RMS = 0.0144	$k = 0.0076$ $a = 8.5200$ $b = -7.3679$	$R^2 = 0.931$ RMS = 0.0185
Midili $MR = a \cdot e^{-k \cdot t^n} + b \cdot t$	$k = 0.1882$ $n = -0.5706$ $a = 1.2853$ $b = -0.0809$	$R^2 = 0.974$ RMS = 0.0126	$k = 0.6782$ $n = -0.2428$ $a = 2.0694$ $b = -0.0810$	$R^2 = 0.948$ RMS = 0.0161
Diffusional Model $MR = a \cdot e^{-k_1 \cdot t} + (1-a) \cdot e^{-k_2 \cdot t}$	$k_1 = 0.2192$ $k_2 = 0.2224$ $a = 86.2272$	$R^2 = 0.942$ RMS = 0.0189	$k_1 = 0.1857$ $k_2 = 0.1885$ $a = 88.3513$	$R^2 = 0.921$ RMS = 0.0110
Two exponencial terms $MR = a \cdot e^{-k_1 \cdot t} + b \cdot e^{-k_2 \cdot t}$	$k_1 = 0.2496$ $k_2 = 0.2570$ $a = 51.8334$ $b = -51.0016$	$R^2 = 0.958$ RMS = 0.0162	$k_1 = 0.2013$ $k_2 = 0.2103$ $a = 37.2655$ $b = -36.4392$	$R^2 = 0.931$ RMS = 0.0185

t is time in days
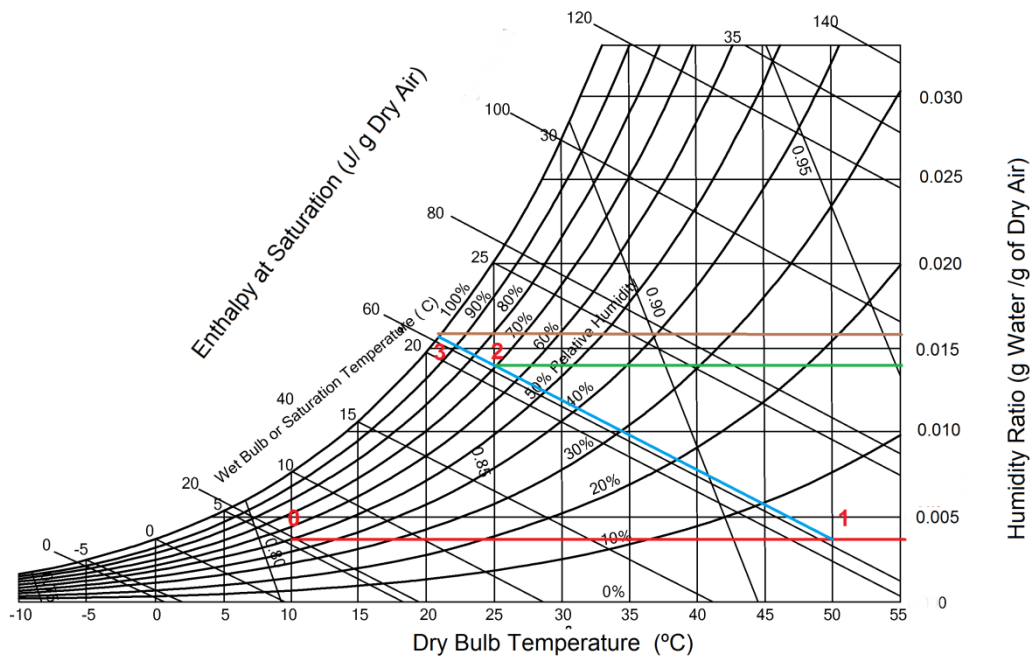
Figure 8. Psychometric diagram

According equation (15) the time taken to dry the 15 cm pieces of orange wood material uniformly, aired considering $MR==\dfrac{40-10}{50-10}=0.75$, is 4.29 days.

If external air, for feeding the dryer, is at 10 °C with a relative humidity at 50% (point 0 of the diagram), to reach the temperature of point 1 (50ºC) is necessary to heat the air, being constant absolute humidity (Line 0-1). The heat to carry the air from point 0 to 1 is given by the product of the mass flow rate of air by the difference between its enthalpy between point 1 and 0.

CONCLUSIONS

Methods have been developed to predict residual biomass from pruning of orange trees. These models only use dendrometric variables; such as: tree height, crown height, stem height and crown diameter. It is shown that the use of normalized dimensionless variables improve the accuracy of adjustment to predict the amount of available biomass. The use of standardized variables involves knowing the maximum and minimum values of the parameters used in every orchard. The application of these predictive equations is more difficult than in models with non-normalized variables, but accuracy significantly increases. The good fit of the obtained models allows them to be applied in surveys process.

Based on the obtained values, the Page and Midili models were adequate in describing outdoor drying phenomena of pruned materials in Guaranda conditions. These models allow to predict the moisture content from the drying days. The minimum moisture

content reachable is 15%. The obtained models allow to determinate the design values for industrial dryers.

The amount of available biomass as well as the drying process before transportation allows a more adequate logistical planning.

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