UNDER PEER REVIEW

Original Research Article

Estimating of area and dry mass of cashew leaf: Effect of tree position within a plantation

Abstract.

Background and Aims: Accurate and non-destructive methods to determine individual leaf areas and dry mass of plants are very important because they are key parameters linked to plant production and they are used in functional–structural plant models to simulate plant growth. This paper describes an investigation of the variation in cashew leaf dimensions at different sites within a plantation with the aim of developing a model for calculating leaf area and dry mass.

Methods: Five positions (south, central, north, east and west) were considered in an eight years old rectangular cashew plantation, with an area of 3.5 ha. Two trees were selected randomly by location. Their crown was divided vertically into three zones. Within each zone, 60 leaves were collected randomly on different categories of axis of the tree. The length, width, area, and the dry mass of each leaf were measured.

Key Results: The longest leaves were obtained in the north, center and south of the plantation (15.27 cm). The leaves of trees located in the south of plantation were the largest (9.6 cm) and had the largest areas (109.1 cm²). The largest quantities of dry mass were obtained from the leaves of the trees located in the south and in the east of the plantation (1.35 g per leaf). The best models according to adjustment and prediction qualities were in all cases as such $S^{\lambda} = aln(LW) + b$ for leaf area and $m^{\lambda} = aln(LW) + b$ for dry mass.

Conclusions: These data demonstrate that there is an important variation in leaf size and dry mass according to a tree position in the plantation. Therefore, it is important to take into account this variability in the sample constitution when trying to estimate leaf area and dry mass.

Key words: Leaf area, dry mass, tree position, sunlight, cashew, models, Benin.

UNDER PEER REVIEW

Introduction

Leaves are one of the main plant components involved in plant biomass production through photosynthesis [1] (Tondjo *et al*. 2015). On an individual plant scale, the leaf area and specific leaf area, i.e. the ratio between leaf area and dry biomass, have been shown to be good indicators of plant productivity, for instance on poplar clones [2] (Marron *et al*., 2005). Leaf area is furthermore an important variable for most ecophysiological studies in terrestrial ecosystems concerning light interception, evapotranspiration, photosynthetic efficiency, fertilizers, and irrigation response and plant growth [3] (Blanco and Folegatti, 2005). In addition, the leaf area is required for assessments fruit growth, evaluation of training and pruning systems, and estimation of pest population densities ([4], [5]) (Lang, 2000, 2005). Functional–structural plant models (FSPM) [6] (Fourcaud *et al*., 2008) can facilitate the understanding of the functional links among leaf characteristics, carbon production and allocation. Consequently, the easy, economical and precise estimate of leaf area or dry mass of leaf has been a concern to plant scientists for a long time. The most common approach is to develop ratios and regression estimators by using easily measured leaf parameters such as length and width [7] (Kvet and Marshall, 1971). Comparing several non-destructive models of leaf area of taro, Lu *et al*., [8] (2004) proposed that the simple and linear relationships between leaf area and leaf dimensions (length, width) could be useful for non-destructive estimation of leaf area. Thus, non-destructive models for leaf area determination have been established for many species such as maize [9] (Stewart and Dwyer 1999), bean [10] (Bhatt and Chanda, 2003), taro [8] (Lu *et al*., 2004), kiwi [11] (Mendoza-de Gyves *et al*., 2007), ginger [12] (Kandiannan *et al*., 2009) and watermelon [13] (Rouphael *et al*., 2010). Similarly within the framework of fruit trees, several combinations of measurements and models relating length and width to area have been developed for several fruit trees, such as grape ([14], [15]) Montero *et al*., 2000; Williams and Martinson 2003) and avocado [16] (Uzun and

UNDER PEER REVIEW

Celik, 1999). However, models to estimate the leaf area of cashew are almost absent in the literature.

The cashew tree is native to the Caribbean and the North East of Brazil. It is now widely cultivated in all tropical areas, such as Africa, Caribbean, Brazilian Northeast, Southeast Asia and India. The economic importance of this plant lies mainly in its fruit (cashew nuts). For example, in Benin, cashew nuts is the second export crop after cotton and its importance is increasingly growing in agricultural production systems [17] (PADSE, 2003). Cashew accounted for 8% of the total value of exports in 2008, 7% of agricultural GDP and 3% of GDP [18] (Tandjiekpon, 2010).

Moreover, the predictive accuracy of non-destructive models of leaf area or biomass depends on the variation of the leaf shape within the same plant and between accessions [19] (De Swart *et al.*, 2004). This variation may also be related to environmental factors including the quantity of sunlight captured by the plant. Indeed, plants produce several types of leaves during their development. The first few true leaves produced are usually smaller, simpler, and anatomically different from leaves produced later in development [20] (Poethig, 1997). Change in shape and size of successive leaves on a plant are related to physiological changes associated with increasing age of the plant [21] (Esau, 1965), interaction between the shoot apical meristem and the developing leaf primordial [22] (Byrne *et al.*, 2001), genetically regulated programs of shape maturation and a variety of environmental factors [20] (Poethig, 1997). Therefore a good estimate of the production model requires accurate estimation of the area and mass of leaves taking into account any possible variability.

The aim of this study is thus to develop a non-destructive estimation model of the area and dry mass of leaves of cashew taking into account the trees position in a planting for a better understanding of the variability of matters production by photosynthesis.

UNDER PEER REVIEW

Material and methods

Data collection

The cashew tree selected for the study was 8 years old, rectangular and with an area of 3.5 ha and a density of 400 trees/ha. It is located in the district of Parakou (9°20 'north latitude and 2°35' East longitude). The climate is of Sudanese type with a rainy season (June to November) and a dry season (December to May). The average annual rainfall varies from 1100 to 1200 mm per year. The annual average temperature varies between 26° C and 30° C. The warmest month of the year is February while the cooler is August. The relative humidity varies from 15% in the dry season (January-February) to 99% in the rainy season (August-September) while the annual average insolation varies between 2,200 and 2,400 hours.

The plantation was divided into five zones (south, central, north, east and west) according the direction of solar radiation movement. In each zone two trees were randomly selected. Selected trees have an average diameter of 20.68 cm and an average height of 5.15 m. The crown of each tree has been divided vertically into three zones. In each zone, 60 leaves were collected from random manner taking into account the possible wide range of dimensions for the categories of axes. In total, a sample of 180 leaves were collected per tree. On each leaf, the following data were collected:

- the length of the leaf representing the distance between the top of the leaf blade and stipule of the leaf (petiole base)
- the width of the leaf corresponding to the leaf width measured at half of the length;
- the leaf area representing the entire area occupied by the blade. Each leaf was photographed with a digital resolution of 18 Mega pixel camera. The leaf area

UNDER PEER REVIEW

corresponding to each image obtained was determined using the Mesurim Pro version 3.4 software;

- the dry mass is the mass of the leaf when it is free of all the amount of water it contains. To determine the mass, each leaf was dried in an oven at 103 °C for 24 hours and then stored in a room heated closed storage for 24 hours. They were then weighed using a balance to 0.01 g accuracy.

Data analysis

Initially, data was described. Secondly, the effect of tree position on the dimensions of the cashew leaf was evaluated using analysis of variance method with factors for the position (five modalities: south, central, north, west and east) and the trees. The Newman-Keuls test was also used to structure the mean in case of significant difference. The method of covariance was used to test the effect of the position on the estimation of the leaf area and dry mass. The position was considered as a dummy variable in the models studied. The estimation models of leaf area and dry mass were established using the linear regression method. In this context, different types of models were tested (Table 1). The Box and Cox transformation was applied to the response variable in order to make valid the conditions of application of the method. The Box-Cox transformation is indeed a transformation of the dependent variable that can be closer to the normal distribution and make constant variances.

The prediction quality of the models was evaluated by the cross-validation method in order to limit problems like overfitting. Indeed, cross-validation tests the predictive accuracy of a model in a testing dataset relative to the predictive accuracy of the training dataset from which the model was established. Ideally, with a large enough sample, a proportion of

UNDER PEER REVIEW

observations is assigned to the training dataset and the remaining observations are assigned to the testing dataset. The model is constructed using the observations of the training dataset, and the predictive power is tested using observations from the testing dataset. The prediction error is estimated by calculating on the testing dataset, the mean square error. The sample size is not large enough in the context of this study, the approach used was leave-on-out cross validation method which consist to divide the original sample in n samples (n is the sample size), then select one of the n samples as the validation set and the (n-1) other samples formed the training set. The mean square error was calculated. The operation was repeated n times by selecting another validation sample from the (n-1) samples which have not yet been used for model validation. The average of n mean square errors were calculated to estimate the prediction error.

Table 1

Results

Description of data

Leaf length is on average between 13.70 cm and 15.49 cm, respectively, with an average error of 0.12 cm and 0.15 cm (Table 2). The highest length was obtained on the leaves of the trees situated north while the shorter length was obtained on the leaves of trees located to the west. With regard the width of the leaves, they vary in average of 8.37 cm to 9.60 cm. The greatest width was achieved on the leaves of the trees to the south and the lowest value was obtained on the leaves of trees located to the west. As for the leaf area, values were on average between 66.77 cm2 (obtained in the east) and 109.14 cm2 (obtained in the south). The dry mass of the leaves varies on average from 1.03 (obtained in the west) and 1.29

UNDER PEER REVIEW

(obtained in the south). The variability was of same order of magnitude for most positions regardless of the parameters considered.

Table 2

Effect of the trees position on the characteristics of the leaves

Evaluation of the effect of the tree position in the planting with respect to the solar radiation on the features of the cashew leaf (Table 3) showed that the leaves having larger dimensions and greater dry weight were obtained from trees located in the south area of the plantation (15 cm in length, 9.6 cm in width, 109.1 cm² for the area and 13 g/leaf to the dry mass). Whereas, the leaves of the trees from the west side of the plantation are small and have the lowest value of dry mass (13.7 cm in length, 8.4 cm in width, 71.4 cm for area and 1 g/leaf to the dry mass). We also note a slight gradient to lower values from south to north and from east to west.

Table 3

Estimation of leaf area and dry mass

The results of analysis of variance previously obtained, showed that tree position influenced the area and dry mass of the leaves. These effects were confirmed by analysis of covariance whose results have not been presented in the paper for brevity. Indeed, the results of covariance analysis showed that the dummy variable had a significant effect in each model. These results suggested that estimating the leaf area and dry mass must be done for each tree position in the plantation.

UNDER PEER REVIEW

Examining the results, regardless of the position, showed that the best models from the point of view of fit quality and prediction quality were in the form $S^{\lambda} = aln(LW) + b$ for leaf area (Table 4) and in the form $m^{\lambda} = aln(LW) + b$ for dry mass (Table 5). Indeed, for these models adjusted R^2 values are highest, indicating that they were relatively well adapted to data. In addition, in terms of prediction, the mean square errors obtained by cross-validation were lowest.

Moreover, the diagnostic results of the residuals (Figures 1 and 2) comply with the conditions of applications of the method. Thus, the histograms indicated no potential outliers in the data. Normal probability plot of the residuals showed almost linear plots, consistent with a normal distribution. Diagrams residual values based on the adjusted values presented a random pattern, suggesting that the residuals had constant variance. Graphs of the order according to the residual values showed no particular pattern. Therefore, these models were those that best predicted the area and the dry mass of a new leaf from a tree located at a given position of the planting.

Although the models of form $S^{\lambda} = aLW + b$, $S^{\lambda} = aL^2 + b$ and $S^{\lambda} = aW^2 + b$ to leaf area in the one part and form $m^{\lambda} = aLW + b$, $m^{\lambda} = aL^2 + b$ and $m^{\lambda} = aW^2 + b$ for dry mass, on the other hand, had relatively high adjustment qualities, near of the selected models, they nevertheless presented poorer predictive qualities. The form models $S^{\lambda} = aL + b$, $S^{\lambda} = aW + b$, $S^{\lambda} = aln(L) + b$ and $S^{\lambda} = aln(W) + b$ to leaf area of the one part and form $m^{\lambda} = aL + b$, $m^{\lambda} = aW + b$, $m^{\lambda} = aln(L) + b$ and $m^{\lambda} = aln(W) + b$ for r dry mass, on the other hand, gave intermediate results.

Table 4

Table 5

Figure 1

Figure 2

UNDER PEER REVIEW

Discussion

In this study, the effect of the cashew tree position in the plantation was evaluated on the estimation of leaf area and of the dry mass of the leaves. In the literature, several models were described to estimate the leaf area. For many plants, these models were generally functions of the length and width, but very little information was available for cashew.

The average values obtained for the leaves dimensions for different tree positions in the plantation were consistent with those reported in the literature (the length varies between 10 and 20 cm and width varies between 6 and 10 cm in width). Similarly the values of the leaf area are consistent with those reported by Archak *et al*. [23] (2003) who reported leaf size of 87.2 cm^2 and a range of 51.4 to 174.3 cm^2. Assessing the effect of the trees position on the characteristics of the leaf showed a significant effect on both the dimensions of the leaf on its dry mass. The heaviest leaves and large dimensions were obtained in the south, and lighter and smaller dimensions were obtained in the east and west of the plantation. The quantity of dry mass produced per leaf follows the same trend. The function of leaves is to gather energy from sunlight, and exchange carbon dioxide and oxygen with the atmosphere through photosynthesis. The anatomy and growth of leaves is complex. The soil is more or less homogeneous in the plantation and trees receiving the same silvicultural treatment, this result can be explained among other things by the fact that trees located in the south of plantation have more sunlight and therefore produce more dry mass for their growth and development. Indeed, a leaf subjected to a given illumination (useful quantum light for photosynthesis), will absorb a certain quantity of carbon dioxide from the air (CO2) and, following various photochemical processes and dark reactions produce carbohydrate base compounds of the plant growth [24] (Jones, 1992). However, a key feature which influences the interception of photosynthetic radiation of a vegetation canopy is the inclination and azimuth of the leaves

UNDER PEER REVIEW

[24] (Jones, 1992). Under natural conditions, the total incident radiation (PAR) at a given time on a canopy comes from all directions of the celestial canopy, in varying quantities according to each of these directions [25] (Deneroy *et al*., 2002). The canopy is not isotropic, interception is different for each incidence angle of the radiation [24] (Jones, 1992). In addition the angular distribution of the incident radiation intensities also vary over time, especially along the height of sun in the sky [25] (Deneroy *et al*., 2002). Furthermore, observations in the field showed that natural vegetation located south of the plantation was more open with the presence of yam fields in particular. Niinemets *et al*. [26] (2007) reported that variation in leaf size is associated with major changes in within-leaf support investments and in large modifications in integrated leaf chemical and structural characteristics.

The variability of the leaf area and dry mass according to the position measured by the coefficient of variation, in the order of 30% suggest that the shape of the leaf and therefore the quantity of dry mass content varies according to the position of the leaf on the tree. This result is consistent with those known in the literature ([21] Esau, 1965; [27] Wardlaw, 1968; [19] De Swart *et al*., 2004). Other authors like Verwijst and Wen [28] (1996) and De Swart *et al*. [19] (2004) also mentioned a difference in shape between the leaves on the main stem and those made by the lateral branches respectively in *Salix viminalis* and *Capsicum annuum*. However, Tondjo *et al*. [1] (2015) did not detect a difference between the shape of the leaves from the stem and leaf shape of the branches in teak. These latter authors found out differences between the dry mass of the leaves from the stems and those of the branches. Similar results were also obtained by Leroy *et al*. [29] (2008) who mentioned the existence of the variability in leaf mass area linked to the architectural position and the axis category of the parent shoots.

Evaluation of the influence of the tree positions on estimating the leaf area and dry mass of leaves showed a significant effect thus confirming the previous results. In fact, the

UNDER PEER REVIEW

comparison in pairs of the five estimation models for each characteristic (leaf area and dry mass of the leaf) showed that different models should be used for each position. Whatever the considered position, the models better predict the leaf area and dry mass of a new leaf in a plantation of cashew, from measurements of the length and width are logarithmic models of the form $S^{\lambda} = a\ln(LW) + b$ for leaf area and the form form $m^{\lambda} = a\ln(LW) + b$ for dry mass. In terms of fit quality of the data, the models obtained are significant and generally satisfactory (R^2 varies from 0.51 to 0.86, for leaf area and 0.30 to 0.80 for the dry mass). Moreover, the prediction errors obtained by cross-validation are rather low and vary from 0.0001 to 0.2978 for leaf area and from 0.0001 to 0.0116 for dry mass. Prediction quality of leaf area of a new leaf are more efficient for models established in tree positions in the north, center and east. It is less efficient for those in tree position of south and west. Regard to the dry mass, all models obtained predict efficiently the dry mass of a new leaf although a number of these models have a relatively poorer fitting quality. These results confirm that the leaf area and dry mass of the leaf can be estimated with good accuracy from the maximum length and the maximum width of the sheet. Unlike the logarithmic models obtained in this study, Murthy *et al*. [30] (1985) had determined a linear relationship between leaf area and the product of the length and width for the same species. The differences between the models can be linked among other to climate effects, variety and especially the fact that these authors did not used to their selection, a criterion based on the assessment of the prediction quality on new leaf. Non-destructive estimation models of leaf area based on the measurement of linear dimensions such as length and width have been established for many species such as avocado [16] (Uzun and Celik, 1999), banana [31] (Potdar and Slovak, 1991), kiwi [16] (Uzun and Celik, 1999), maize [9] (Stewart and Dwyer, 1999) and sunflower [32] (Bange *et al*., 2000). Other authors have seen the power models of the length and/or width as most suitable for plants such as black pepper [33] (Kandiannan *et al*., 2002), vines [15] (Williams and

UNDER PEER REVIEW

Martinson, 2003), the dwarf coconut [34] (Souza *et al*., 2005), jatropha [35] (Pompelli *et al*., 2012) and teak [1] (Tondjo *et al*., 2015). Others again were established models from a single characteristic of the leaf (length or width). Thus, Reynolds [36] (1971) proposed two models based on each of the two characteristics (length or width) to predict leaf area of a cocoa leaf, Kobayashi [37] (1988) used the length to predict leaf area of a guava leaf and Willaume *et al*., [38] (2004) also estimated leaf area of the apple leaf from measuring only the length of the leaf. In this study, power models and models based on the use of a single characteristic (length and width) are less good in terms of quality prediction. The differences between the models can be related to the conditions of the study environment and the specificity of the leaf shape of the species studied. The same types of models were obtained for all positions, suggesting that grow cashew leaves retaining their shape regardless of the position. These results are consistent with those of [1] Tondjo *et al*. (2015) on the Teck, who claimed, on the basis of the linear relationship between the leaf area and the product of the length and width that the leaves have a simple expansion without change shape. We therefore conclude that both length and width measurements are necessary to estimate leaf area and dry mass accurately of cashew leaves and the tree position in the plantation affects the quantity of sunlight intercepted by the trees.

Conclusion

This aim of the study was firstly to assess the effect of the tree position in the plantation on the characteristics (length, width, area, dry mass) of the cashew leaves, and secondly to estimate with good accuracy leaf area and dry mass of the leaves. The tree position in the plantation had an influence on the characteristics of the leaf including the leaf area and dry mass. The best models for estimating the leaf area and the dry mass of cashew leaves were function of the logarithm of the product of the length and width and vary according to the tree

UNDER PEER REVIEW

position in the plantation. It therefore appears necessary to consider the position of trees in the sample design for the estimation of leaf area and dry mass of the leaves at a plantation and in default to develop a specific model for each position of the trees according the movement of the solar radiation.

References

1. Tondjo K, Brancheriau L, Sabatier SA, Kokutse AD, Akossou A, Kokou K, Fourcaud T. Non-destructive measurement of leaf area and dry biomass in *Tectona grandis*. *Trees*, 2015, 29(5): 1625–1631.
2. Marron N, Villar M, Dreyer E, Delay D, Boudouresque E, Petit J-M, Delmotte FM, Guehl J-M, Brignolas F. Diversity of leaf traits related to productivity in 31 *Populus deltoides* x *Populus nigra* clones. *Tree Physiol*, 2005, 25: 425–435.
3. Blanco FF, Folegatti MV. Estimation of leaf area for greenhouse cucumber by linear measurements under salinity and grafting. *Agricultural Scienc*e, 2005, 62(4): 305–309.
4. Lang GA. Precocious, dwarfing and productive – How will new cherry rootstocks impact the sweet cherry industry? *HortTechnol.,* 2000, 10: 719–725.
5. Lang GA. Underlying principles of high density sweet cherry production, *Acta Hortic.* 2005, 667: 325–335.
6. Fourcaud T, Zhang XP, Stokes A, Lambers H, Koerner C. Plant growth modelling and applications: the increasing importance of plant architecture in growth models. *Ann. Bot.* 2008, 101: 1053–1063.
7. Kvet J, Marshall JK. Assessment of leaf area and other assimilating plant surfaces. In Z. Sestak, J. Catsky, and P. G. Jarvis, Eds., *Plant Photosynthetic Production*, Manual of Methods, Junk Publishers, The Hague, The Netherlands, 1971, 517–555.

UNDER PEER REVIEW

8. Lu HY, Lu CT, Wei ML, Chan LF. Comparison of different models for non-destructive leaf area estimation in taro. *Agronomy Journal*, 2004, 96(2): 448–453.
9. Stewart DW, Dwyer LM. Mathematical characterization of leaf shape and area of maize hybrids. *Crop Science*, 1999, 39(2): 422–427.
10. Bhatt M, Chanda SV. Prediction of leaf area in *Phaseolus vulgaris* by non-destructive method. *Bulgarian Journal of Plant Physiology*, 2003, 29(2): 96–100.
11. Mendoza-de Gyves E, Rouphael Y, Cristofori V, Mira FR. A non-destructive, simple and accurate model for estimating the individual leaf area of kiwi (*Actinidia deliciosa*). *Fruits*, 2007, 62(3): 171–176.
12. Kandiannan K, Parthasarathy U, Krishnamurthy KS, Thankamani CK, Srinivasan V. Modelling individual leaf area of ginger (*Zingiber officinale* Roscoe) using leaf length and width. *Scientia Horticulturae*, 2009, 120(4): 532–537.
13. Rouphael Y, Mouneimne AH, Rivera CM, Cardarelli M, Marucci A, Colla G. Allometric models for non-destructive leaf area estimation in grafted and ungrafted watermelon (*Citrullus lanatus* Thunb), *Journal of Food, Agriculture and Environment*, 2010, 8(1): 161–165.
14. Montero FJ, De Juan Cuesta JA, Brasa A. Non-destructive methods to estimate leaf area in *Vitis vinifera* L. *HortScience*, 2000, 35(4): 696–698.
15. Williams L, Martinson III TE, Non-destructive leaf area estimation of “Niagara” and “Dechaunac” grapevines. *Scientia Horticulturae*, 2003, 98(4) : 493–498.
16. Uzun S, Celik H. Leaf area prediction models for different horticultural plants. *Tropical Journal and Agricultural Forest*, 1999, 23(6): 645–650.
17. Projet d’Amélioration et de Diversification des Systèmes d’Exploitation (PADSE). Diagnostic global de la filière anacarde au Bénin. *Rapport*, MAEP/PADSE, Bénin, 2003.

UNDER PEER REVIEW

18. Tandjiékpon AM. *Analyse de la chaine de valeur du secteur anacarde du Bénin. Rapport d'étude*, Initiative du Cajou Africain (ICA/GIZ), Bénin, 2010.
19. De Swart EAM, Groenwold R, Kanne HJ, Stam P, Marcelis LFM, Voorrips RE. Non-destructive estimation of leaf area for different plant ages and accessions of *Capsicum annuum* L. *Journal of Horticultural Science & Biotechnology,* 2004, 79 (5): 764–770.
20. Poethig RS. Leaf morphogenesis in flowering plants. *The Plant Cell*, 1997, 9: 1077–87.
21. Esau K. The leaf. In: Esau, K., eds. *Plant anatomy*. John Wiley and sons. New York, London, Sidney, 1965, 467–80.
22. Byrne M, Timmermans M, Kidner C, Martienssen R. Development of leaf shape. *Current Opinion in Plant Biology*, 2001, 4: 38–43.
23. Archak S, Ambika B, Gaikwad D, Gautam EV, Rao VB, Swamy KRM, Karihaloo JL. DNA fingerprinting of India cashew (*Anacardium occidentale* L.), varieties using RAPD and ISSR techniques, *Euphytica*, 2003, 130: 397-404.
24. Jones HG. *Plants and microclimate. A quantitative approach to environmental plant physiology*. 3rd edn. Cambridge: Cambridge University Press, 1992.
25. Deneroy P, Thiebeau P, Goss G. Une méthode pour estimer l'interception du rayonnement par un couvert bas: application au colza avant montaison. *Oléagineux, Corps Gras, Lipides*, 2002, 9(1): 54-63.
26. Niinemets Ü, Portsmuth A, Tena D., Tobias M, Matesanz S, Valladares F. Do we underestimate the importance of leaf size in plant economics? Disproportional scaling of support costs within the spectrum of leaf physiognomy, *Annals of Botany*, 2007, 100 (2): 283-303.

UNDER PEER REVIEW

27. Wardlaw CW. Leaves and buds: further observations. In: Wardlaw, CW, eds. *Morphogenesis in plants. A contemporary study*. Methuen & Co TLD, London, UK, 1968, 181–225.

28. Verwijst T, Wen DZ. Leaf allometry of *Salix viminalis* during the first growing season. *Tree Physiology*, 1996, 16: 655–60.

29. Leroy C, Guéroult M, Wahyuni NS, Escoute J, Céréghino R, Sabatier S, Auclair D. Morphogenetic trends in the morphological, optical and biochemical features of phyllodes in *Acacia mangium* Willd (Mimosaceae). *Trees Struct Funct*, 2008, 23(1): 37–49.

30. Murthy KN, Kumar KV, Bhagavan S, Subbaiah CC, Kumaran PM. A rapid non-destructive method of estimating leaf area in cashew. *Acta Horticulturae*, 1985, 108: 46-48.

31. Potdar MV, Pawar KR. Non-destructive leaf area estimation in banana, *Sci. Hortic.* 1991, 45: 251–254.

32. Bange MP, Hammer GL, Milroy SP, Rickert KG. Improving estimates of individual leaf area of sunflower. *Agronomy Journal*, 2000, 92: 761–5.

33. Kandiannan K, Kailasam C, Chandaragiri KK, Sankaran N. Allometric model for leaf area estimation in black pepper (*Piper nigrum* L.). *J. Agric. Crop. Sci*., 2002, 188:138–140.

34. Souza EF, Araújo MC, Posse RP, Detmann E, Bernardo S, Berbert PA, Santos PA. Estimating the total leaf area of the green dwarf coconut tree (*Cocos nucifera* L.). Sci. Agric., 2005, 62: 597-600.

35. Pompelli MF, Antunes WC, Ferreira DTRG, Cavalcante PGS, Wanderley-Filho HCL, Endres L. Allometric models for non-destructive leaf area estimation of *Jatropha curcas*. *Biomass and Bioenergy*, 2012, 36: 77-85.

UNDER PEER REVIEW

36. Reynolds SGA. A note on estimation of leaf areas of Cacao (*Theobroma cacao* L.) from three leaf parameters, *Trop. Agric.* 1971, 48: 177–179.

37. Kobayashi KD. Estimating leaf area of 'Beaumont' guava, *Trop. Agric*. 1988, 65: 173–175.

38. Willaume M, Lauri PE, Sinoquet H. Light interception in apple trees influenced by canopy architecture manipulation. *Trees*, 2004, 18:705–713

Table 1: Different forms of regression models tested

Model	Equation	
	Leaf area	Dry mass
1	$S^{\lambda} = aLW + b$	$m^{\lambda} = aLW + b$
2	$S^{\lambda} = aln(LW) + b$	$m^{\lambda} = aln(LW) + b$
3	$S^{\lambda} = aL + b$	$m^{\lambda} = aL + b$
4	$S^{\lambda} = aln(L) + b$	$m^{\lambda} = aln(L) + b$
5	$S^{\lambda} = aW + b$	$m^{\lambda} = aW + b$
6	$S^{\lambda} = aln(W) + b$	$m^{\lambda} = aln(W) + b$
7	$S^{\lambda} = aL^2 + b$	$m^{\lambda} = aL^2 + b$
8	$S^{\lambda} = aW^2 + b$	$m^{\lambda} = aW^2 + b$

S = leaf area, m = quantity of dry mass, L = length of leaf, W = width of leaf, λ = coefficient maximizing Box-Cox transformation, ln = natural logarithm, a, b = constant to be estimated.

UNDER PEER REVIEW

Table 2: Description of the leaves characteristics according to the tree position

Characteristics	Tree position	Mean	Mean error	Coefficient of Variation	Minimum	Maximum
Length (cm)	Center	15.28	0.15	18.80	4.50	25.00
	East	14.06	0.14	18.59	4.80	20.60
	North	15.49	0.14	16.71	7.50	22.30
	West	13.70	0.12	16.32	2.50	20.30
	South	15.02	0.15	18.40	8.80	24.00
Width (cm)	Center	8.45	0.08	17.70	5.30	14.00
	East	8.57	0.08	18.75	3.80	13.80
	North	8.44	0.08	16.87	3.90	12.20
	West	8.37	0.07	15.38	5.70	12.20
	South	9.60	0.09	18.56	5.20	14.70
Area (cm^2)	Center	96.42	1.88	36.98	32.44	234.18
	East	66.77	1.29	36.34	12.73	155.80
	North	91.79	1.70	34.81	29.36	198.78
	West	71.41	1.19	31.30	17.52	139.17
	South	109.14	2.11	36.66	34.61	251.49
Dry mass (g)	Center	1.19	0.02	31.78	0.50	2.47
	East	1.24	0.03	40.01	0.18	3.47
	North	1.19	0.02	32.44	0.38	2.49
	West	1.03	0.02	32.81	0.21	2.06
	South	1.29	0.02	35.02	0.35	2.90

Table 3: Comparison of average values of the characteristics of the leaf according to the trees position in the planting

Position	Length (cm)	Width (cm)	Area (cm^2)	Dry mass (g/leaf)
South	15^a	9.6^a	109.1^a	1.3^a
Center	15.3^a	8.5^b	96.4^b	1.2^b
North	15.5^a	8.4^b	91.9^b	1.2^b
East	14.1^b	8.6^b	66.7^c	1.2^{ab}
West	13.7^b	8.4^b	71.4^c	1.0^c

For a given characteristic, mean sharing no letter are significantly different at the 5% level.

UNDER PEER REVIEW

Table 4: Prediction models of leaf area according to the tree position in the plantation.

Tree Position in plantation	Model	λ max	Parameters		Adjustment parameters			Prediction error
			a	*b*	*F*	*p*	*Raj*	
Center	$S^{\lambda} = aLW + b$	0.274	0.006	2.657	734.1	0.00	0.67	0.0385
	$S^{\lambda} = aln(LW) + b$	**0.032**	**0.033**	**0.996**	**818.2**	**0.00**	**0.70**	**0.0001**
	$S^{\lambda} = aL + b$	0.087	0.013	1.281	615.3	0.00	0.63	0.0008
	$S^{\lambda} = aln(L) + b$	-0.041	-0.054	0.975	620.3	0.00	0.63	0.0001
	$S^{\lambda} = aW + b$	0.171	0.069	1.581	540.0	0.00	0.60	0.0071
	$S^{\lambda} = aln(W) + b$	0.081	0.187	1.043	549.3	0.00	0.61	0.0007
	$S^{\lambda} = aL^2 + b$	0.211	0.002	2.184	577.4	0.00	0.62	0.0151
	$S^{\lambda} = aW^2 + b$	0.248	0.008	2.499	497.0	0.00	0.58	0.0319
East	$S^{\lambda} = aLW + b$	0.428	0.016	3.931	495.70	0.00	0.59	0.3541
	$S^{\lambda} = aln(LW) + b$	**0.119**	**0.145**	**0.948**	**473.00**	**0.00**	**0.57**	**0.0021**
	$S^{\lambda} = aL + b$	0.256	0.076	1.826	412.20	0.00	0.54	0.0334
	$S^{\lambda} = aln(L) + b$	0.092	0.182	0.985	394.50	0.00	0.53	0.0011
	$S^{\lambda} = aW + b$	0.295	0.165	2.001	381.80	0.00	0.52	0.0640
	$S^{\lambda} = aln(W) + b$	0.174	0.484	1.027	371.00	0.00	0.51	0.0083
	$S^{\lambda} = aL^2 + b$	0.389	0.007	3.593	419.20	0.00	0.54	0.2327
	$S^{\lambda} = aW^2 + b$	0.401	0.020	3.814	378.10	0.00	0.52	0.2891
North	$S^{\lambda} = aLW + b$	0.437	0.025	3.839	1886.00	0.00	0.84	0.1922
	$S^{\lambda} = aln(LW) + b$	**-0.088**	**-0.062**	**0.974**	**2249.00**	**0.00**	**0.86**	**0.0001**
	$S^{\lambda} = aL + b$	0.334	0.187	1.566	1473.00	0.00	0.81	0.0546
	$S^{\lambda} = aln(L) + b$	0.110	0.348	0.688	1510.00	0.00	0.81	0.0008
	$S^{\lambda} = aW + b$	0.097	0.033	1.262	1074.00	0.00	0.75	0.0007
	$S^{\lambda} = aln(W) + b$	-0.135	-0.137	0.839	1181.00	0.00	0.77	0.0002
	$S^{\lambda} = aL^2 + b$	0.536	0.023	5.322	1372.00	0.00	0.79	0.9056
	$S^{\lambda} = aW^2 + b$	0.293	0.014	2.699	931.70	0.00	0.72	0.0414
West	$S^{\lambda} = aLW + b$	0.555	0.037	6.199	354.30	0.00	0.50	1.7200
	$S^{\lambda} = aln(LW) + b$	**0.418**	**1.894**	**-3.046**	**372.90**	**0.00**	**0.51**	**0.2978**
	$S^{\lambda} = aL + b$	0.419	0.237	2.676	258.50	0.00	0.42	0.3593
	$S^{\lambda} = aln(L) + b$	0.362	2.216	-1.142	265.80	0.00	0.43	0.1623
	$S^{\lambda} = aW + b$	0.534	0.908	2.076	370.20	0.00	0.51	1.3046
	$S^{\lambda} = aln(W) + b$	0.462	4.880	-3.208	368.80	0.00	0.51	0.5283
	$S^{\lambda} = aL^2 + b$	0.469	0.011	5.142	243.00	0.00	0.41	0.7021
	$S^{\lambda} = aW^2 + b$	0.602	0.078	7.338	359.60	0.00	0.50	2.9732
South	$S^{\lambda} = aLW + b$	0.485	0.026	5.787	401.00	0.00	0.53	1.4494
	$S^{\lambda} = aln(LW) + b$	**0.314**	**1.054**	**-0.899**	**407.50**	**0.00**	**0.53**	**0.1238**
	$S^{\lambda} = aL + b$	0.434	0.309	2.885	337.30	0.00	0.48	0.7835
	$S^{\lambda} = aln(L) + b$	0.354	2.520	-1.603	325.30	0.00	0.48	0.2537
	$S^{\lambda} = aW + b$	0.388	0.328	2.932	272.00	0.00	0.43	0.4551
	$S^{\lambda} = aln(W) + b$	0.322	1.836	0.339	271.90	0.00	0.43	0.1697
	$S^{\lambda} = aL^2 + b$	0.516	0.018	6.968	332.70	0.00	0.48	2.3817
	$S^{\lambda} = aW^2 + b$	0.448	0.025	5.631	255.00	0.00	0.42	1.0869

S= area, *L* = length, *W* = width, λ = coefficient maximizing the Box-Cox transformation, *ln* = natural logarithm, *a, b* = constant estimate.

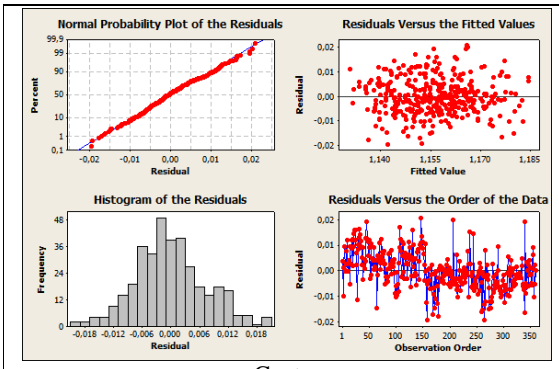
UNDER PEER REVIEW

Table 5: Prediction models of leaf dry mass according to the tree position in the plantation.

Tree position in plantation	Model	λ max	Parameters		Adjustment parameters			Prediction error
			a	*b*	*F*	*p*	*Raj*	
Center	$m^{\lambda} = aLW + b$	0.399	0.001	0.871	593.10	0.00	0.63	0.00186
	$m^{\lambda} = aln(LW) + b$	**0.075**	**-0.043**	**1.199**	**688.50**	**0.00**	**0.66**	**0.00011**
	$m^{\lambda} = aL + b$	0.097	-0.002	1.023	465.60	0.00	0.57	0.00002
	$m^{\lambda} = aln(L) + b$	-0.061	-0.204	1.535	495.70	0.00	0.58	0.00100
	$m^{\lambda} = aW + b$	0.328	0.027	0.793	510.90	0.00	0.59	0.00115
	$m^{\lambda} = aln(W) + b$	0.188	0.069	0.860	519.00	0.00	0.59	0.00010
	$m^{\lambda} = aL^2 + b$	0.228	0.000	0.953	417.80	0.00	0.54	0.00043
	$m^{\lambda} = aLW + b$	0.451	0.002	0.859	475.60	0.00	0.57	0.00322
East	$m^{\lambda} = aLW + b$	0.515	0.004	0.551	912.90	0.00	0.73	0.0134
	$m^{\lambda} = aln(LW) + b$	**0.037**	**0.247**	**-0.136**	**1020.00**	**0.00**	**0.75**	**0.0028**
	$m^{\lambda} = aL + b$	0.268	0.049	0.374	682.30	0.00	0.67	0.0081
	$m^{\lambda} = aln(L) + b$	0.026	0.417	-0.057	691.60	0.00	0.67	0.0033
	$m^{\lambda} = aW + b$	0.343	0.090	0.300	764.80	0.00	0.69	0.0093
	$m^{\lambda} = aln(W) + b$	0.149	0.544	-0.112	782.40	0.00	0.69	0.0049
	$m^{\lambda} = aL^2 + b$	0.450	0.002	0.625	637.30	0.00	0.65	0.0146
	$m^{\lambda} = aLW + b$	0.510	0.006	0.609	698.80	0.00	0.67	0.0155
North	$m^{\lambda} = aLW + b$	0.454	0.005	0.405	779.40	0.00	0.69	0.0221
	$m^{\lambda} = aln(LW) + b$	**0.122**	**0.493**	**-1.302**	**771.20**	**0.00**	**0.69**	**0.0116**
	$m^{\lambda} = aL + b$	0.332	0.070	0.018	569.30	0.00	0.62	0.0195
	$m^{\lambda} = aln(L) + b$	0.194	0.921	-1.424	568.70	0.00	0.62	0.0146
	$m^{\lambda} = aW + b$	0.287	0.128	0.019	627.10	0.00	0.64	0.0181
	$m^{\lambda} = aln(W) + b$	0.131	0.888	-0.797	611.00	0.00	0.64	0.0134
	$m^{\lambda} = aL^2 + b$	0.454	0.003	0.500	550.40	0.00	0.61	0.0255
	$m^{\lambda} = aLW + b$	0.431	0.009	0.488	607.30	0.00	0.63	0.0243
West	$m^{\lambda} = aLW + b$	0.687	0.006	0.309	1320.00	0.00	0.79	0.0115
	$m^{\lambda} = aln(LW) + b$	**0.352**	**0.530**	**-1.500**	**1403.00**	**0.00**	**0.80**	**0.0060**
	$m^{\lambda} = aL + b$	0.405	0.069	0.050	835.80	0.00	0.71	0.0092
	$m^{\lambda} = aln(L) + b$	0.239	0.799	-1.084	865.80	0.00	0.72	0.0062
	$m^{\lambda} = aW + b$	0.572	0.145	-0.204	1029.00	0.00	0.75	0.0116
	$m^{\lambda} = aln(W) + b$	0.447	1.085	-1.288	1026.00	0.00	0.75	0.0091
	$m^{\lambda} = aL^2 + b$	0.547	0.003	0.473	767.50	0.00	0.69	0.0128
	$m^{\lambda} = aLW + b$	0.695	0.009	0.356	969.00	0.00	0.74	0.0149
South	$m^{\lambda} = aLW + b$	0.431	0.002	0.854	138.10	0.00	0.28	0.0152
	$m^{\lambda} = aln(LW) + b$	**0.390**	**0.200**	**0.084**	**155.80**	**0.00**	**0.30**	**0.0116**
	$m^{\lambda} = aL + b$	0.391	0.024	0.709	130.10	0.00	0.27	0.0125
	$m^{\lambda} = aln(L) + b$	0.368	0.340	0.153	141.30	0.00	0.28	0.0106
	$m^{\lambda} = aW + b$	0.444	0.041	0.694	108.60	0.00	0.23	0.0177
	$m^{\lambda} = aln(W) + b$	0.431	0.367	0.262	110.40	0.00	0.23	0.0166
	$m^{\lambda} = aL^2 + b$	0.412	0.001	0.890	115.60	0.00	0.24	0.0146
	$m^{\lambda} = aLW + b$	0.456	0.002	0.888	100.60	0.00	0.22	0.0192

m = mass, *L* = length, *W* = width, λ = coefficient maximizing the Box-Cox transformation, *ln* = natural logarithm, *a, b* = constant estimate.

UNDER PEER REVIEW



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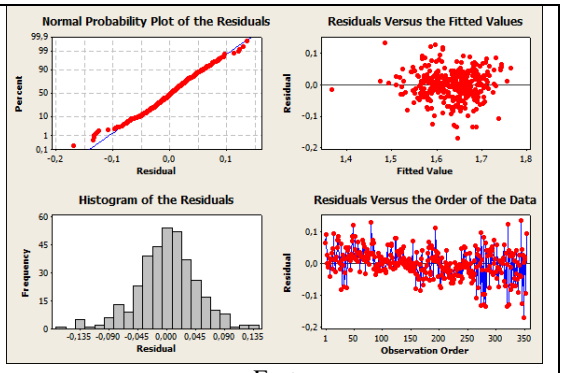

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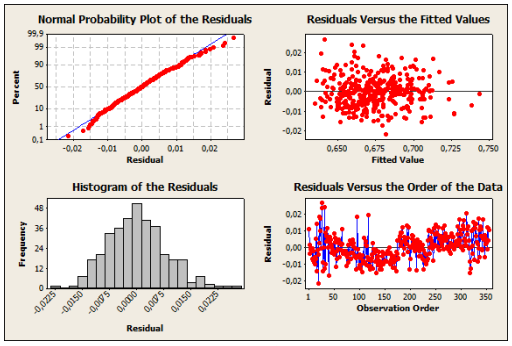

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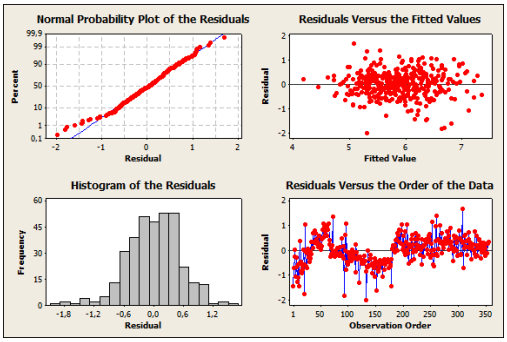

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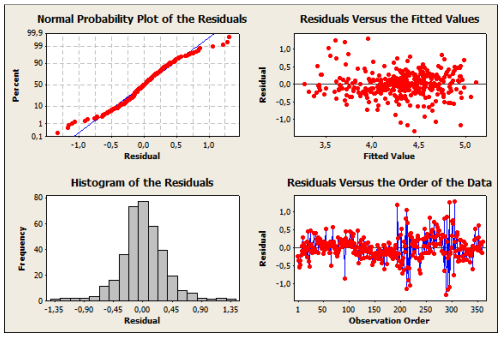

South

Figure 1. Diagnostics of residuals from the regression of leaf area according to tree position.

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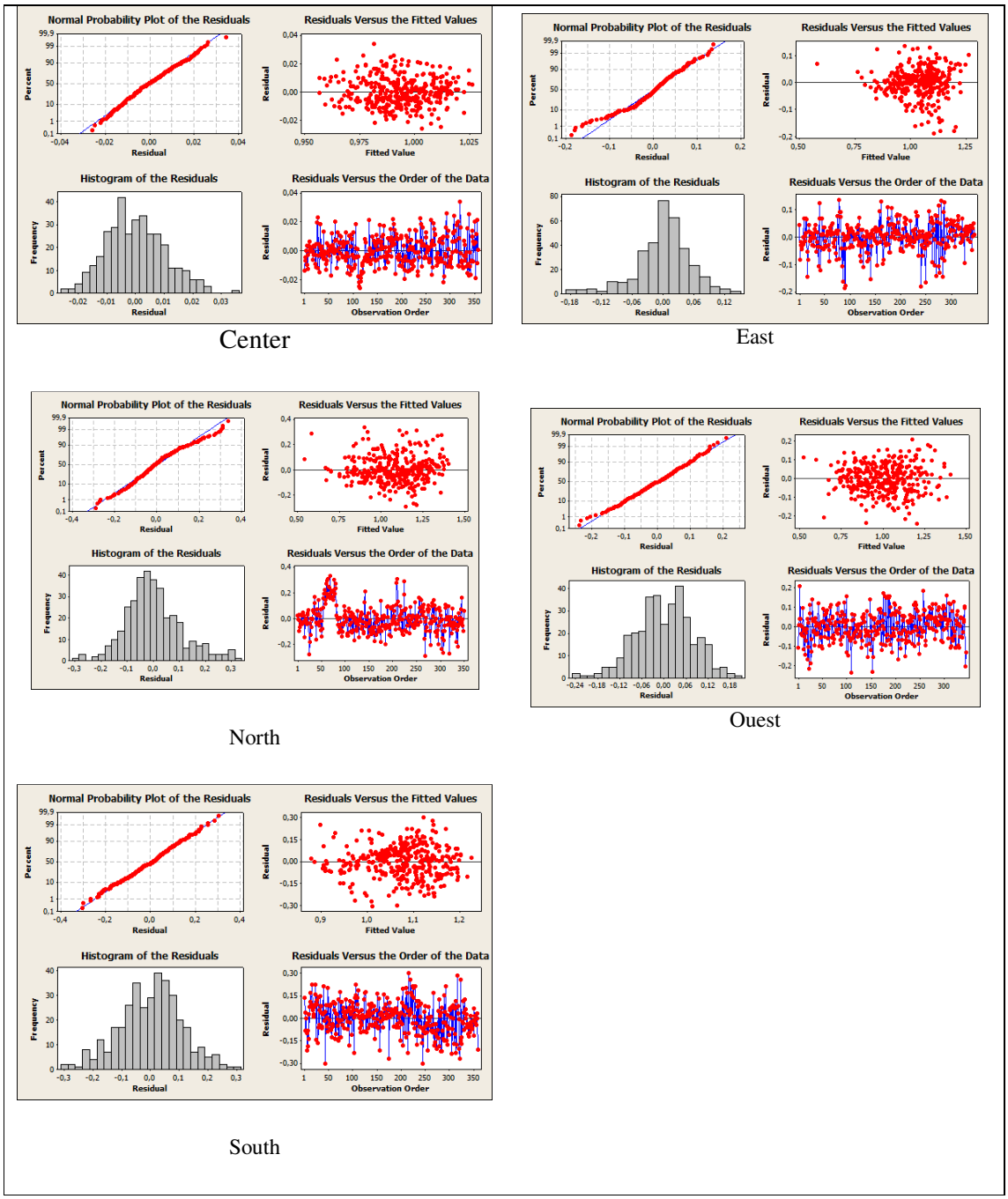

Figure 2. Diagnostics of residuals from the regression of dry mass according to tree position.