COMPARTMENTALIZED ALLOMETRIC EQUATION FOR ESTIMATING VOLUME AND BIOMASS OF EUCALYPTUS IN AGROFORESTRY SYSTEMS IN KENYA

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ABSTRACT

This study used a sample of forty-one *Eucalyptus grandis* trees ranging from 4 to 44 cm diameter at breast height (dbh). The trees were destructively sampled in Nakuru and Kiambu counties, purposely selected in agro-ecological zone II, III and IV, to collect data on the different compartments to develop compartmentalized volume and biomass models. Stem volumes for the whole tree height or to a specific diameter point from the root point were calculated by integrals of splines formed from taper curves of different diameter points. Densities of different compartments of the stem, branches, stump and roots were determined by dividing their sample disks oven dry weight (wood and bark separately) with the fresh volume of the sample disk, whereas, twigs and foliage densities were determined by dividing their sample dry weight with fresh weight. Compartment's biomass was calculated by multiplying their volume with respective density. Five equations relating volume/biomass of the different compartments to variables including dbh, tree height and crown length were fitted to the data using R -3.3.3 statistical software. The best model was the one with the lowest Akaike Information Criterion values (AIC) and Residual Standard Error (RSE). The findings show that tree height and dbh were the best predictor for volume and biomass of the different compartments.

The developed models are recommended for quantification of compartmentalized products of *E. grandis* and their carbon stocks. The utilized methodology may also be of interest to researchers, planners and academicians.

INTRODUCTION

Eucalyptus species were originally introduced in Kenya in 1902 by the colonial government to supply fuelwood for the Kenyan-Uganda railway locomotives (Githiomi and Kariuki, 2010; Oballa *et al*., 2010). Since their introduction, the genus has dominated various agro-ecological zones due to its fast growth, multiple uses, and suitability to small scale farmers. Furthermore, the species continues to support key sectors of the economy such as manufacturing, construction and energy (KFS, 2009).

Among *Eucalyptus* species found in Kenya, *Eucalyptus grandis* is the most popular species grown. The species is among the fastest growing and grows well in both flooded and well drained soils in wide ranges of altitudes from 0 to 2000 m asl (Oballa *et al.,* 2010). Though the species have been grown for a long period in Kenya since its introduction, there is still need of more studies on its allometry, specifically on compartmentalized allometric models that promote sustainable harvesting and estimation of carbon stock of the different parts of the tree.

In a review on registered equations Matieu *et al.* (2011) found Kenya to have only one general equation on *Eucalyptus saligna*, that considered tree biomass in an agroforestry system in western Kenya. Houghton (2001) notes that some developing countries are yet to develop volume and biomass allometric equations for some vegetation types. However, efforts to develop allometric equations for the estimation of volume and biomass have been increasing in the recent years (Chave *et al*. 2005). But there is demand for compartmentalized tree volume and biomass models to promote sustainable harvesting of tree parts while retaining the tree (Hyvonen *et al*., 2016). With the growing demand for total and sustainable utilization of wood products, it is important for entrepreneurs to be able to estimate the value of different compartments of the tree such as stem, to quantify timber production and the branches for firewood, using reliable variables. Likewise, farmers growing eucalyptus and willing to participate in carbon financing would be interested in estimation of the carbon stock in various tree components in order to make informed decisions while participating in the carbon trade.

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Given certain parameters, those utilizing *Eucalyptus grandis* would want to estimate the worth of the different compartments of the tree such as stem (quantity of timber), branches (firewood), and roots. For this to be achieved, compartmentalized volume and biomass equations must be developed. None of the past studies on *E. grandis* have developed such models. The objectives for this study were therefore, to develop compartmentalized models for estimating *E. grandis* volume and biomass.

MATERIALS AND METHODS

Study area

The study was conducted in Nakuru and Kiambu counties of Kenya. In Nakuru County, there were three sites; Molo, Njoro and Rongai whereas in Kiambu County there was one site, Kikuyu (Figure 1). All the four sites are located in sub-humid and semi-humid Agro-ecological zones of Kenya (Figure 1). Nakuru County has a mean annual temperature of 18 °C and mean annual rainfall of 1200 mm. Kiambu County has a mean annual temperature of 26 °C and mean annual rainfall of 2000 mm. All the study sites have deep rich volcanic soils. The main economic activity in both counties is agriculture. Eucalyptus spp. and *Grevillea robusta* are the major agroforestry trees grown in these regions. The trees are distributed in varying development stages, density and management regimes.

Field measurements and biomass sampling

Fourty one trees selected across all diameter classes were destructively sampled within the four study sites in line with the recommended protocol (Hyvonen *et al*.2016). The dbh of the sample trees ranged from 4.0 cm to 44.0 cm. The following preparatory actions were taken before a tree was felled: digital photograph of the tree, felling direction, tree dbh at 1.3 m above ground using a diameter tape and a point marked by circling the stem with a marker,

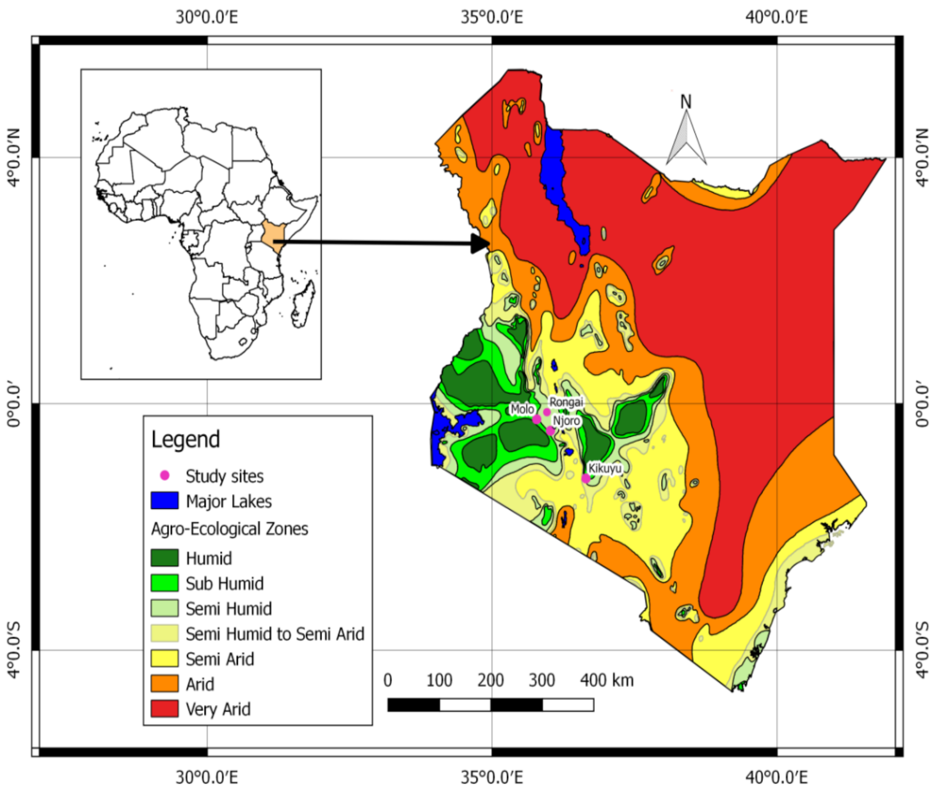

Figure 1. Agro-climatic zones and the locations of the study sites in Kenya (Source: Sombroek *et al*, 1982)

a point where a tree was planned to be cut (stump height); class of tree crown in relation to other trees, height using a Suunto hypsometer, and height and diameter of the stump. The measurements taken after a tree was felled were: stump height (to nearest 1 cm); stump diameter over-bark (1 mm), stump diameter under-bark (1 mm), under-bark dbh (1 mm); length to the base of living crown (0.01 m); length of living crown in three equal sections; stem length (0.01 m); stem over and under bark diameter (1 mm) at 14 relative heights of 1, 2.5, 5, 7.5, 10, 15, 20, 30, … , 80, and 90% converted to absolute heights in metric scale using the total length of the stem; over-bark diameter of all living primary branches (1 mm) and diameter at least 2 cm.

The living crown of a tree was divided into three sections of equal lengths and from each section, three primary branches: the smallest, average and the largest according to branch diameter (at the base) were selected as sample branch. Thus, each tree had nine sample branches, except for four trees that were considered as 100% sample trees where all branches were sampled. Biomass samples of branch wood were taken by diameter classes (Æ); Æ < 2 cm, 2 ≤ Æ < 7 cm, 7≤ Æ < 20 cm and Æ ≥ 20 cm (Figure 2).

Roots and stumps were excavated using manpower. The soil particles on the surface of both the roots and stump were carefully removed by a sturdy brush before commencing the measurements. The data for roots were collected in the same manner as for branches, except that the upper over bark diameter limit was 0.5 cm and only two roots in opposite directions were assessed, and there were no measurements of diameter under bark. For the case of 100% trees all roots were assessed. The sample roots were separated into four size classes (Æ): 0.5 < Æ < 2 cm, 2 ≤ Æ < 7 cm, 7 ≤ Æ < 20 cm and Æ ≥ 20 cm. Fresh weight of samples (0.1 g) from the last three classes were taken using a spring balance. The total fresh weight (100 g) of the stump including the below ground portion after the roots were separated was taken using a spring balance. A vertical segment from the stump (approximately 12.5% or < 1000 g) was extracted and weighed using a digital scale.

The sample of each tree compartment was wrapped in waterproof paper with a tag placed inside and all samples of an individual tree packed in a gunny bag and transported to Kenya Forestry Research Institute (KEFRI) headquarter for laboratory analysis.

Laboratory analysis

The samples of tree compartments analyzed in the laboratory were stem and branch wood, stem and branch bark, dead branches wood, stump wood, roots, twigs, leaves, flowers and pods. Sample wood disks had been extracted from the bottom of the stem, at dbh and at the relative heights of 15%, 50% and 80%. Branch wood samples were obtained from disks or pieces 10-15 cm

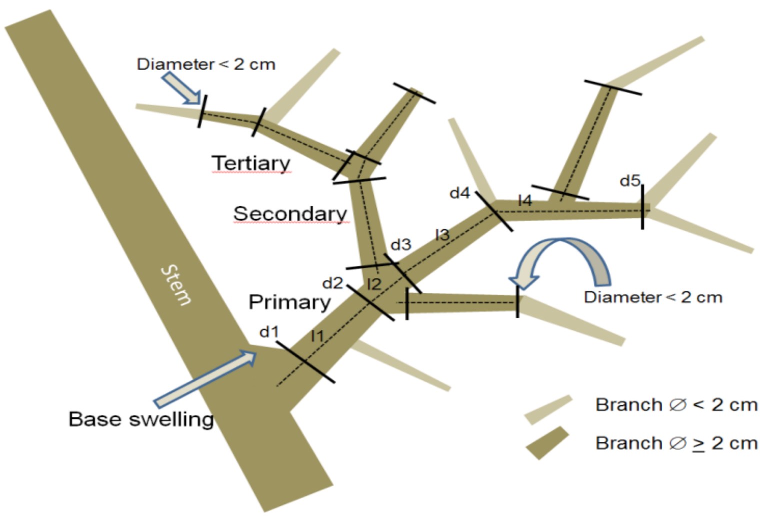

Figure 2. Illustration for measurement of diameter and length of a sample branch

long of branch size classes 2 ≤ Æ < 7 cm, 7 ≤ Æ < 20 cm and Æ ≥ 20 cm. The bark samples were obtained from the stem/branch disks and from the branch pieces. The appropriate weight of the fresh laboratory samples was 500–1000 g but could be less if the available materials were not enough. The fresh weights and volumes of stem and branch wood samples with and without bark to accuracy of 0.01 g were determined by water displacement technique using a digital balance that has the ability to tare weight to zero. Weight increment on immersing the wood sample for about five seconds equals the fresh volume of the wood sample. The samples together with their respective bark were wrapped in waterproof paper and a tag placed inside. Samples of stump wood, root wood, twigs, leaves, flowers and pods were treated in a similar manner excluding the bark. The samples were then dried in an oven (Kottermann (R) 2713) at the temperature of 103^{o}C for 1 to 3 days or when constant dry-weight (0.1 g) was achieved. Samples density (g cm^{-3}) was determined as the ratio of oven dry weight (g) to fresh volume (cm^{-3}).

Data analyses

After the data collection was completed, the data was recorded on excel and imported to R, it was then checked for errors, prior to analysis, and screened for outliers using scatter plots. These scatter plots also revealed the relationship between the volume biomass and predictor variables. Since most of the sampled trees had irregular stems, direct calculation of the volumes from formulae would be inaccurate. Cubic splines were therefore used in volume calculation. With splines, the measurements of tree height and over-bark and under-bark diameters at 14 relative heights of 1, 2.5, 5, 7.5, 10, 15, 20, 30, …, 80, and 90% along the stem were used in calculation of cross cut areas directly. Taper curves for stem volume calculation were formed by a monotone spline according to Fritch and Carson (1980) and calculated with R's splinefun command. This command computes a spline that is increasing or decreasing according to the data, where no values are higher or lower than measured values between measured intervals. They are defined by the use of cubic polynomials on interspaces between diameter points and by continuity of the first and second derivatives in all points of the taper curve. Using this method, stem volumes were calculated by integral of these taper curves. Stem volumes for the whole tree or up to a specific diameter, e.g. 5 cm, were calculated by integral of spline curves from the tree root point.

The volumes of stem barks were calculated as a difference of stem volume with and without bark. The over-and under-bark volumes of sample branches, up to top diameter ≥2 cm, were calculated from the branches' section measurements using the formula of truncated cone (Equation 1). The volume of branch bark were also calculated as the difference of over- and under-bark volumes.

$$V\_branch=h^{*}\ (A1+A2+\sqrt{(A1^{*}A2)})/3 \quad \textit{Equation 1}$$

Equation 1

Where; *h* is section length, *A1* area at the base of section, *A2* area at the end of section.

Because not all branches of the trees were measured, a model using the over-bark diameter at the branch base was fitted to estimate branches under-bark wood volume (equation 2, Table I). A similar model using branch over-bark diameter at the branch base was fitted to estimate the volume of branch bark. The volume of branch with bark will be the sum of under-bark and over-bark volumes.

TABLE I - VOLUME MODELS FOR EUCALYPTUS GRANDIS

Model	**Model formula**	**Parameter**	**Estimate**	**Standard error of parameter**	**RSE, model**	**AIC, model**
equation 2	b	a	1.335e-8***	2.139e-9	0.0008725	-3711.491
n = 220		3.065***		3.245e-2		
equation 3	b	a	2.964633e-8**	9.169e-9	0.0000449	-3888.845
n = 220		2.614***		6.322e-2		

Significant codes 0: ***, 0.001: **, 0.01: *, 0.05

(V = volume in m^{3}, FW = fresh weight in grams, fcp=fruits, cones and pods, d = over bark diameter at the base of the branch in mm, a,b,c are model parameters)

Volume of all branches with a top diameter ≥ 2 cm in a tree were obtained by summing the sample branch volumes (calculated volume) and the estimated volume of the other branches. The above ground volumes of stump (m^3), both over-bark and under-bark were estimated by applying the same truncated cone (frustum) formula as with sample branches (Equation 1). Stump diameter at cutting point multiplied by 1.3 was used as the stump diameter at ground level. The volume of stump bark was the difference of over- and under-bark volumes.

The fresh weight of big branches (diameter ≥ 2 cm) and twigs (branch diameter < 2 cm) and foliage (leaves) of the sample branches were used to fit models utilizing branch over bark diameter at the base (Equations 4-1, 4-2, 4-3and 4.4, Table II) in order to estimate fresh weight of these components for other branches.

Where; V/B: Volume or Biomass, *d*: diameter in cm at breast height; *h*: tree height in m, *cl*: length of living crown in m, and *a*, *b*, *c* are model parameters)

These systems of equations were fitted using "nls" regression in R software for the different tree compartments. The best models were those with the lowest AIC values. The AIC is a way of selecting an equation from a set of (alternative) equations by balancing changes in the goodness-of-fit versus difference in the number of parameters (Kuyah *et al.* 2013)

RESULTS

Some models developed underestimated volume at smaller dbh (Figure 3) e.g.,volume model V.stem3 developed for the stem compartment underestimated volume at dbhs less than 5 cm but had better agreement with V.stem

TABLE II- FRESH WEIGHT MODELS FOR EUCALYPTUS GRANDIS

Model	Model formula	Parameter	Estimates	Standard error of parameter	RSE, model	AIC, model
equation 4-1		a	2.129853***	0.006966	356.5	3431.8
n = 235						
equation 4-2	b	a	0.01108***	0.00.223		3506.9
n = 235	c	197.3***		11.08	416.5	
		-3453***		1003		
equation 4-3	b	a	0.03444***	0.02893		3373.786
n = 235	c	9.216***		3.854	353.9	
		-9.916*		3.933		
equation 4-4	b	a	-286.821***	17.502	46.14	2471.8
n = 235		77.658***		4.033		

Significant codes 0: ***p<0.001, ** p< 0.01, * p< 0.05 .

FW = fresh weight in grams, fcp=fruits, cones and pods, d = over bark diameter at the base of the branch in mm, a,b,c are model parameters

Dependent variables (calculated volume and calculated biomass) were then plotted against several explanatory variables to examine the range and shape of the functional relationship and to assess the heterogeneity of the variance. The following linear models for prediction of volume and biomass were then tested for each of tree compartment.

$$V/B = a * d^b$$
$$V/B = a * d^b * h^c$$
$$V/B = a + d^b + h^c$$
$$V/B = a * d^b * cl^c$$
$$V/B = a + d^b + cl^c$$

The volume models developed for each compartment and their resulting coefficients and other statistics are shown in Table 3. and V.stem2 at intermediate dbhs *Ps*: One observation (point approx. 75, 2) was added manually for estimation purposes.

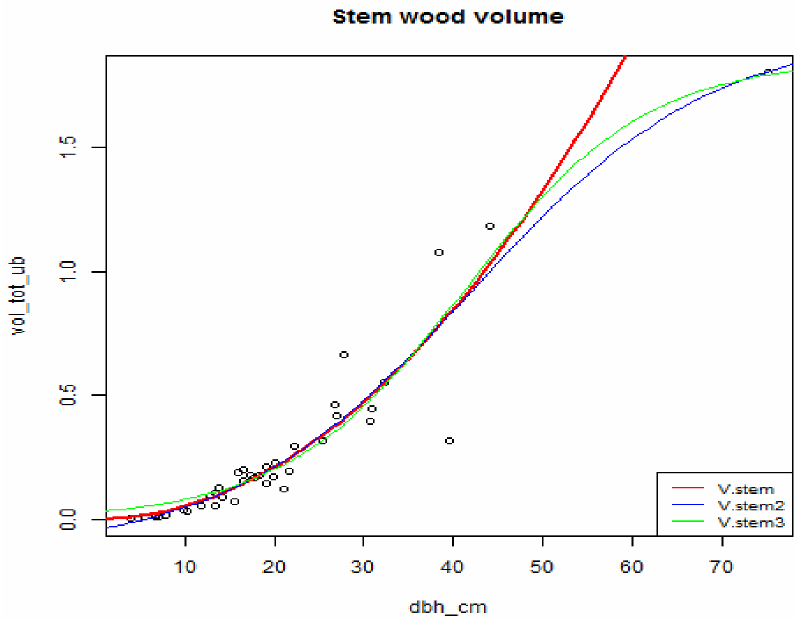

Figure 3. A comparison of volume models developed for stem compartment.

TABLE III- PARAMETERS AND STATISTICS OF THE BEST FITTED VOLUME MODELS FOR *EUCALYPTUS GRANDIS*

Model	Model formula	Parameter	Estimate	Standard error of parameter	RSE, model	AIC, model
Stem wood up to 5 cm top diameter	b	a	0.00046**	0.0003		-55.75928
		2.03284***		0.1937	0.1147	
Stem wood, whole tree	b	a	0.00050**	0.00034		-55.70913
		2.01513***		0.1918	0.1148	
Stem bark, up to 5 cm top diameter	b	a	0.00005*	0.000025		-280.13
		1.434***		0.0860	0.0069	
	c	0.7943***		0.1658		
Stem bark, whole stem	b	a	0.000050*	0.000024		-280.84
	c	1.435***		0.0861	0.0068	
		0.8131***		0.1658		
Branch wood	b	a	1.606e-31	2.039e-30		-102.6498
		1.870e+01**		3.358	0.0527	
Branch bark	b	a	2.536e-16	1.474e-15		-190.4843
		9.004		1.546***	0.0150	
Stump wood	b	a	-1.0172***	2.064e-9		-328.0125
		0.0081***		1.379	0.0038	
Stump bark	b	a	-2.005099***	5.788e-11		-420.11
		0.001999**		1.842	0.0011	
	c	0.0004611		1.954		

Significant codes 0: ***, 0.001: **, 0.01: *, 0.05 .

V = volume in m³, *d* = diameter at dbh in cm, *h* = height in m, *a,b,c* are model parameters

It is clear from the above equations that dbh and height were the best predictors for calculation of volume for the various compartments, all the best equations for the different compartments have either dbh (d) or a combination of dbh (d) and height (h).

Biomass equations developed for the various compartments are shown in table IV.

TABLE IV- PARAMETERS AND STATISTICS OF THE BEST FITTED BIOMASS MODELS FOR *EUCALYPTUS GRANDIS*

Model	**Model formula**	**Parameter**	**Estimates**	**Standard error of parameter**	**RSE, model**	**AIC, model**
Stem wood, whole stem		a	0.09133*	0.06115	19.32	432.2517
		b	1.58749***	0.21333		
		c	1.00656*	0.27375		
Stem bark		a	0.009788	0.012082	21.55	363.08
		b	2.53748***	0,343383		
Branch wood, diameter >=2 cm		a	0.1025	0.2424	30.79	324.69
		b	1.1005*	0.467		
		c	1.0196	0.8164		
Branch bark		a	0.0963	0.3552	34.1	330.45
		b	1.6165	1.0604		
Twigs, diameter < 2cm		a	0.00425	2.2894	5.475	229.44
		b	2.5620***	0.0666		
		c	-0.54641	0.1778		
Foliage		a	-4.8745*	2.0931	5.844	234.15
		b	0.5867***	0.1413		
		c	0.4041.	0.2034		
Stump wood		a	-4.41171***	0.51671	1.456	144.86
		b	0.57208***	0.06009		
		c	0.16086.	0.08638		
Stump bark		a	-2.53009**	0.81313	1.925	165.69
		b	0.41595***	0.08001		
Aboveground, all		a	0.224	0.1657	68.93	457.05
		b	1.7238***	0.1639		
		c	0.6251*	0.2541		
Roots		a	-6.19625	1.11757	0.6617	10.5
		b	059671.	0.04719		
		c	0.51299	0.09094		
Stump, belowground		a	-9.93054	3.04654	2.035	19.49
		b	0.80755.	0.08547		
		c	0.51075	0.17109		
Belowground, all		a	0.50209.	0.07691	0.07622	-6.79
		b	0.40363.	0.03466	1.0785 (1	
		c	0.35964	0.06133		

(1 RSE calculated with estimated real values (not from model's residuals which are in logarithmic scale), Significant codes 0: ***, 0.001: **, 0.01: *, 0.05: .

(*B* = biomass in kg, *d* = diameter at dbh in cm, *h* = height/length in m, *cl* = crown length in m, *ln* = natural logarithm, and *a,b,c* are model parameters).

DISCUSSION

Nonlinear models were fitted for volume and biomass estimation for each tree component. The difference between the performance of linear and non-linear models for tree components has been noted to be negligible (Magalhães and Seifert, 2015), however Salis *et al.,* 2006 and Schroeder *et al*., 1997 found nonlinear models to perform better than linear models, their findings therefore informed this works analysis.

The volume equations developed for the different compartments of *E. grandis* were functions of dbh alone or a combination of dbh and height. Most parameter estimates were significant at 5% confidence level. All the biomass models developed for the different compartments excluded height as a predictor and used either dbh alone or a combination of dbh and crown length. Crown parameters are generally difficult to measure accurately, nonetheless, our equations show that inclusion of crown length improves the accuracy of the trees biomass (Kuyah *et a1.,* 2012)

The relationships between stem wood and stem bark biomass compartments with dbh were more pronounced than other compartments. Relationships of the other compartments were not pronounced because they are influenced by various management practices applied to the agroforestry trees, which have been reported by Víquez and Perez (2005) and Petersen *et al*. (2008).

CONCLUSION

Diameter at breast height, crown length and height were effective predictors for the different categories of volumes and biomass. Tree height and dbh were the best predictor for volume and biomass of different compartments of *E. grandis*. The developed allometric equations can be used to estimate volume and biomass of the different compartments of *Eucalyptus grandis* in agricultural landscapes in similar agro-ecological zones, provided that tree growth parameters fall within similar ranges to those of the sampled population. The methodology used in data collection can also be of interest to forest managers, researchers and academicians.

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