forests

MDPI

Article

Tree Climbing Techniques and Volume Equations for *Eschweilera* (Matá-Matá), a Hyperdominant Genus in the Amazon Forest

Bruno O. Gimenez *, Leandro T. dos Santos, Jonas Gebara, Carlos H. S. Celes, Flávia M. Durgante, Adriano J. N. Lima, Joaquim dos Santos and Niro Higuchi

Forest Management Laboratory (LMF), National Institute of Amazonian Research (INPA), Manaus 69060-001, Brazil; leandrotavaress@gmail.com (L.T.d.S.); jonas@imaflora.org (J.G.); carlosceles@yahoo.com.br (C.H.S.C.); flaviamdflorestal@gmail.com (F.M.D.); adrianolmf@gmail.com (A.J.N.L.); joca@inpa.gov.br (J.d.S.); niro@inpa.gov.br (N.H.)

* Correspondence: bruno.oliva.gimenez@gmail.com; Tel.: +55-92-9-8184-3581

Academic Editors: Robert Evans and Timothy A. Martin

Received: 13 March 2017; Accepted: 27 April 2017; Published: 3 May 2017

Abstract: The *Eschweilera* genus has great ecological and economic importance due to its wide abundance in the Amazon basin. One potential use for the *Eschweilera* genus is in forest management, where just a few trees are removed per hectare. In order to improve the forest management in the Amazon, this study assessed two critical issues: volume equations fitted for a single genus and the development of a non-destructive method using climbing techniques. The equipment used to measure the sample trees included: climbing rope, ascenders, descenders, and carabiners. To carry out the objectives of this study, 64 trees with diameter at breast height (DBH) $\geq$ 10 cm were selected and measured in ZF-2 Tropical Forestry Station near the city of Manaus, Brazil. Four single input models with DBH and four dual input models with DBH and merchantable height (H) were tested. The Husch model ($V = a \times DBH^b$) presented the best performance (R^2 = 0.97). This model does not require the merchantable height, which is an important advantage, because of the difficulty in measuring this variable in tropical forests. When the merchantable height data are collected using accurate methods, the Schumacher and Hall model ($V = a \times DBH^b \times H^c$) is the most appropriated. Tree climbing techniques with the use of ropes, as a non-destructive method, is a good alternative to measure the merchantable height, the diameter along the stem, and also estimate the tree volume (m^3) of the *Eschweilera* genus in the Amazon basin.

Keywords: forest management; forest inventory; tropical forests; non-destructive method

1. Introduction

The most common method used to fit volume and biomass equations in tropical forests is the destructive method, where trees are selected and harvested to measure different sections of the stem [1–3]. There are also non-destructive methods that can provide good results [4]. One alternative method is the use of dendrometric equipment [5]. This kind of equipment is suitable to use in temperate forests or in lands with planted forests, but in tropical forests the dense understory needs to be cleared away from the stem for visibility. This can inadvertently affect the rates of natural regeneration which are vital to the recruitment patterns in tropical forests [6,7]. In addition, the regeneration within permanent plots cannot be cut. Therefore, tree climbing techniques using ropes, as a non-destructive method, can be useful to collect the diameter along the stem and access the tree crown to collect seeds and branches [8–11]. This technique is different than methods that use climbing spikes, which can cause multiple types of injuries in tree rhytidome affecting their survival [9,12], particularly in tropical trees where the bark and the sapwood thicknesses are very thin [13,14].

The *Eschweilera* genus (Lecythidaceae Family), popularly known as Matá-Matá, is one of the most abundant genera in the Amazon forest, and this genus includes many species that are difficult to separate on the species level [15,16]. The difficulty to separate the different species of the *Eschweilera* genus is being overcome by the development of Near Infrared (NIR) spectroscopy techniques [17]. The *Eschweilera* genus, aside from being the most abundant genus, has significant potential for the forest management in the Amazon region as it provides a diversity of wood products and biomass for green energy [18].

In Brazil, the method to estimate the tree volume varies according to the land use. In forest plantations, for example, it is common to fit volume equations by genus, species, or clone [19–21]. In deforested areas in the Amazon basin created for converting forest into pasture, the wood volume estimate is obtained by the form factor model (the ratio of tree volume to the volume of a cylinder) $(\pi \times \mathrm{DBH}^2/4 \times \mathrm{height}) \times 0.7$. The most common methods used in forest management areas within the Amazon basin are the adjustments of equations based on many different species [22]. There are many errors associated with this kind of approach, due to the fact that the stems of the tropical trees have numerous types of form factors [23,24] and just a few of these genera are managed for the procurement of wood products.

In order to improve forest management techniques in the Amazon region, volume equations were developed, by this study, using an innovative non-destructive method (climbing techniques with the use of ropes) for the most abundant tree genus of the Amazon forest, the *Eschweilera* genus.

2. Materials and Methods

2.1. Study Area

The *Eschweilera* trees sampled were measured in two transects oriented in east-west (E-W) and north-south (N-S) directions with 20 m × 2500 m (5 hectares each—total 10 hectares) [25] located in the ZF-2 Tropical Forestry Station of the National Institute for Amazon Research (INPA), which consists of approximately 23,000 hectares surrounded by continuous tropical forest of the Central Amazon (Figure 1).

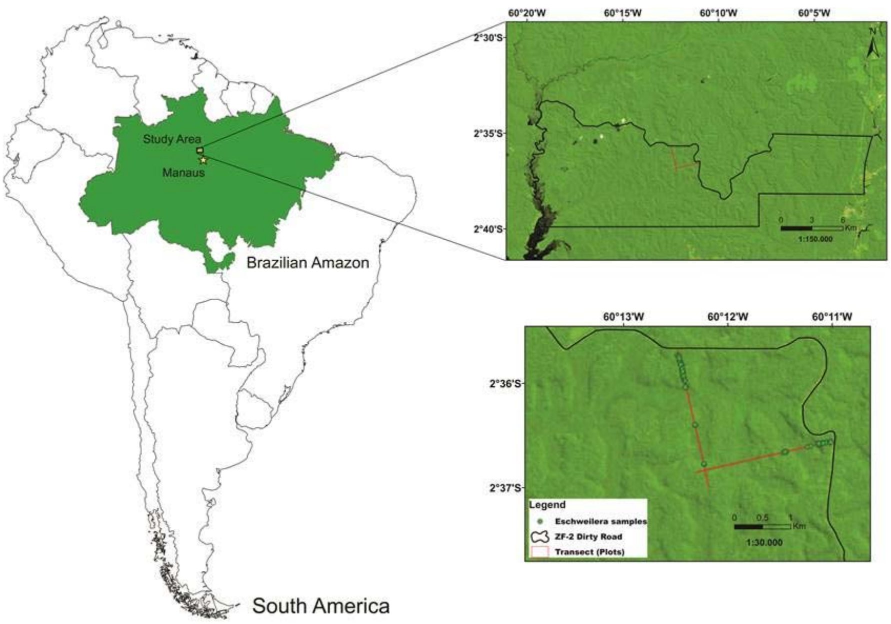

Figure 1. Location map of the Brazilian Amazon, ZF-2 Tropical Forestry Station in proximity to the city of Manaus and the two transects (east-west (E-W) and north-south (N-S)) in red, where the *Eschweilera* sample trees were measured.

2.2. Climbing Technique

The sample trees were measured using climbing ropes, ascenders, descenders, climbing helmet, and carabiners. This method has been used and described in many surveys on tropical forests [8,9,11]. The diameters along the stem were measured at selected locations using a diameter tape (Forestry Suppliers®, Inc., Jackson, MS, USA) and the merchantable height (H) was measured with a metric tape plugged to the climber. The locations of these sections measured were at: 0 m; 0.5 m; 1.0 m; 1.30 m; 2.0 m, and from this location every 1 meter to the first branches of the crown (Figure 2).

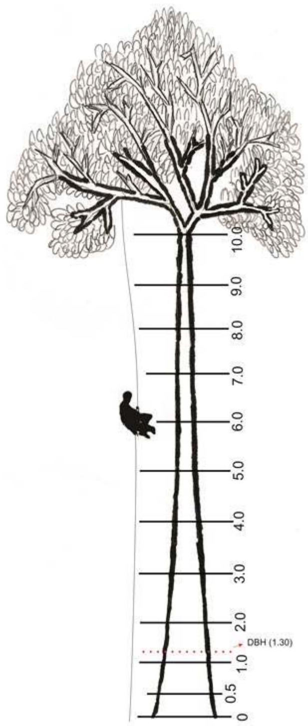

Figure 2. Samples trees of *Eschweilera* genus measured with climbing techniques using ropes.

The Smalian method (Equation (1)) was used to estimate the tree volume as follows:

$$V_{smalian} = \left[\frac{\frac{(\pi \times D_1^2)}{40.000} + \frac{(\pi \times D_2^2)}{40.000}}{2} \right] \times Ls + \ldots + \left[\frac{\frac{(\pi \times D_{ith}^2)}{40.000} + \frac{(\pi \times D_{ith}^2)}{40.000}}{2} \right] \times Ls \quad (1)$$

where $D_1{}^2$ is the diameter squared of the first section in cm, $D_2{}^2$ is the diameter squared of the second section in cm, $D_{ith}{}^2$ is the diameter squared of the *ith* section in cm, and *Ls* is the length of the section in meters.

2.3. Selection Method of Eschweilera Trees

The forest inventory in the north-south/east-west transects was made by the Forest Management Laboratory (LMF-INPA) which has measured all trees with diameter at breast height (DBH) $\geq$ 10 cm since 1996 until 2016 (20 years of data collection) (Figure 3A). All trees with DBH $\geq$ 10 cm were identified by previous studies [26]. The distribution of the *Escheweilera* genus by DBH-classes (Figure 3A) showed negative exponential curves, which is the same pattern that has been ascribed to mature tropical forests [27–29] and for some *Escheweilera* species, like *Escheweilera albiflora* in the Central Amazonian várzea floodplains [30]. The selection of *Escheweilera* individuals in this study (Figure 3B) followed the distribution of *Eschweilera* genus described in the forest inventory of the two transects conducted in 2010 (Figure 3A).

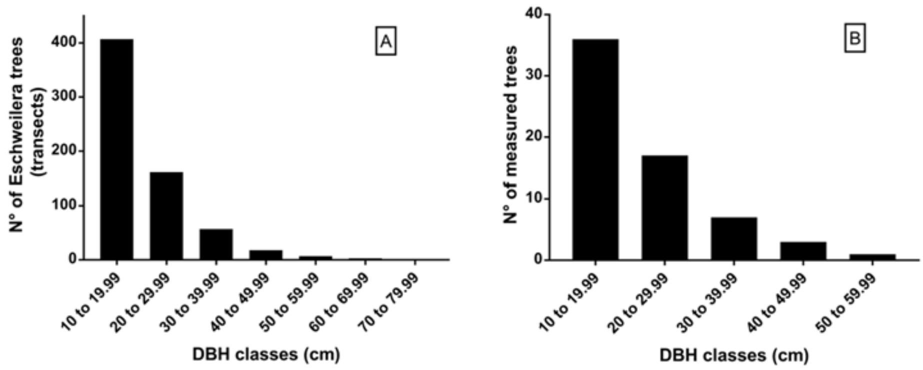

Figure 3. (**A**) Diameter at breast height (DBH) distribution of *Eschweilera* genus ≥10 cm in the two transects (10 hectares) described by the forest inventory data; (**B**) DBH distribution of the 64 *Eschweilera* sample trees measured by this study.

The *Eschweilera* genus has more than 90 species [15]. Prior to using the volume equations developed in this study, it is important to verify the species composition described in Table 1. In total, 64 *Eschweilera* trees were sampled over the 10 ha of the two north-south/East-West transects (see Table S1 for details).

Table 1. Number of measured individuals per species of *Eschweilera* genus.

Species	No. of Trees
Eschweilera atropetiolata S.A.Mori	1
Eschweilera bracteosa (Poepp. ex O.Berg) Miers	1
Eschweilera coriacea (DC.) S.A.Mori	6
Eschweilera grandiflora (Aubl.) Sandwith	1
Eschweilera micrantha (O.Berg) Miers	1
Eschweilera pedicellata (Rich.) S.A.Mori	4
Eschweilera pseudodecolorans S.A.Mori	5
Eschweilera sp.	7
Eschweilera truncata A.C.Sm	8
Eschweilera wachenheimii (Benoist) Sandwith	30
Total	64

2.4. Tested Models

Four single input models with DBH as the independent variable and four dual input models with DBH and merchantable height (H) as independent variables were tested (Table 2).

Table 2. Tested models to estimate the merchantable volume of *Eschweilera* genus.

No.	Model	Author
1	$Vi = a \times DBHi^{b} + \varepsilon$	Husch [31]
2	$Ln\ (Vi) = a + b \times \ln DBHi + \varepsilon$	Husch [31]
3	$Vi = a + b \times DBHi^{2} + \varepsilon$	Spurr [32]
4	$Vi = a + b \times DBHi + c \times DBHi^{2} + \varepsilon$	Hohenadl/Kreen and Prodan [33,34]
5	$Vi = a \times DBHi^{b} \times Hi^{c} + \varepsilon$	Schumacher and Hall [35]
6	$Ln\ (Vi) = a + b \times \ln DBHi + c \times \ln Hi + \varepsilon$	Schumacher and Hall [35]
7	$Vi = a + b \times (DBHi^{2} \times Hi) + \varepsilon$	Spurr [32]
8	$Vi = a \times (DBHi^{2} \times Hi)^{b} + \varepsilon$	Spurr [32]

Where Vi is the *ith* tree volume in m^3; DBHi is the *ith* tree diameter at breast height in cm; Hi is *ith* tree merchantable height in m; ln is the natural logarithm; and ε is the random error.

To check a possible multicollinearity effect between the independent variables, the Pearson´s correlation test was performed. Aside from the *R*-squared values, the best models were selected by observing other statistics such as: the standard error of estimate (*S.E.E*) Equation (2), the distribution of residuals in percentage (*R*%) Equation (3), and the significance of the coefficients of each model (*p*-value).

$$S.E.E = \frac{\sqrt{\sum_{i=1}^{n}\left(v_{i(obs)} - v_{i(pred)}\right)^2}}{n-k} \tag{2}$$

$$R(\%) = \left(\frac{v_{i(pred)} - v_{i(obs)}}{v_{i(obs)}}\right) \times 100 \tag{3}$$

where $vi_{(obs)}$ is the *ith* observed volume in m^3; $vi_{(pred)}$ is the *ith* predicted volume in m^3; n is the number of observations, and k is the number of estimated coefficients.

2.5. Form Factor

The form factor is the relationship between the cylinder volume (*v cylinder*) and the tree volume (*v Smalian*) obtained by the Smalian method Equation (1). Form factor values close to 1 are related to the cylinder form (where the diameters along the tree height are equal). The form factor can also be associated to the quality of tree stem to obtain timber products [36] and with the wood yield in the sawmills [37]. To estimate the form factor (f) per tree the equation used was:

$$f = \frac{\sum v_{(i)smalian}}{\sum v_{(i)cylinder}} \tag{4}$$

where $\sum v_{(i)smalian}$ is the sum of the *ith* tree volume obtained by the Smalian method in m^3; $\sum v_{(i)cylinder}$ is the sum of the *ith* tree volume obtained by the adapted cylinder volume formula ($\pi \times DBH^2/4 \times$ Height) in m^3.

3. Results

The total volume observed for all the 64 measured trees of *Eschweilera* genus was 26.70 m^3 with a mean of 0.417 m^3 per tree. The diameter at breast height (DBH) varied by 10.5 to 56.0 cm, with 56.25% of the trees concentrated in the first DBH-class (10 to 19.99 cm). The highest form factor was 0.98 for *Eschweilera wachenheimii* and the lowest was 0.65 for *Eschweilera truncata*. The form factor values of *Eschweilera* genus varied inversely with DBH. Trees with DBH > 20 cm tended to present lower form factors (0.65 to 0.75) and trees with DBH < 20 cm tended to present high form factors (0.90 to 0.97) (see Table S2 for details).

All tested models showed high R^2 values (Table 3). The statistics of the dual input models with the DBH and merchantable height (H) were slightly better than the single input models that had only the DBH. The Pearson Correlation value for the variables DBH and merchantable height (H) was 0.63, indicating a moderate correlation between these two variables. The highest merchantable height measured was 17.0 m and the lowest was 5.0 m (Average of 10.1 m for all measured trees). The highest values of merchantable height were found to for *Eschweilera pseudodecolorans* (12.36 m), *Eschweilera coriacea* (11.67 m), and *Eschweilera truncata* (11.44 m). The lowest values of merchantable height were found for *Eschweilera atropetiolata* (10.0 m), *Eschweilera pedicellata* (9.25 m), and *Eschweilera wachenheimii* (8.53 m).

Model 3 ($V = a + b \times DBH^2$) tends to underestimate the volumes of trees with DBH $\leq$ 15 cm. Excluding model 3, all the other tested models presented the residuals distribution without bias. The Hush model ($V = a \times DBH^b$) presented the best performance of all single input models tested. Similarly, the Schumacher and Hall model ($V = a \times DBH^b \times H^c$) showed the best performance of all dual input models tested (Figure 4).

Table 3. Estimated coefficients of tested models using 64 sample trees of *Eschweilera* genus and their respective statistics: *p*-value, R^2, and standard error of estimate (*S.E.E*).

ID	Model	Coefficients		*p*	R^2	*S.E.E* (m^3)
1	$V = a \times DBH^b$	a	0.00032	0	0.97	0.07
		b	2.242681	0		
		c	-	-		
2	$Ln (V) = a + b \times \ln DBH$	a	−8.413954	0	0.97	0.08
		b	2.348828	0		
		c	-	-		
3	$V = a + b \times DBH^2$	a	−0.068854	0	0.97	0.07
		b	0.000841	0		
		c	-	-		
4	$V = a + b \times DBH + c \times DBH^2$	a	0.019768	0.743	0.97	0.07
		b	−0.00712	0.135		
		c	0.00096	0		
5	$V = a \times DBH^b \times H^c$	a	0.000089	0	0.99	0.04
		b	2.107657	0		
		c	0.70496	0		
6	$Ln (V) = a + b \times \ln DBH + c \times \ln H$	a	−9.18928	0	0.99	0.05
		b	2.023415	0		
		c	0.769948	0		
7	$V = a + b \times (DBH^2 \times H)$	a	0.003958	0.657	0.98	0.05
		b	0.000062	0		
		c	-	-		
8	$V = a \times (DBH^2 \times H)^b$	a	0.000052	0	0.98	0.05
		b	1.018465	0		
		c	-	-		

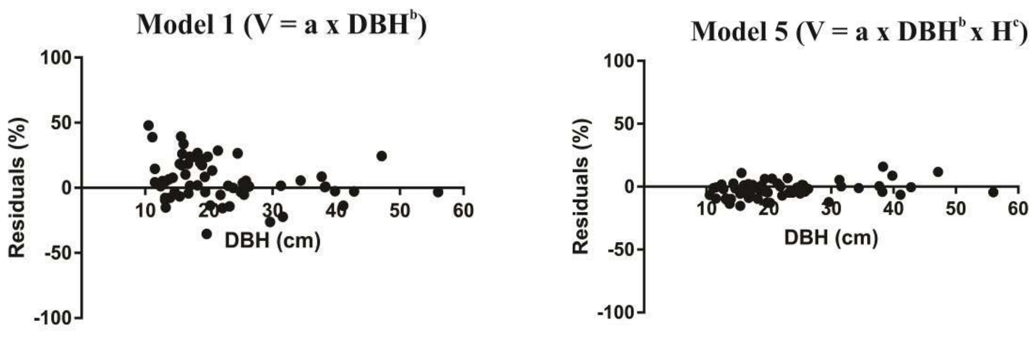

Figure 4. Residuals vs. DBH of the best single input model tested (Model 1) and the best dual input model tested (Model 5).

The forest inventory data of the two transects (10 hectares) showed that the most abundant genus is the *Eschweilera* genus. Five thousand fifty-four trees with DBH $\geq$ 10 cm were measured in the year of 2010, in which 655 trees (11.19%) belonged to the *Eschweilera* genus. In second place, the most abundant genus is the *Protium* genus (6.80%), and in third place is the *Pouteria* genus (6.51%). Palm species were not included in the forest inventory data. The total volume of *Eschweilera* genus in the two transects (N-S/E-W) was 234.60 m^3, which represents 23.46 m^3/ha. In terms of species, the *Eschweilera wachenheimii* represents 23.99% (5.63 m^3/ha) of the total volume of *Eschweilera* genus, followed by *Eschweilera coriacea* (19.46%; 4.57 m^3/ha), *Eschweilera truncata* (15.85%; 3.72 m^3/ha), *Eschweilera pseudodecolorans* (8.12%; 1.91 m^3/ha), and *Eschweilera romeu-cardosoi* (7.83%; 1.84 m^3/ha). The other species of *Eschweilera* genus represent 24.75% (5.81 m^3/ha) of the total volume (Figure 5).

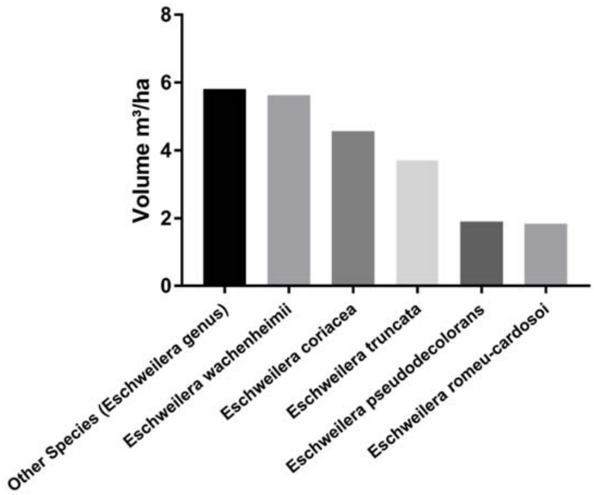

Figure 5. Volume per hectare of *Eschweilera* genus in which five species (of 20 species identified by the forest inventory in the N-S/E-W transects) represent almost 75% of the total volume of the genus.

4. Discussion

The resolution n° 406/2009 of the Conselho Nacional do Meio Ambiente (CONAMA) [38] states that in the forest management plans in the Amazon, the minimum diameter for logging (DMC) has to be greater than 50 cm for any species. In the north-south/east-west transects, the forest inventory data showed that only 11 individuals of *Eschweilera* genus had a DBH greater than 50 cm, representing 1.57 individuals per hectare. The lower DBH classes concentrate 70% of the total volume per hectare (Figure 6). Trees of the *Eschweilera* genus with a DBH $\geq$ 50 cm are rare and sparse [25,26,28,39,40]. Paragraph 3 of the CONAMA resolution allows for changes to the minimum diameter permitted for logging (DMC) [38]. For this reason, the manager must have the diameter distribution of the genus that will be managed and information for the use and destination of the genus (sawmills or biomass facilities, for example) [38]. In regard to the forest management of the *Eschweilera* genus, it is suggested that the minimum diameter available for logging be lowered due to the fact that it is economically unfeasible to manage *Eschweilera* trees with DBH greater than 50 cm in the central Amazon. Also, it is important to concentrate the forest management of the *Eschweilera* genus on the intermediate DBH classes (20 to 29.99 cm; 30 to 39.99 cm; and 40 to 49.99 cm), excluding the extremes (10 to 19.99 cm; 60 to 69.99 cm; and 70 to 79.99 cm) (Figure 6). This kind of approach can preserve future stocks of wood and biomass for energy [18] (first class—10 to 19.99 cm) and the old/big trees which can perform several ecological services like seed production and floral reproduction [41] (60 to 69.99 cm and 70 to 79.99 cm classes).

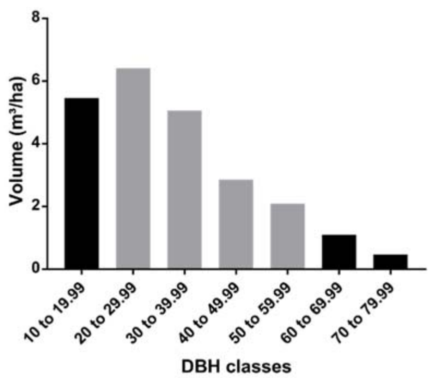

Figure 6. Total volume per hectare by DBH classes (cm) of the *Eschweilera* genus in the N-S/E-W transects. The gray columns highlight the DBH classes (cm) to concentrate the forest management in order to focus on the sustainability of the *Eschweilera* genus.

It is estimated that there are approximately 16,000 tree species throughout all the Amazon basin [16]. However, these differences are not well distributed in terms of number of individuals (abundance) [16]. There are only a few botanical genera that represent nearly half of all trees in the Amazon, with the *Eschweilera*, *Protium*, and *Euterpe* genera being the most abundant [16,40,42]. Trees of the *Eschweilera* genus, aside from their huge abundance in the Amazon basin [16], have a large density of individuals in the central Amazon [28]. The timber companies of the Amazon region have logged just a few genera, and fitted equations to estimate the wood volume of the forest using different species [22,43]. There are many errors associated with this kind of approach, due to the fact that the stems of the tropical trees have numerous types of form factors [23,24] and that just a few genera are managed for the procurement of wood products [44].

The high canopy levels and the presence of vines make it difficult to determine tree height measurements, which increases non-sampling errors [45–47]. Thus, the Husch single model ($V = a \times DBH^b$) presented the best performance ($R^2 = 0.97$ and $S.E.E = 0.07$) and is the most appropriate model to estimate the volume of the *Eschweilera* genus in the Manaus region. However, the consolidation of technologies that can reduce the non-sampling error of tree height measurements in tropical forests, such as the portable profiling laser scanning technology (Light Detection and Ranging (LiDAR)) [48,49], the Schumacher and Hall double entry model ($V = a \times DBH^b \times H^c$) ($R^2 = 0.99$ and $S.E.E = 0.04$), could be used due to the best fit compared with all other models evaluated. In summary, when the merchantable height data are collected using accurate methods, the Schumacher and Hall model ($V = a \times DBH^b \times H^c$) is the most appropriate, otherwise the Husch model ($V = a \times DBH^b$) is the best option.

In the Amazon forest, tree height measurements are normally made by the visual estimation of this variable and, additionally, this variable can also be estimated by the use of a clinometer and a tape measure [50,51]. Using the clinometer approach, the understory has to be cleared away from the target direction to triangulate the measurements [51]. For the climbing technique with the use of ropes method, a tape measure is attached to the climber, thereby making it possible to measure the tree height directly without cutting the understory. The impacts on the environment are negligible and, in this study, amounted on average to four trees measured a day.

Compared to other traditional climbing methods like the use of climbing spikes, for example, that can be dangerous due to the significant weight of the equipment and the continuous contact with the trunk [9,12], the climbing technique with the use of ropes method has many safety advantages [9] and it has been widely reported in many studies [8,9,11]. Using the appropriate equipment like ascenders and descenders (Petzl® stop descender model, Recreational Equipment, Inc., Seattle, WA, USA, for example) the climber can descend quickly in an possible emergency (in case wasps or bees attack, for example) and access the first branches of the crown more quickly and easily [44,45].

The climbing techniques using ropes amounted to four trees measured a day, and although the production is lower than destructive methods, the costs are lower and the impacts on the environment are negligible. The stem form is an important variable to consider when the objective is to use a non-destructive method to measure the volume and biomass. The *Eschweilera* stem is relativity cylindrical (0.83 was the average form factor obtained by all the sixty-four trees measured by this study), without irregularities to the bole, callus, and hollows [15,28]. Species with irregular stems like *Minquartia guianensis* (Acariquara), *Aspidosperma nitidum* (Carapanaúba), and large diameters like *Dinizia excelsa* (Angelim) may decrease the accuracy and the production of the tree climbing with ropes method when the objective is to adjust volume or biomass equations.

5. Conclusions

Volume equations fitted for a single genus can be a good alternative for forest management in the Amazon region. The non-destructive method using climbing techniques with ropes is a potential alternative to destructive methods to adjust volume equations for the *Eschweilera* genus. The Husch model ($V = a \times DBH^b$) ($a = 0.000320$; $b = 2.242681$; $R^2 = 0.97$; and $S.E.E = 0.07$ m^3) which does not need a merchantable height (because the high uncertainty associated with the measurements of this variable in tropical forests) is the best model to estimate the volume for the *Eschweilera* genus. However, when the forest inventory is supported by portable profiling laser scanner imagery such as LiDAR (Light Detection and Ranging), the non-sampling errors of tree height measurements decrease significantly and the Schumacher and Hall model ($V = a \times DBH^b \times H^c$) (a = 0.000089; b = 2.107657; c = 0.704960; R^2 = 0.99; and $S.E.E$ = 0.04 m^3) can be used to generate volumes more precisely.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/8/5/154/s1, Table S1: Measured sample trees, Table S2: Dendrometric variables.

Acknowledgments: The authors would like to acknowledge CNPq for the financial support of the first author (Process: 132168/2011-1), the INCT-Madeiras da Amazônia for the technical support, and the ZF-2 staff. Many thanks to Márcio Amaral and Tatiana Gaui for the instruction with climbing techniques in the tropical forests, Daniel DeArmond for the paper revision, and Lorena Nacif-Marçal for the help on the field activities.

Author Contributions: B.O.G. collected the experimental data and wrote the manuscript. All co-authors participated equally in experimental design, data analysis, and manuscript preparation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Higuchi, N.; dos Santos, J.; Ribeiro, R.J.; Minette, L.; Biot, Y. Biomassa da parte aérea davegetação da floresta tropical úmida de terra-firme da amazonia. *Acta Amazon.* **1998**, *28*, 153–166. [CrossRef]
2. Magnabosco Marra, D.; Higuchi, N.; Trumbore, S.E.; Ribeiro, G.H.P.M.; dos Santos, J.; Carneiro, V.M.C.; Lima, A.J.N.; Chambers, J.Q.; Negrón-Juárez, R.I.; Holzwarth, F.; et al. Predicting biomass of hyperdiverse and structurally complex central Amazonian forests—A virtual approach using extensive field data. *Biogeosciences* **2016**, *13*, 1553–1570. [CrossRef]
3. Ngomanda, A.; Engone Obiang, N.L.; Lebamba, J.; Moundounga Mavouroulou, Q.; Gomat, H.; Mankou, G.S.; Loumeto, J.; Midoko Iponga, D.; Kossi Ditsouga, F.; Zinga Koumba, R.; et al. Site-specific versus pantropical allometric equations: Which option to estimate the biomass of a moist central African forest? *For. Ecol. Manag.* **2014**, *312*, 1–9. [CrossRef]
4. Nelson, B.W.; Mesquita, R.; Pereira, J.L.G.; Garcia Aquino de Souza, S.; Teixeira Batista, G.; Bovino Couto, L. Allometric regressions for improved estimate of secondary forest biomass in the central Amazon. *For. Ecol. Manag.* **1999**, *117*, 149–167. [CrossRef]
5. Alder, D.; Synnott, T.J. *Permanent Sample Plot Techniques for Mixed Tropical Forest*; Oxford Forestry Institute: Oxford, UK, 1992; p. 124.
6. Felfili, J.M. Dynamics of the natural regeneration in the Gama gallery forest in central Brazil. *For. Ecol. Manag.* **1997**, *91*, 235–245. [CrossRef]
7. Laurance, W.F.; Ferreira, L.V.; Rankin-de Merona, J.M.; Laurance, S.G.; Hutchings, R.W.; Lovejoy, T.E. Effects of forest fragmentation on recruitment patterns in Amazonian tree communities. *Conserv. Biol.* **1998**, *12*, 460–464. [CrossRef]
8. Laman, T.G. Safety recommendations for climbing rain forest trees with "single rope technique". *Biotropica* **1995**, *27*, 406–409. [CrossRef]
9. Perry, D.R. A method of access into the crows of emergent and canopy trees. *Biotropica* **1978**, *10*, 155–157. [CrossRef]
10. Ter Steege, H.; Cornelissen, J.H.C. Collecting and studying bryophytes in the canopy of standing rain forest trees. *J. Hattori Bot. Lab.* **1988**, *285*, 285–290.
11. Whitacre, D.F. Additional techniques and safety hints for climbing tall trees, and some equipment and information sources. *Biotropica* **1981**, *13*, 286–291. [CrossRef]
12. de Castilho, C.V.; Magnusson, W.E.; Oliveira de Araujo, R.N.; da Costa Pereira, E.; de Souza, S.S. The use of french spikes to collect botanical vouchers in permanent plots: Evaluation of potential impacts. *Biotropica* **2006**, *38*, 555–557. [CrossRef]
13. James, S.A.; Meinzer, F.C.; Goldstein, G.; Woodruff, D.; Jones, T.; Restom, T.; Mejia, M.; Clearwater, M.; Campanello, P. Axial and radial water transport and internal water storage in tropical forest canopy trees. *Oecologia* **2003**, *134*, 37–45. [CrossRef] [PubMed]

14. Ryan, M.G.; Hubbard, R.M.; Clark, D.A.; Sanford, R.L. Woody-tissue respiration for *Simarouba amara* and *Minquartia guianensis*, two tropical wet forest trees with different growth habits. *Oecologia* **1994**, *100*, 213–220. [CrossRef] [PubMed]
15. Mori, S.A.; Lepsch-Cunha, N. Lecythidaceae of a Central Amazonian moist forest. *Mem. N. Y. Bot. Gard.* **1995**, *75*, 1–55.
16. Ter Steege, H.; Pitman, N.C.A.; Sabatier, D.; Baraloto, C.; Salomão, R.P.; Guevara, J.E.; Phillips, O.L.; Castilho, C.V.; Magnusson, W.E.; Molino, J.-F.; et al. Hyperdominance in the Amazonian tree flora. *Science* **2013**, *342*, 1243092. [CrossRef] [PubMed]
17. Durgante, F.M.; Higuchi, N.; Almeida, A.; Vicentini, A. Species Spectral Signature: Discriminating closely related plant species in the Amazon with Near-Infrared Leaf-Spectroscopy. *For. Ecol. Manag.* **2013**, *291*, 240–248. [CrossRef]
18. Moutinho, V.H.P.; Couto, A.M.; Lima, J.T.; De Aguiar, O.J.R.; De Oliveira Gonçalves Nogueira, M. Energetic characterization of Matá-matá wood from the Brazilian rainforest (Eschweilera Mart Ex Dc). *Sci. For. Sci.* **2011**, *39*, 457–461.
19. Bernardo, A.L.; Reis, M.G.F.; Reis, G.G.; Harrison, R.B.; Firme, D.J. Effect of spacing on growth and biomass distribution in *Eucalyptus camaldulensis*, *E. pellita* and *E. urophylla* plantations in southeastern Brazil. *For. Ecol. Manag.* **1998**, *104*, 1–13. [CrossRef]
20. Calegario, N.; Daniels, R.F.; Maestri, R.; Neiva, R. Modeling dominant height growth based on nonlinear mixed-effects model: A clonal *Eucalyptus* plantation case study. *For. Ecol. Manag.* **2005**, *204*, 11–20. [CrossRef]
21. Gama, F.F.; dos Santos, J.R.; Mura, J.C. *Eucalyptus* biomass and volume estimation using interferometric and polarimetric SAR Data. *Remote Sens.* **2010**, *2*, 939–956. [CrossRef]
22. Higuchi, N.; Ramm, W. Developing bole wood volume equations for a group of tree species of central Amazon (Brazil). *Commonw. For. Rev.* **1985**, *64*, 33–41.
23. Da Silva, J.A.A.; Borders, B.E.; Brister, G.H. Estimating tree volume using a new form factor. *Commonw. For. Rev.* **1994**, *73*, 14–17.
24. Larson, P.R. Stem form development of forest trees. *For. Sci.* **1963**, *9*, a0001.
25. Da Silva, R.P.; Dos Santos, J.; Tribuzy, E.S.; Chambers, J.Q.; Nakamura, S.; Higuchi, N. Diameter increment and growth patterns for individual tree growing in Central Amazon, Brazil. *For. Ecol. Manag.* **2002**, *166*, 295–301. [CrossRef]
26. Carneiro, V.M.C. *Composição Florística e Análise Estrutural na Floresta Primária de Terra Firme da Bacia do rio Cuieiras, Manaus-AM*; Instituto Nacional de Pesquisas da Amazônia (INPA): Manaus, Brazil, 2004; p. 67.
27. De Assis, R.L.; Wittmann, F. Forest structure and tree species composition of the understory of two central Amazonian várzea forests of contrasting flood heights. *Flora Morphol. Distrib. Funct. Ecol. Plants* **2011**, *206*, 251–260. [CrossRef]
28. Lopes, M.A. Population structure of *Eschweilera coriacea* (DC.) S.A. Mori in forest fragments in eastern Brazilian Amazonia. *Rev. Bras. Bot.* **2007**, *30*, 509–519. [CrossRef]
29. Zent, E.L.; Zent, S. Floristic composition, structure, and diversity of four forest plots in the Sierra Maigualida, Venezuelan Guayana. *Biodivers. Conserv.* **2004**, *13*, 2453–2484. [CrossRef]
30. Schöngart, J. Growth-Oriented Logging (GOL): A new concept towards sustainable forest management in Central Amazonian várzea floodplains. *For. Ecol. Manag.* **2008**, *256*, 46–58. [CrossRef]
31. Husch, B.; Beers, T.W.; Kershaw, J.A., Jr. *Forest Mensuration*; John Wiley & Sons: Hoboken, NJ, USA, 2002.
32. Spurr, S.H. *Forest Inventory*; Ronald Press Co.: New York, NY, USA, 1952; p. 476.
33. Hohenadl, W. Neue Grundlagen der holzmessung. *Forstwiss. Cent.* **1922**, *44*, 184–194. [CrossRef]
34. Krenn, K.; Prodan, M. *Die Bestimmung der Echten Schaftholzformzahl und Ausbauchungsreihe aus Dem Echten Formquotienten*; Frankfurt am Main: Frankfurt, Germany, 1944.
35. Schumacher, F.X.; Dos Santos Hall, F. *Logarithmic Expression of Timber-Tree Volume*; US Government Printing Office: Washington, WA, USA, 1934.
36. Gray, H.R. *The Form and Taper of Forest-Tree Stems*; Imperial Forestry Institute: Oxford, UK, 1956.
37. Danielli, F.E.; Gimenez, B.O.; de Oliveira, C.K.A.; dos Santos, J.; Higuchi, N. Yield modeling in sawing logs of *Manilkara* spp. (Sapotaceae) in sawmill in the state of Roraima, Brazil. *Sci. For.* **2016**, *44*, 641–651.
38. Brazil CONAMA. Resolução No 406 de 02 de Fevereiro de 2009. Available online: http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi=597 (accessed on 1 May 2017).

39. Fauset, S.; Johnson, M.O.; Gloor, M.; Baker, T.R.; Monteagudo, M.A.; Brienen, R.J.W.; Feldpausch, T.R.; Lopez-Gonzalez, G.; Malhi, Y.; ter Steege, H.; et al. Hyperdominance in Amazonian forest carbon cycling. *Nat. Commun.* **2015**, *6*, 6857. [CrossRef] [PubMed]
40. De Oliveira, A.N.; do Amaral, I.L.; Ramos, M.B.P.; Nobre, A.D.; Couto, L.B.; Sahdo, R.M. Composição e diversidade florístico-estrutural de um hectare de floresta densa de terra firme na Amazônia Central, Amazonas, Brasil. *Acta Amazon.* **2008**, *38*, 627–641. [CrossRef]
41. Guariguata, M.R.; Pinard, M.A. Ecological knowledge of regeneration from seed in neotropical forest trees: Implications for natural forest management. *For. Ecol. Manag.* **1998**, *112*, 87–99. [CrossRef]
42. Da Silva, F.; Suwa, R.; Kajimoto, T.; Ishizuka, M.; Higuchi, N.; Kunert, N. Allometric equations for estimating biomass of euterpe precatoria, the most abundant palm species in the Amazon. *Forests* **2015**, *6*, 450–463. [CrossRef]
43. Nogueira, E.M.; Fearnside, P.M.; Nelson, B.W.; Barbosa, R.I.; Keizer, E.W.H. Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories. *For. Ecol. Manag.* **2008**, *256*, 1853–1867. [CrossRef]
44. Higuchi, N. O desmatamento insustentável na Amazônia. *Ciência Hoje* **2006**, *39*, 67–71.
45. Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Fölster, H.; Fromard, F.; Higuchi, N.; Kira, T.; et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **2005**, *145*, 87–99. [CrossRef] [PubMed]
46. Segura, M.; Kanninen, M. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica1. *Biotropica* **2005**, *37*, 2–8. [CrossRef]
47. Kitahara, F.; Mizoue, N.; Yoshida, S. Effects of training for inexperienced surveyors on data quality of tree diameter and height measurements. *Silva Fenn.* **2015**, *44*, 657–667. [CrossRef]
48. De Almeida, D.R.A.; Nelson, B.W.; Schietti, J.; Gorgens, E.B.; Resende, A.F.; Stark, S.C.; Valbuena, R. Contrasting fire damage and fire susceptibility between seasonally flooded forest and upland forest in the Central Amazon using portable profiling LiDAR. *Remote Sens. Environ.* **2016**, *184*, 153–160. [CrossRef]
49. Schietti, J.; Martins, D.; Emilio, T.; Souza, P.F.; Levis, C.; Baccaro, F.B.; da Pinto, J.L.P.V.; Moulatlet, G.M.; Stark, S.C.; Sarmento, K.; et al. Forest structure along a 600 km transect of natural disturbances and seasonality gradients in central-southern Amazonia. *J. Ecol.* **2016**, *104*, 1335–1346. [CrossRef]
50. Gimenez, B.O.; Danielli, F.E.; De Oliveira, C.K.A.; Dos Santos, J.; Higuchi, N. Volume equations for merchantable timber species of Southern Roraima state | Equações volumétricas para espécies comerciais madeireiras do sul do estado de Roraima. *Sci. For. Sci.* **2015**, *43*, 291–301.
51. Hunter, M.O.; Keller, M.; Victoria, D.; Morton, D.C. Tree height and tropical forest biomass estimation. *Biogeosciences* **2013**, *10*, 8385–8399. [CrossRef]