Stacking factor in transporting firewood produced from a mixture of Caatinga biome species in Brazil

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The energetic requirements of the Brazilian gypsum industry are mainly provided by firewood transported by road. The cost of transporting firewood is greatly affected by the stacking factor. In this study, we determined how the stacking factor for trailer trucks varied for the firewood harvested from forest species in the Caatinga biome, Brazil. For this purpose, the following steps were carried out: i) the logs were stacked in a frame (volume, 1 stere) and weighed; ii) the solid over bark volume of each log was obtained by scanning and by xylometry (immersion in water); iii) the stacked volume of logs on the truck was measured; and iv) the stacking factor, the stacking density and the apparent density of the unpeeled wood were computed for each of 60 truck trips. The stacking factor was, on average, 1.12. This value is lower than reported for other species; the greater compaction of the timber represents an advantage in terms of transport costs. However, the maximum variation in the load weight was 20 %, which is not negligible from an economic point of view because of the associated loss of energy efficiency in the supply chain for the lowest loads.

Keywords: bioenergy transport; forest logistics; hauling; piling up; wood technology; xylometer

Introduction

Measurement of stacked firewood

Small dimension wood is commercially important as firewood or as raw material for chipping and pulping. However, the volume of small dimension logs cannot be easily and accurately determined with the geometric equations used for larger logs. Other methods must therefore be used to obtain log volumes. Some of these methods consist of measuring the apparent volume of complete piles of logs, while others accurately determine the amount of wood by scanning, weighing or by xylometry (immersion of logs in an open water tank where the level of the displaced liquid, equivalent to the volume of submerged logs, is measured) (Pardé and Bouchon 1988). The xylometric method is assumed to be the most accurate method for estimating volume. It tends to underestimate volumes because wood and bark adsorb water, but the amount of water adhering to each log is considered insignificant (Martin 1984). For full loads on vehicles, weighing is an easier method than xylometry for determining the amount of wood, although the weight is greatly influenced by the wood moisture content, which decreases rapidly immediately after the wood is felled (Diéguez Aranda et al. 2003; Kim and Murphy 2013).

A wood pile or stack is a heap of logs piled in the shape of a parallelogram. The volume of the pile is not equal to the volume of the timber alone as it includes both the logs and the air between them. The unit used to measure the volume of wood piles is the stere, which is equal to one cubic meter (Pardé and Bouchon 1988; Mytting 2016). A stere therefore contains one cubic meter of stacked wood (including wood, bark and air space) (Wenger 1984). The stere is the unit usually used for the stacked or apparent volume of firewood logs (Diéguez Aranda et al. 2003).

Stacking factor for estimating the wood volume in a pile

Although measuring the volume of prismatic piles in steres is relatively easy, it is not appropriate for logistic and commercial purposes because the abundance of gaps in wood piles would remain unknown in trade agreements for forest transport. Thus, the biomass (volume or weight) of wood in a known volume of a pile of stacked wood must be estimated to enable determination of the cost of transport per unit of volume or weight (Machado et al. 2009). The stacking factor, i.e. the ratio between the total volume of the pile of stacked wood and the volume occupied by solid wood in the pile (Husch et al. 2003), is an easy method of estimating the wood volume in a pile of firewood (logs solid volume over bark). The value of the stacking factor is always higher than or equal to one and represents the number of steres per cubic meter of solid wood (Pardé and Bouchon 1988). The inverse of the stacking factor, called the stacking density, is also used and its value is always lower than or equal to one. The solid wood volume with bark or without bark can be used to calculate these ratios (Wenger 1984). When the stacking factor is available for a particular tree species and local conditions, the stacked volume can be easily measured to enable calculation of the solid wood volume in the pile. The coefficient is also an indirect measurement of the relative abundance of spaces in the wood pile.

The stacking factor is on average 1.1-1.7 in Norway (Mytting 2016; FAO 2020), and it ranges from 1.30 to 2.27 in Spain (Valladares Conde and Hernández Mor 2005) and from 1.45 to 1.54 in Slovenia and Croatia (FAO 2020).

The theoretical minimum value for the stacking factor would be 1.274 for cylindrical logs all with the same diameter and piled perfectly with the center of the logs arranged in a square (square piling) and 1.102 if the center of the logs were arranged in hexagon. In other words, a stack of 1.274 m^3 with square piling yields 1 m^3 of solid wood and 1.102 m^3 with hexagon piling yields 1 m^3 of solid wood.

The stacking factor is influenced by a number of factors: the type of wood product in the cargo (load), the type of stacking method (manual/mechanical), the type of support used for the piles (floor or platform of the truck) (Bertola et al. 2003; Husch et al. 2003), the vehicle capacity and the haulage costs (Batista and Couto 2002; Soares et al. 2003). In relation to the type of wood, the stacking factor is affected by the species, diameter classes, tree height, forest site, shape (e.g. irregularities, thickening) (Bertola et al. 2003; Vignote Peña and Martínez Rojas 2006) and tree taper (Batista and Couto 2002; Husch et al. 2003).

The stacking factor increases as the length and distortion of the logs increase because long, curved or distorted pieces are difficult to stack. The stacking factor decreases with the increasing diameter of logs (thicker pieces fill more space than thinner ones) (Valladares Conde and Hernández Mor 2005). In addition to size and straightness, limbing also affects the stacking factor because remnant snags can prevent compact stacking (Batista and Couto 2002; Vignote Peña and Martínez Rojas 2006).

The stacking factor decreases when there is a large variation in log diameters, because there are more small logs with which to fill gaps in the pile. This filling effect cannot be fully achieved with pieces of *Eucalyptus* wood or wood of other species from even-aged stands, with uniform stems and a narrower range of log diameters. The following factors related to the harvesting method also affect the stacking factor: the logging length, the presence/absence of bark, buckles or branches, the amount of time the logs remain in the open air and the type and length of the forest road (Bertola et al. 2003).

The piling effect is also important because the stacking factor increases from 1.35 to 2 within a pile of disordered pieces of length 30 cm. To prevent this, piling will necessarily be slow because each piece is like a brick that must be fitted correctly in the pile under construction, and some effort is thus required to reduce imbalance (Mytting 2016). The ability and care taken by the stacking operator to fill air spaces with the smallest logs and sticks are therefore also important (Diéguez Aranda et al. 2003).

Training the work force is known to yield higher efficiency in the activity. For instance, it has been demonstrated that a team of two workers carrying out manual stacking performed 2.5 times more efficiently after receiving training (Meza and Solano 2004).

Influence of the stacking quality on the storage and transport cost

The wood loaded on forest transport vehicles must be stacked as compactly as possible to reduce harvesting and transport costs (Paula Neto and Rezende 1992). After being harvested, the wood must also be stacked in a way that facilitates loading the material on to the forest transport vehicle (Kanzian et al. 2013; Barlow et al. 2014) and that ensures the stability of the piles. Firewood should be transported in such a way that prevents the pieces falling from the loading platform of the vehicles to the transit route during transport. The pile becomes more compacted due to the weight of the logs, and because of that the piling operators can increase the height of the piles by 3-6 % more than the desirable height (Pardé and Bouchon 1988).

The stacking process should contribute to maintaining the energetic efficiency of wood, by reducing or preventing absorption of moisture to minimize the load weight, to keep the calorific value and to minimize the development of wood-decay microorganisms (Kim and Murphy 2013; Negrão et al. 2014; Eufrade-Junior et al. 2021). Access to the wood by beetles, mice and snakes must also be prevented (Petrice and Haack 2006). Other undesirable consequences of stacking are the eventual occurrence of sprouting (Bond and Midgley 2001) and the phytosanitary risks inherent in the transportation of biological material (Goebel 2010). More than 15,900 registered patents in the United States are related to wood stacking methods for storage and transport (USPTO 2021), illustrating the importance of the aforementioned factors.

A study conducted in Santa Catarina state (Brazil) revealed that the process of loading the logs on the truck trailer represents 15 % of the cost of both the harvesting (considering felling, logging and hauling of wood inside the forest) and the loading on the truck (Belli et al. 2013).

Other factors affecting costs are the price of fuel, the exchange rate, the state of conservation of the roads (rail transport is not an alternative in some countries), wood decay and other physical changes in wood (mainly drying and oxidation) due to outdoor exposure during transport (Ernstson and Rasmuson 1993; Angus-Hankin et al. 1995).

Caatinga forest as fuel supplier for the Brazilian gypsum industry

The typical vegetation in northeast Brazil is known as Caatinga biome, a steppe-like savanna covering 10 % of the Brazilian territory. Caatinga is characterized by the abundance of xerophilic species, which are deciduous throughout the dry season. Caatinga species are generally small trees with twisted stems and thorny shrubs (Leal et al. 2003).

The architecture of the species harvested in the Caatinga biome to produce firewood is characterized by multiple, large branches with an uneven geometry that is impossible to model (da Silva et al. 2006; Barros et al. 2010). Therefore, timber volume estimation based on conventional equations is only reliable on short logs, being the main advantages of logging short pieces the simplification of the manual stacking process on the transport truck and the suitability of short logs for use as firewood.

Knowledge of the stacking factor of the species from the Caatinga biome is important as the current demand for firewood in Brazil is 82.9 million tons, an almost constant value during the decade 2011-2020 (EPE 2021). In Pernambuco State (Fig. 1) most firewood is transported distances of more than 200 km to the Polo de Yeso de Araripe (municipality of Araripina). This industrial region has 42 mines, 174 calcination industries and about 750 gypsum premoulding industries, which use firewood as 73 % of their energy matrix (Granja et al. 2017). In small industries, 100 % of the energy needs are provided by firewood from the Caatinga (da Silva 2009; ITEP 2014; Granja et al. 2017).

The extraordinary demand for firewood in the Araripe industrial hub is supplied by road, by heavy trucks. The maximum allowable load for trailers in Brazil is limited by mass and volume: the maximum load is 48.5 Mg, and the maximum gross weight of the vehicle is 57 Mg. In addition, the maximum height of the load on the trailer is limited to the dimensions of the front panel, whilst the length and width are limited to the vehicle bodywork dimensions, according to domestic standards (Resolução Contran nº 196/2006; Resolução Contran nº 246/2007). In theory, about 1,710,000 loads of firewood, transported by 48.5 Mg payload trucks, are required annually to cover the national requirements for firewood, considering Brazilian load transport regulations, which are similar to patterns for firewood transportation in United States and Canada (Angus-Hankin et al. 1995; Machado et al. 2009).

Objectives

The overarching aim of this study was to increase understanding of factors influencing roundwood hauling costs. Considering the influence of the stacking factor in roundwood hauling costs, the goals of the present study were: i) to determine the variation in the stacking factor associated with the transportation of logs obtained from a combination of twelve tree Caatinga biome species used extensively as firewood; and ii) to compare two volume estimation methods: scanning and xylometry.

Materials and methods

Caatinga region and tree species analyzed

The wood considered in the study originated from twelve areas managed according to sustainable forest management plans and located in the Pernambuco backcountry (Fig. 1). This is a region characterized by an annual rainfall of 1,000 mm and a mean annual temperature above 27 °C. According to the Köppen-Geiger climatic classification, this corresponds to a hot semi-arid (steppe) desert climate (BSh) (Peel et al. 2007).

Twelve woody species were selected for sampling among the predominant shrubby or tree-like species in the study area (Table 1). The species exhibited a cover of 91 % (Rodal et al. 2008; Barbosa et al. 2012; Calixto Jr and Drumond 2014), averaging 1,271 trees per hectare (Rede de Manejo Florestal da Caatinga 2005; Rodal et al. 2013).

The firewood in the native Caatinga biome is the product of clearcutting areas where stems and branches are cut into 1-m length logs (Ramos and Albuquerque 2012), which is the log length considered for this study. The branches are usually removed from the main stem, which is frequently distorted, forked and relatively small (basal diameter outside bark less than 30 cm) (Fig. 1).

Study design

Data acquisition was initiated by tree felling, and one-meter-long logs were cut along the stem. The logs were stacked in an aluminum frame with a storage capacity of one cubic meter (one stere: Fig. 2). The container filled with firewood was weighed (in tons) on a platform scale (Lider Balanças model B 650) in order to determine the over bark weight of unpeeled solid wood needed to occupy one stere (Fig. 2). As the logs and branches obtained were very unevenly shaped, the volume of the pieces was not estimated using the conventional equations (e.g. Huber, Smalian, Newton) but with an industrial 3D Scanner (3D scanner – KDLS – DK – FK – four Lens, Foshan Shangke 144 Machinery Co. Ltd., Guangdong Province, China), with 2 mm accuracy and installed on a portable computer (Fig. 2). The volume of each log was also measured by xylometry (immersion in an on-site graduated container, of accuracy 0.05 dm^3, xylometer in Fig. 2) (Pardé and Bouchon 1988; Imaña-Encinas 2011) in order to compare the two theoretically accurate volume estimation methods: scanning and xylometry. Only logs of basal outside bark diameter greater than 2 cm and branches of diameter greater than 1 cm were considered for measurement in the study.

The measured firewood was loaded onto a truck trailer (10.7 × 2.6 m base and admissible load capacity 48.5 Mg). The vehicle, a single-unit truck, model VW 24 250 6×2 traction (Fig. 2), made 60 trips bearing firewood from clearcutting of the twelve species analyzed, considering the load as the sampling unit.

The stacked or apparent volume of the piled wood in the trailer (V, in m^3) was computed multiplying the height of the stacks on the trailer, measured for each load, by the area of the base of the trailer.

The truck loading was performed by a team of three workers, one who operated a Caterpillar® 325D FM forest machine equipped with a hydraulic log loading grapple, and the other two who performed auxiliary stacking tasks. The machine operator and both assistants were trained and certified for the activity according to the Brazilian SESI/SENAI system (SESI: *Serviço Social da Industria* and SENAI: *Serviço Nacional de Aprendizagem Industrial*). Training the work force affects the efficiency in the activity and the full loading and stacking of the material in the trailer took about four hours per truck.

Calculations

The unit of analysis was truck load, and the variables considered were computed for each load. The sample size was therefore 60 (the number of loads processed in the study). The tree species composition of each load was not considered because the trial was conducted under real work conditions, in which the logs are not separated by species. The stacking factor for the trailer was calculated as the ratio between the stacked or apparent volume of the pile and the solid volume contained in the pile, determined by xylometry (Equation 1) or scanning (Equation 2):

$$SFX = V/VX \qquad (1)$$

where *SFX* is the stacking factor (ratio) determined by xylometry, *V* is the stacked or apparent volume of the piled wood in the trailer (m^3) and *VX* is the solid volume outside bark of the stacked logs and branches in the trailer (m^3), obtained by the xylometric method, and:

$$SFS = V/SV \tag{2}$$

where *SFS* is the stacking factor (ratio) determined by scanning and *SV* is the solid volume outside bark of the stacked logs and branches in the trailer (m^3), obtained with the scanner (Batista and Couto 2002; Husch et al. 2003). The apparent density of the stacked wood on the truck was calculated as follows (Equation 3):

$$D = W/V \tag{3}$$

where *D* is the apparent density (Mg m^{-3}) and *W* is the weight of the wood piled on the truck, for moisture conditions on loading, and with bark (Mg).

The wood moisture content was measured in the field by a xylohygrometer (Holzfeuchtemessgerat MT-10 Hark Co. Ltd., Bonn, Germany) and checked in the laboratory on a subsample of logs, on the basis of the difference in weight between the air-dry state (logs in the aluminum frame) and the oven-dry state, and expressed as a percentage of the weight in the oven-dry state.

Mean, standard deviation, coefficient of variation of the variables and relative residual error of the estimations were computed with Bioestat 5.3 software. The relative residual error (*RE*) (expressed as a percentage) was computed as follows (Equation 4):

$$RE = \frac{SV - VX}{\frac{\sum(SV + VX)}{2n}} 100 \tag{4}$$

where *RE* is the residual error (percentage) and *n* is the number of truck loads analyzed (60).

The significance of the difference between *SV* and *VX* means was determined using the Mann-Whitney statistic. Results were considered statistically significant at $p < 0.05$.

Results

Comparison of xylometric and scanning methods for log volume measurement

The mean firewood volume per truck load differed depending on the measurement method used (xylometry or scanning) (Table 2). However, the difference between means was not significant ($p > 0.05$), and the individual difference between load volume determined by scanning and load volume by xylometry was less than 1 % for almost all the 60 trips considered (Fig. 3). However, most of the residual values were positive, $SV > VX$, indicating that the scanning method tends to overestimate and/or the xylometric method tends to underestimate the real volume. Lower volumes were obtained by the xylometric method, which may be partly attributable to absorption of some water by the wood or bark (< 0.1 mm) during dipping. If the mean difference in load volume measured by the two methods (55.104 m^3 and 54.559 m^3, Table 2) could only be attributed to absorption of water by wood or bark, the additional amount of water in the load in the xylometric method would be 545 kg (2 % of the load weight). The absorption effect is expected to be higher for the driest pieces and the most porous wood and bark tissues. Neither volume estimation method based on geometrical equations was of practical value as the shape of the logs did not correspond (even approximately) to either a cylinder or the trunk of a cone (Fig. 1) and the log volumes cannot therefore be accurately measured using dendrometry equations.

Variation in the firewood load between trips

The stacked volume of the firewood logs on the trailer varied slightly between trips (ranging from 60.705 to 63.742 m^3 and coefficient of variation 1.3 %: Table 2), as expected because the base of the trailer was fixed and the height (h) of the stacks on the trailer scarcely varied in the 60 trips analyzed (ranging from 2.15 to 2.28 m: Fig. 2). The stacking factor (obtained by xylometry, Equation 1, or by scanning, Equation 2) varied more widely between trips (coefficient of variation 4.3 %: Table 2) because of the source of variation introduced by the variable level of compaction of the loads of firewood, which is expected in a manual task such as firewood stacking. It is considered that the level of compaction was influenced by the size and shape of the firewood and the operator skill.

The trip load (in volume or in weight) varied most among the variables analyzed (Table 2) because of the influence of the two sources of variation: stacking factor and stacked volume of the piled wood on the truck. The trip load in weight (W) was more variable than the trip load in solid volume (VX, SV) (see coefficients of variation in Table 2). This difference was attributed to the influence of water content on wood weight because the mean value obtained for wood moisture content (17.1 %) was far from homogeneous in the sample (coefficient of variation, 12.9 %) and acted as an additional source of variation in the load weight.

The distribution of load weight data displayed some symmetry (Fig. 4), and the amount of firewood supplied per trip was therefore predictable, but did not remain constant among trips, with a maximum deviation of ± 2.7 Mg or + 7.4 m^3 around the mean, i.e. 5.6 % of the load capacity of the truck in terms of weight. The loss in different truck loads reached 5.4 Mg or 10.6 m^3 when the load variation was added to the variation in the same sign between solid volume determined by xylometry and volume of the pile.

Discussion

The remarkable variation in the load volume between trips is explained by the process of loading the logs on the truck trailer. Loading was not very efficient because of the variable height of the piles on the truck between trips (*h*, Fig. 2) and because of the variable compaction, as revealed by the stacking factor (Table 2). This variation was the cause of the loss of approximately 20 % of the value of the load in the supply of the firewood industrial consumers. This key technical feature has not yet been solved in the national production system, in which 99 % of the domestic firewood production is transported exclusively by road (Leite 2013).

However, the mean value of the stacking factor (*SFX* and *SFS*) obtained in the study was close to 1, the ideal value, and it was lower than previously reported for native or fast-growing species (Table 3) and other species.

The level of compaction of firewood in terms of the stacking factor was better than in the published studies consulted: those cited in Table 3 and Valladares Conde and Hernández Mor (2005), Mytting (2016) and FAO (2020). This may be due to the careful and therefore necessarily slow stacking by the field working crew. However, the task yield was about 13.7 m^3 of solid wood stacked per hour or 15.3 steres per hour (see Table 2), indicating a high level of efficiency relative to the standardized 5.6 steres per hour for a crew of two manual stackers (COIM 2004). Comparison was not carried out with other studies about work efficiency because the terms steres and cubic meters are frequently confused, even in scientific publications, as reported by da Silva (2009).

Transporting harvested firewood from native Caatinga vegetation is therefore more efficient than transportation in other regions with different type of wood. This can probably be attributed to the variable size and uneven shape of the trunks and branches of the trees in the Caatinga biome, enabling small wood pieces to be fitted into the spaces between larger pieces of wood in the piles, although this task is very time-consuming. The filling effect due to the range of sizes of the logs is shown in Fig. 4, in which the stacking factor in several loads is below 1.102, the ideal value for logs of equal diameter in a triangular arrangement. The relative straightness of the logs and the absence of large thorns in some of the species sampled for the study (Barros et al. 2010) may influence the higher level of compaction than reported in other studies.

In accordance with the results of compaction yielded by the stacking factors, the mean wood density in the truck trailer (apparent density, Equation 3) was 0.44 Mg m^{-3} (at 17.1 % wood moisture content), which is higher than the values reported for *Swietenia macrophylla* (0.33 Mg m^{-3}) (Gullison and Hardner 1993) and *Eucalyptus* (0.37 Mg m^{-3}) (Spinelli et al. 2009). The high apparent density obtained in the study compared with both dense wood species can be partly attributed to the moderately high moisture content of the analyzed logs, corresponding to dry wood for trading purposes but not completely air-dry wood. In addition, the moisture content constitutes a source of variation for the apparent density that partly explained the high coefficient of variation (Table 2).

The estimated value of the firewood volume per truck load differed depending on the measurement method used (xylometry or scanning each log). The differences between the values yielded by the two methods (averaging 2 % if referred to weight) were not statistically significant, although volumes estimated by the scanning method were generally higher than those estimated by the xylometric method. The lower volumes estimated by the xylometric method are probably due to absorption of some water by the logs during dipping. However, in a study with hardwood tree logs, Martin

(1984) reported that the absorption effect was negligible, although the quantity of water absorbed was not yielded. This study (op. cit.) also showed that the variation in the volume results, attributable to errors when reading the graduated xylometer scale, was negligible for practical purposes. Moreover, xylometry is largely considered the most accurate method for measuring real volumes, with the volume estimated by this water immersion and displacement method considered the “true” or “actual” volume (Martin 1984; Figueiredo Filho and Schaaf 1999; Figueiredo Filho et al. 2000; Thomas and Bennett 2014; West 2015; Chaves et al. 2018). The method has the advantage of being independent of the shape of the logs, and it eliminates some measuring errors, because the diameters and lengths of sections along the stem are not measured (Miguel et al. 2018).

Although the log volume may be slightly underestimated in the xylometric method, due to the mentioned water absorption effect, it is assumed that xylometry is the most accurate method for log volume estimation. On the other hand, the scanning method may overestimate volume due to the image data processing. A high-resolution log scanner is used to create detailed three-dimensional external log images from which the log volume can be accurately determined. However, the scanning output includes missing data due to shadowing of the log surface because of the orientation of the scanner, and it also includes outlier data caused by dust, hanging bark or branches (Thomas and Bennett 2014). The image processing software identifies all missing points and outliers, removing most of the outliers and filling in the others by mean of algorithms, with the corresponding wrong consideration of empty spaces as wood or bark. This volume overestimation effect is probably higher in crooked logs, such as those analysed here.

Xylometry was therefore considered more accurate than scanning for the material tested in the study. The xylometric method is easier and cheaper to implement, and it is also considered more accurate (Figueiredo Filho et al. 2000; Thomas and Bennett 2014; West 2015; Chaves et al. 2018), although both methods of log volume estimation probably give rise to errors (positive and larger in case of scanning and negative and smaller in case of xylometry), and neither are entirely satisfactory for field use (West 2015). Owing to the need for easy and accurate log volume measurements obtaining the volumes by means of registering the log taper with a scanner provided with two sources of scanning, located in two different positions around the log to minimize the shadow areas (Oja et al. 2000) should be tested, together with the use of a device with higher resolution.

Conclusions

The procedure used enabled calculation of the stacking factor for forest transport vehicles and for the firewood from a combination of twelve species of the Caatinga biome. The quality of the manual stacking was very high as the stacking factor was lower and apparent density was higher than reported for other species. However, variations in the truck loads (20 % in wood weight or wood solid volume) may lead to unpredictable transport costs and consequent economic losses, with inefficient energy consumption in the supply and production chain. The sample used for comparison between two log volume estimation methods (xylometry and scanning) was large enough for use as the basis of future studies on the relationships between volume estimates by xylometry versus volume estimated by scanning.

Declaration of interest statement

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Conflicts of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Geolocation information

Pernambuco State, Brazil.

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Table 1. Firewood species selected for study

Species	Family
Acacia kallunkiae J.W. Grimes & Barneby	*Leguminosae*
Acacia piauhiensis Benth.	*Leguminosae*
Anadenanthera colubrina (Vell.) Brenan. var. *cebil* (Griseb.) Reis	*Leguminosae*
Aspidosperma pyrifolium Mart.	*Apocynaceae*
Caesalpinia pyramidalis Tul.	*Leguminosae*
Croton sonderianus Müll. Arg.	*Euphorbiaceae*
Erythrina velutina Willd.	*Leguminosae*
Jatropha elliptica (Pohl.) Müll. Arg.	*Euphorbiaceae*
Maytenus rigida (Mart.) Benth.	*Celastraceae*
Mimosa caesalpiniifolia Benth.	*Leguminosae*
Myracrodruon urundeuva All.	*Anacardiaceae*
Peltophorum dubium (Spreng.) Taub.	*Leguminosae*

Table 2. Statistical summary of the measurements of the 60 loads. *VX*: solid volume, measured by xylometry; *SV*: solid volume, measured by scanning; *SFX*: stacking factor, measured by xylometry, for the volume piled on the truck; *SFS*: stacking factor, measured by scanning, for the volume piled on the truck; *V*: stacked volume of the load on the truck; *W*: weight of the load; *D*: apparent density of the load; s.d.: standard deviation; c.v.: coefficient of variation (as a percentage).

Statistics	volume		stacking factor		stacked volume	weight	apparent density
	with xylometer	with scanner	with xylometer	with scanner			
	VX (m^3)	*SV* (m^3)	*SFX*	*SFS*	*V* (m^3)	*W* (Mg)	*D* (Mg m^{-3})
max.	61.956	62.576	1.194	1.182	63.742	29.625	0.477
mean	54.559	55.104	1.124	1.113	61.212	26.965	0.440
min.	51.371	51.885	1.008	1.067	60.705	24.223	0.401
s.d.	2.897	2.926	0.048	0.048	0.828	1.549	0.023
c.v.	5.3	5.3	4.3	4.3	1.3	5.7	5.2

Table 3. Stacking factors reported for different species and the corresponding reference

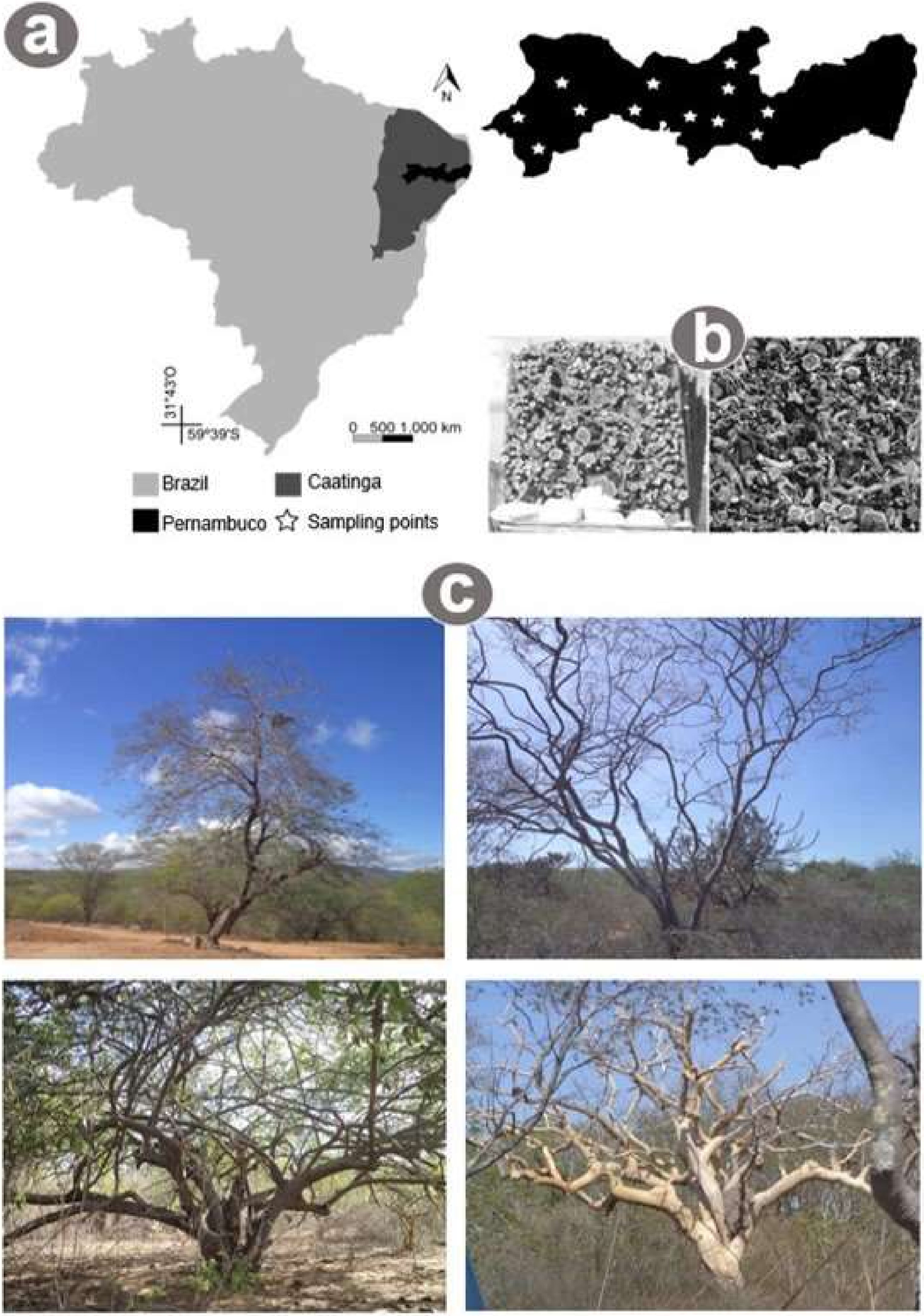
Species (origin/family)	Stacking factor	Reference
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.31	(Bertola et al. 2003)
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.42	(Barros et al. 2008)
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.42	(Couto and Bastos 1988)
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.44	(Paula Neto and Rezende 1992)
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.45	(Paula Neto et al. 1993)
Eucalyptus saligna Sm. (*Myrtaceae*)	1.47	(Couto and Bastos 1988)
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.48	(Lisboa et al. 2009)
Gmelina arborea Roxb. (*Lamiaceae*)	1.51	(Meza and Solano 2004)
Native savanna (India)	1.57	(Kishwan et al. 2012)
Brachystegia longifolia Benth. (*Leguminosae*)	1.62	(Lowore et al. 1994)
Swietenia macrophylla R. A. King (*Meliaceae*)	1.68	(Gullison and Hardner 1993)
Eucryphia cordifolia Cav. (*Cunoniaceae*)	1.69	(Triana 2001)
Eucalyptus grandis W. Mill ex Maiden (*Myrtaceae*)	1.77	(Soares et al. 2003)
Anadenanthera colubrina (Vell.) Brenan var. *cebil*	2.37	(Barros et al. 2010)
Mimosa caesalpiniaefolia Benth.	2.55	(Barros et al. 2010)

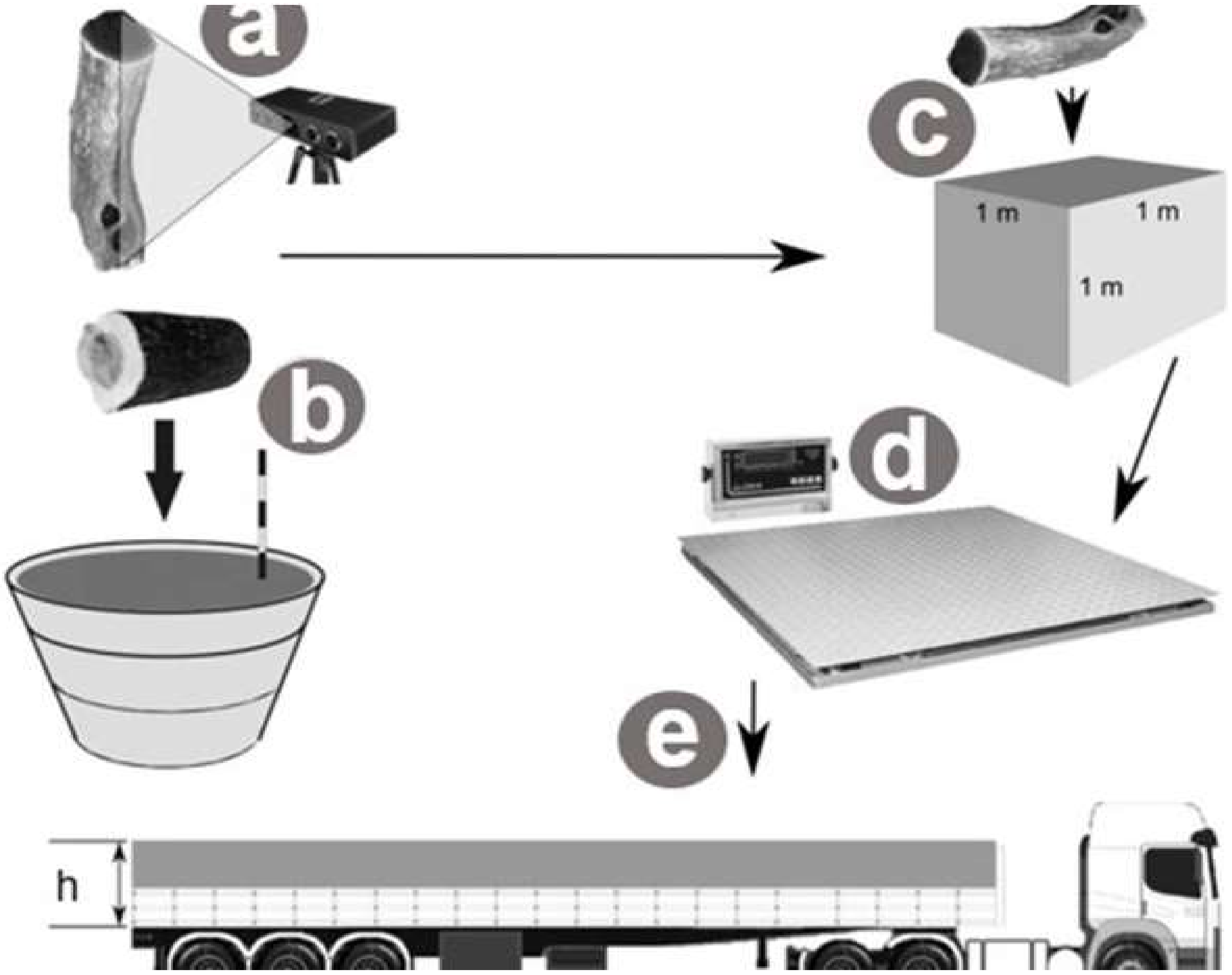
Figure 1. Sampling area. a) Study area (Caatinga biome, Pernambuco State, data collection locations); b) Stacked firewood for the study (cross-sections of the stacks on the trailer truck); c) Typical architecture of trees from the Caatinga.

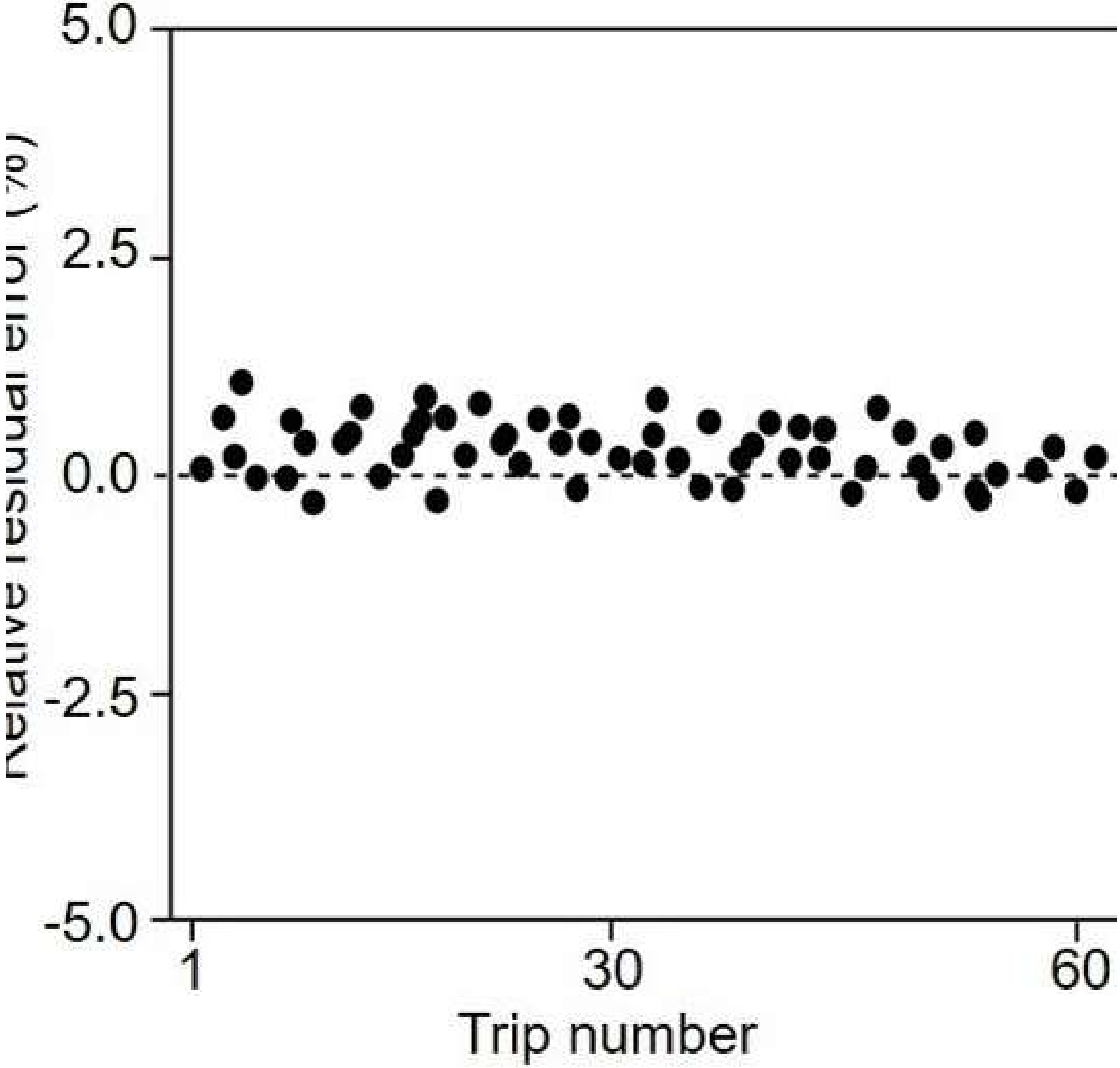
Figure 2. Data acquisition. a) Volume estimation by industrial 3D scanner; b) Scheme of volume estimation by xylometry (immersion); c) Stereo principle; d) Scale; e) Forest transport vehicle (*h*, height of the load on the trailer).

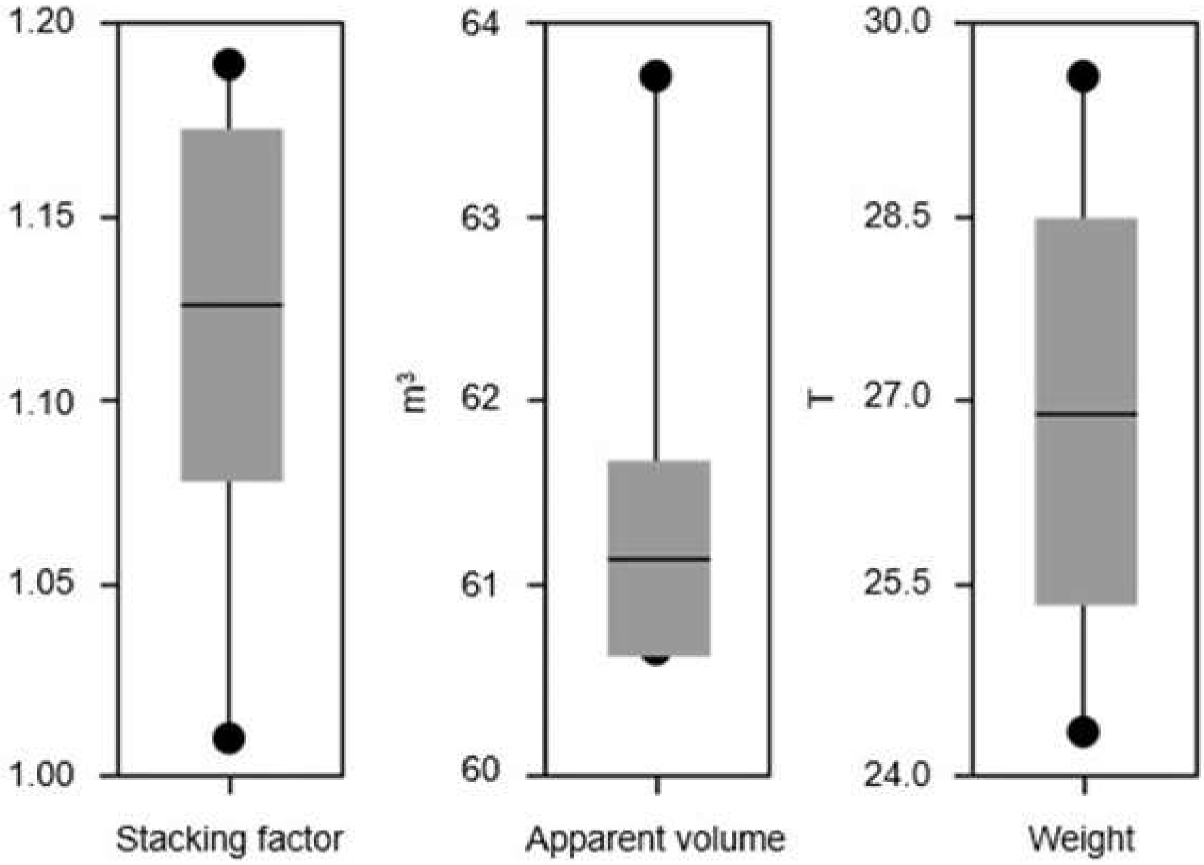
Figure 3. Relative residual error (Equation 4) between value of firewood volume measured by scanning and measured by xylometry (immersion).

Figure 4. Variation in the stacking factor determined by xylometry (*SFX*), stacked volume and weight of the wood loaded on the truck.


a
N
31°43'O
59°39'S
0 500 1,000 km
Brazil
Caatinga
Pernambuco
Sampling points
b
c


a
c
1 m
1 m
1 m
b
d
e
h


Relative residual error (%)
5.0
2.5
0.0
-2.5
-5.0
1
30
60
Trip number


1.20
1.15
1.10
1.05
1.00
Stacking factor
64
63
m^3
62
61
60
Apparent volume
30.0
28.5
T
27.0
25.5
24.0
Weight