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Factors Influencing Directional Tree Felling in the *Tapajós* National Forest, Amazon, Brazil

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Abstract

Given its complexity, directional felling is considered one of the most dangerous activities in the exploratory phase of forest management projects for timber obtention. Therefore, detailed studies of the variables influencing its execution are necessary. The present research was conducted in the *Tapajós* National Forest, Brazilian Amazon, and analyzed 1,075 trees logged using the directional felling technique in a 504.30 ha area. To better understand directional felling, the studied variables were subjected to descriptive analyses and principal component analysis, a multivariate procedure that enables the simultaneous evaluation of several variables. While the diameter, basal area, and stem and branch volume explained most of the variability concerning directional felling, the commercial height influenced the least. Trees of the species *Hymenolobium petraeum* (angelim pedra) strongly correlated with the dendrometric variables diameter and stem and branch volume. Those of the species *Hymenaea courbaril* (jatobá) showed a strong correlation with the commercial height. *Pseudopiptadenia psilostachya* (fava timborana), *Dipteryx odorata* (cumaru), *Hymenaea parvifolia* (jutai mirim), and *Astronium lecointei* (muiracatiara) had a strong correlation with the basic wood density. Trees of the species *Couratari guianensis* (tauari), *Lecythis pisonis* (sapucaia), *Astronium lecointei* (muiracatiara), *Mezilaurus itauba* (itaúba), and *Goupia glabra* (cupiúba) showed lower correlations with the time needed for planning, cutting, and felling. They also had a reduced correlation with the angular differences between the natural and effective and the intended and effective felling directions. The latter results suggest that these species do not follow a defined pattern concerning the directional felling technique. However, trees of the other species followed a different tendency. In general, the logged trees lacked correlation with the directional felling cutting and total operation time. The analyses suggest that as the diameter of a tree increases, the chances of completing its directional felling decrease.

Keywords: reduced impact logging, directional felling, natural fall, dendrometric variables, chainsaw operator, principal component analysis

1. Introduction

An essential component of forest management is adopting careful logging practices planned to reduce damage to the remaining forest (Johns et al., 1998; Dykstra & Heinrich, 1996; Sabogal et al., 2009; Nogueira et al., 2011). Unplanned forest exploitation dramatically increases the impact on biodiversity and ecosystem functioning (Bicknell et al., 2014; Bicknell et al., 2015; Edwards et al., 2013; Edwards et al., 2014) while destroying much of the pre-existing regeneration of commercially valuable trees. Therefore, this kind of activity tends to impair long-term ecological and economic productivity (Putz & Pinard, 1993; Putz et al., 2012).

The concept of reduced impact logging (RIL) emerged in the 1990s (Putz & Pinard, 1993). It combines a group of techniques aimed at environmental protection within the process of timber production in selectively logged tropical forests (Ellis & Putz, 2019). One of these techniques is the planned and directional tree felling, using chainsaws. Directional felling is crucial for achieving the goal of sustainable forest management (Nikooy et al.,

2013) since improper logging can result in severe damage to the remaining forest community (Naghdi et al., 2016).

Using chainsaws for semi-mechanized logging is the most widespread technique in Brazil (Santanna & Malinovski, 1999). It is a high-risk activity (Nogueira et al., 2011) since handling chainsaws requires specific abilities, technical knowledge, practical experience, and physical conditioning. Therefore, labor becomes an essential component for forestry work, especially in activities with high physical demand, performed manually or semi-mechanically, such as directional felling (Santanna & Malinovski, 2002; Nogueira et al., 2011).

The ability to use a chainsaw correctly implies the transversal and longitudinal cutting of tree segments (logs) in a horizontal position, on the ground or suspended, the complementary cutting of branches and roots, the longitudinal and transversal cutting of standing trees to check for hollows in the stem, and finally, the felling of the tree.

The technical knowledge regarding chainsaw functioning is fundamental for the operator to get maximum performance and safety during its use. Additionally, it helps optimize fuel use and time while using chainsaw-related tools and accessories, such as guide bar, chain, and saw chain files. At the same time, the technical knowledge of the operator about RIL guidelines is also desirable. These recommend the procedures needed for conducting an efficient and safe logging activity from an operational and ergonomic point of view and protecting the remaining forest.

Practical logging experience is crucial since the empirical knowledge acquired through several timber harvests enables the operator to predict tree and species patterns under certain field situations. An example of this is applying cutting techniques, which can vary according to the stem cracking tendency and root dimensions (Nogueira et al., 2011) to reduce stem cracking during the felling operation.

The physical conditioning of the operator is another critical aspect to consider. Their workday usually involves dislocation among several tree species with varying wood density, volume, and height. Besides that, they should carry together the chainsaw and its accessories. Therefore, even with the help of an assistant, the work demands good physical condition. Besides that, it requires mental attention from the operator since decision-making concerning the tree felling direction is also part of the work.

Based on the operational procedures, it is necessary to evaluate the tree felling direction and, if necessary, plan and modify it. The latter will ensure operational safety and avoid further damage to the forest (Amaral et al., 1998; Sabogal et al., 2009). Any error involving the tree felling direction can result in serious accidents involving the operator or members of the cutting team (Sant'anna, 2014), besides damaging the nearby standing timber and possibly altering the planned cutting sequence of the surrounding trees.

The basic principle of directional tree felling is the natural fall tendency (Nogueira et al., 2011). Naturally, every tree has a lean or falling direction dependent on its gravity center. The latter is determined by the crown weight distribution, indirectly influenced by the stem inclination, and by its position regarding the other trees. It is worth noting that the natural lean of a tree is considered one of the main elements in forest harvest planning (Sant'anna, 2014). According to d'Oliveira and Braz (1995), the crown shape, distribution, and weight of a tree determine the direction it would naturally fall.

It is possible to change the direction a tree would naturally fall between 10° and 45° (d'Oliveira & Braz, 1995; Nogueira et al., 2011). The final direction a tree falls and hits the ground is called the effective fall direction. A tree natural lean and the intended and final felling directions improve the analysis regarding the ability of the cutting team to conduct the felling (Naghdi et al., 2016).

Although the damages related to logging are, to some extent, inevitable, there are methods to reduce it (Nikooy et al., 2013). According to Whitmore and Burnham (1984), the damage degree is more dependent on the way of felling the trees than on the volume of trees felled. Planning the felling direction also affects the steps following the fall, such as log hauling, especially for large trees, which might positively or negatively affect the production rate of the hauled timber (Nikooy et al., 2013).

Directional felling consists of cutting a tree in a predetermined direction, avoiding damage to nearby standing trees, and facilitating their removal while preventing damage to previously felled trees (Pinard et al., 1995; Cedergren et al., 2002). Most studies involving directional felling are generic, focused on disseminating the RIL technology (Dykstra & Heinrich, 1996; Braz & d'Oliveira, 1997; Sabogal et al., 2009; Nogueira et al., 2011).

In Brazil, research on directional felling has been conducted in planted forests. However, these studies have limited to observing the economic yield of the felling activity (Santos et al., 2000) or demonstrating the most efficient techniques used by chainsaw operators (Fiedler et al., 2000; Lopes et al., 2001).

Studies conducted in native forests have also focused on analyzing equipment performance and the economic aspects involved in the felling process (Minetti et al., 2000; Behjou, 2012; Behjou et al., 2009) or considering the ergonomic elements of chainsaw use during directional felling (Rêgo et al., 2017).

However, research regarding the variables that interfere in directional felling and the aspects related to its execution is still insufficient. Obtaining this information might improve the understanding of directional felling and, therefore, subsidize the development of criteria and procedures to avoid damaging the nearby standing trees or cracking the felled ones.

There is a debate regarding the validity and viability of directional felling as a preservation strategy of the remaining forest (Cedergren et al., 2002; Jonkers, 2000). Although technically feasible, directional felling has limitations driven by the random spatial distribution of the trees in the forest, the poor visibility of very tall canopies, and the presence of trees with poorly defined natural leans (Jonkers et al., 2000). There are also limitations regarding chainsaw operators, including their experience, abilities, and techniques (Nikooy et al., 2013).

More specific aspects that can interfere with the quality of directional felling comprehend felling direction angles (Cedergren et al., 2002; Krueger, 2004), the time used in the procedures (Lortz et al., 1997; Câmpu & Ciubotaru, 2017; Acosta et al., 2018), and dendrometric variables (Koger, 1983; Jourgholami et al., 2013). Identifying the most relevant components of directional felling can help execute the operation with accuracy, safety, and control (Naghdi et al., 2016).

In this context, applying techniques of multivariate analyses, such as the principal component analysis, becomes appropriate. The latter is especially valid when the researcher intends to reduce the quantity of original data into a smaller set and reproduce part of the variability in fewer linear combinations (Abdi & Williams, 2010; Santos et al., 2019).

The principal component analysis simultaneously evaluates more than one variable and order the sample units in an n-dimensional hyperspace through a mathematical algorithm. The latter reduces the dimensionality of the data while preserving much of its variability. It identifies directions or principal components along which the variation of the data reaches its highest level (Ringnér, 2008; Schirmer et al., 2016).

Meeting the normality assumption is not required for conducting a principal components analysis (Santos et al., 2019). A common aspect of techniques that use exploratory data analysis is applying nonparametric methods, which are less rigorous in their assumptions, sampling, and statistical properties (Kent, 2012).

In this context, the principal component analysis aims to establish a relationship between the variables and the species involved in directional felling to select those that best explain the total variance of the data. While rigorous statistical tests and confirmations are fundamental, several authors affirm that a large part of data analysis has an exploratory approach and consists mainly of looking for order and patterns in the data (Kent, 2012).

The present study pretends to identify the variable or group of variables that mostly correlate with directional tree felling.

2. Material and Methods

2.1 General Characteristics of the Research Area

The research area is located within the Tapajós National Forest (FLONA Tapajós), municipality of Belterra, Pará, between the coordinates 2°40′-4°10′ South Latitude and 54°45′-55°30′ West Longitude (Figure 1). It is bordered to the west by the Tapajós River; to the east by the Cuiabá-Santarém highway; to the north by kilometer marker 50 (fifty) of the Cuiabá-Santarém highway; and to the south by the right margin of the Tapajós River, the Cupari River, and its tributary Santa Cruz, up to the Cuiabá-Santarém highway (Brasil, 1974; Carvalho, 2001; Oliveira et al., 2005).

Inserted in the lower Amazonian region, it presents soils of the type Neossolos Quartzarênicos to the west and Latossolos Amarelos on the plateau (Parrota et al., 1995) similar to Arenosols and Xanthic Ferralsols, respectively, according to IUSS Working Group/WRB (2015). The vegetation is a dense ombrophilous forest (IBGE, 2012), which comprises approximately one-third of the total area of the Tapajós National Forest (Parrota et al., 1995).

The approximate territorial extension of the Tapajós FLONA is 530,000 ha (Andrade et al., 2019), encompassing the municipalities of Aveiro, Belterra, Placas, and Rurópolis. The regional climate type is Am or equatorial monsoon (Kottek et al., 2006). According to Carvalho (1982), the Tapajós FLONA is at an altitude of around 175 m above sea level, with a flat to gently undulating relief.

The region of the Tapajós FLONA has average annual maximum and minimum temperatures of 34.5 °C and 15.9 °C, respectively, with a mean yearly precipitation of 1.892 mm (ICMbio, 2019). It is inserted in a geological domain with large sedimentary basins. These are formed by consolidated sequences of sandstones, siltstones, argillites, and conglomerates from the Paleozoic and Mesozoic. The relief is smooth with a low altimetric amplitude and dominated by soils of the type *Latossolo Amarelo* (Xanthic Ferralsol) in 40% of the territorial extension.

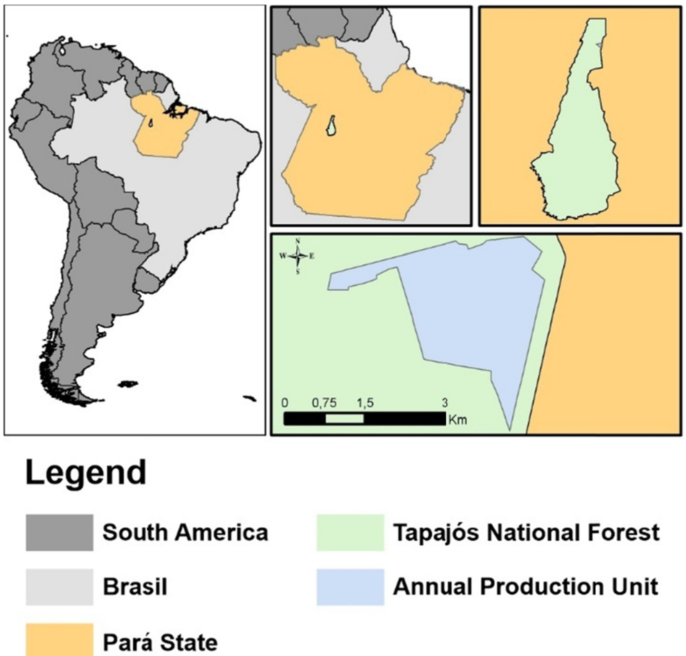

Figure 1. Location of the Tapajós National Forest, Belterra, Pará, Brazil where the study was conducted. Details of the Annual Production Unit 13 (UPA 13) with a 504.30 ha extension within the Samambaia Forest Management Area (FMA). Source: Elaborated by the author

2.2 Data Collection

Within the Samambaia Forest Management Area (FMA), a section of 504.30 ha corresponding to the Annual Production Unit 13 (UPA 13) was selected for the study. A total of 2,102 trees with DBH (diameter at 1.30 m from the ground) ≥ 50 cm were selected, generating an average logging intensity of 28.80 m^3 ha^{-1}. The evaluation regarding the variables and procedures associated with directional felling included 1,075 of these trees (51%).

Data collection occurred during the period of forest exploitation activities, between June and September 2019. Access to the area was possible coming from the km 72 of the highway BR 163, specifically on the left margin of the north/south direction.

The vernacular and scientific names of the tree species, their circumference at breast height (CBH), and commercial height were obtained from the forest inventory spreadsheets of the pre-exploitation census of the Annual Operational Plan n° 13-harvest 2018 (COOMFLONA, 2018).

The CBH was measured in centimeters, assuming a height of 1.30 m from ground level, and the values converted to diameter in centimeters (DBH). The limit for estimating the commercial height of the trees was the first bifurcation. The cross-sectional area of each tree was calculated using the formula $g = (\pi \cdot DBH^2)/40,000$. The sum of the obtained values per species served to assess the dominance or basal area. The volume of the stem and aerial parts of the trees was estimated using specific equations for the management area (COOMFLONA, 2018):

$$Vc/c = EXP[-8.376017145 + 1.753912947 \times Ln(DBH) + 0.848599699 \times Ln(Hc)] \quad (1)$$

where, Vc/c = volume with the bark in cubic meters; DBH = diameter at breast height measured in centimeters; and Hc = commercial height in meters.

$$Vrb/c = 0.211045768114405 + (0.000630439578435079 \times DBH^2) + (-0.00000805819101964133 \times DBH^2 \times Hc) + (-0.0000204270359331579 \times DBH \times Hc^2) + (0.00030907024548338 \times Hc) \quad (2)$$

where, Vrb/c = volume of the gross residue with the bark in cubic meters; DBH = diameter at breast height measured in centimeters; and Hc = commercial height in meters.

Nine cutting teams, each integrated by one chainsaw operator and one assistant, applied the directional felling techniques. Most of the hollowed trees were discarded from felling once the chainsaw operator applied the hollow test. The test consists of the longitudinal insertion of the chainsaw guide bar into the stem of the tree. Hollow trees were exceptionally harvested when the relationship of hollowness to commercial volume production was compensatory, in association with the chainsaw operator verifying the possibility of adequately applying the cutting techniques.

Workers of the cutting teams received training in the technical guidelines of RIL (Dykstra & Heinrich, 1996; Braz & d'Oliveira, 1997; Pereira Júnior, 2003; Sabogal et al., 2009; Nogueira et al., 2011) considering the following aspects:

(1) Field localization of the tree to be felled; (2) confirmation of the identification of the tree based on the inventory plate; (3) execution of the test to verify the occurrence of a hollow stem; (4) evaluation of the tree natural lean and the intended felling direction; (5) extraction of the identification plate of the tree and its respective nail (6) cleaning the base of the tree up to a one-meter radius from the stem; (7) construction of two escape routes with a 45° angle between them and opposite to the intended felling direction; (8) directional felling and fall of the tree; (9) place the identification plate and its respective nail on the residual stump of the felled tree, and; (10) record the actual felling direction on the felling map.

The chainsaw operator responsible for the specific felling activity defined, in the field, the natural lean and the intended felling direction of the tree to be felled. After felling the tree, the landing position at which the tree hit the forest ground allowed defining the effective felling direction. For determining the natural lean, intended, and effective felling angles, the magnetic north and the direction of tree stem projections were used as references (Figure 2), as follows:

(1) The Natural Lean (QN) considers the inclination of the tree and the distribution of the crown branches. It records the location variable in degrees as the difference between the magnetic north and the projection of the tree fall.

(2) The Intended Fall Direction (QP) records the angle in degrees between the magnetic north and the planned projection of the tree fall. The planning considered the tree natural lean and the distribution of nearby standing trees. The intention is to avoid damaging these trees and operational accidents involving the members of the cutting team. Therefore, the alteration of the tree natural lean is planned.

(3) The Effective Fall Direction (QE) records the angle in degrees between the magnetic north and the final projection of the tree stem as it hits the forest ground.

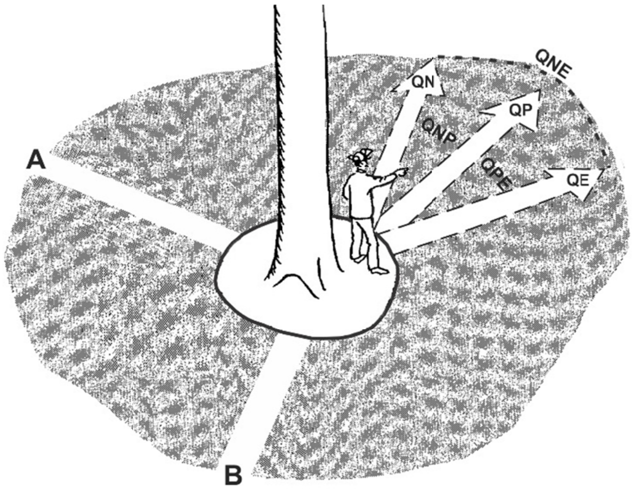

Figure 2. Planning method for directional tree felling. Adapted from Been et al. (1980)

In general, the cuttings applied to the trees followed the procedures below: The first step was making the horizontal bottom cut, which is a cross-sectional cut that covers 1/3 of the tree stem diameter. This cut should be done at a maximum height of 40 cm from the ground and is followed by the sloping top cut. The junction of the bottom and top cuts forms the directional scarf. Finally, the felling cut, also known as the back cut, is made on the opposite side of the scarf. It is opened at a height 8-15 cm above the horizontal bottom cut on the remaining 2/3 of the stem cross-section. While making the felling cut, several wood pieces are left as support, which, after being cut, ultimately direct the tree to fall in the desired location (Figure 3).

Whenever needed, chainsaw operators use metal wedges to help control the tree felling direction. The felling activity considered that all the lianas that could interfere with the process of tree cutting had been removed, an action that is usually conducted a year before the tree felling.

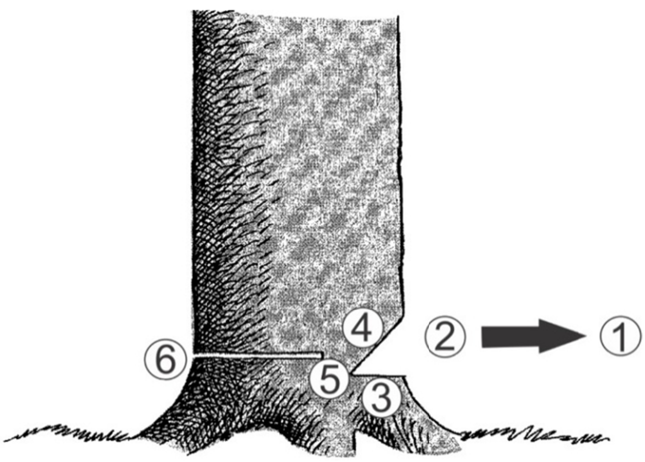

Figure 3. Standard directional cutting method. Adapted from Been et al. (1980)

The planning, cutting, and felling times of each felled tree and their respective natural lean, intended fall, and effective felling angles were obtained as follows:

(1) The planning time included all the activities that preceded the beginning of the tree felling, such as: assessing the intended felling direction; cleaning the stem base; removing the bark of some tree species; removing termite nests, shrubs, and lianas; clearing the escape routes; fueling the chainsaw with lubricating oil and gasoline; and when necessary, adjusting the guide bar and chain of the chainsaw, or sharpening the chain. This variable was measured and expressed in minutes.

(2) The cutting time, in minutes, comprised the time between the cuttings made on the tree and the moment it hit the ground.

(3) The tree felling time, in minutes, was the sum of the planning time and the tree cutting time.

The registered periods also considered all the events that occurred within pauses dedicated to observation, equipment adjustment, tool usage, hydration, and the eventual rest of the team.

After completing the felling of each tree, the number of trees with DBH (diameter at 1.30 m from the ground) ≥ 10 cm and the direct damages derived from the directional felling process were quantified.

The wood density of the analyzed tree species was determined following the methodology described by Carneiro et al., (2020).

2.3 Statistical Analyses

The Kolmogorov-Smirnov test ($\alpha = 0.05$) was applied to assess the normality of the data. For the other analyses, the data were organized by the mean values of the variables per species.

The calculus of the absolute differences between the angles of natural and planned, planned and effective, and natural and effective falls allowed visualizing the angular variation of the directional felling procedure. While difference values near 0° indicated a higher success, those near 180° indicated a higher error in the tree directional felling process.

Converting the data into a percentage scale facilitated the interpretation. For this, a difference of 180° or 0° was assumed as 0% or 100% accuracy, respectively. Therefore, the higher the percentage of angular difference (QN%, QP%, and QE%), the smaller the difference between the fall directions considered in the directional felling.

Box diagrams represented the distribution of the values regarding each of the studied variables and species. The parameters used were mean, median, quartiles, asymmetry, and kurtosis.

Given the number of variables involved in directional felling, a Principal Component Analysis (PCA) was applied to detect possible relationships between the variables and the species. To conduct the PCA, the scales between the variables were standardized ($\mu = 0$, $\sigma = 1$) using the mean values of the variables per species.

The criteria used for selecting the principal components were eigenvalues higher than 1.00 and concentrating more than 60% of the accumulated variance.

Eigenvalues measure the level of variation retained in each dimension of the principal components (Kassambara, 2017), expressed as the ratio between the eigenvalue and the number of variables in the analysis (Kent, 2012). While the first components or dimensions correspond to the highest percentage of the variability present in the data (Bernardi et al., 2009), the remaining components account for directions that do not explain much of the variability (Hongyu et al., 2015) and are often considered as "noise" in the analysis. The positive or negative signs of the eigenvalues denote direct or inverse correlations, respectively (Schirmer et al., 2016).

The eigenvectors correspond with the loadings of the original variables, which work as a measure of the importance of each variable in relation to the dimensions of the principal components and indicate their relationships, whether directly or inversely proportional, positive or negative, respectively (Bernardi et al., 2009). It is possible to compare each variable to a vector, with the correlation coefficient expressed in cosine values, ranging from -1.0 to +1.0, presenting properties of direction, orientation, and length, the latter being directly related to its variance, which makes its geometric representation possible (Kent, 2012).

A Pearson's correlation analysis ($p \leq 0.05$) allowed identifying patterns within the data. The results were interpreted according to Dancey & Reidy (2019), who indicate that values equal to 0.0 represent the absence of correlation, 0.10-0.39 a weak correlation, 0.40-0.69 a moderate correlation, 0.70-0.99 a strong correlation, and 1.0 a perfect correlation.

After this interpretation, variables with correlations higher than 0.7 were classified as significant. Significant correlations of the set of variables indicate the adequacy of the sample for the PCA. Low correlations tend to imply the recommendation of larger sample sizes (Santos et al., 2019).

A biplot served to visualize the distribution of the variables and their respective observations. The latter is a bi-dimensional graph, where the vectors represent the variables, and the points represent the observations or samples.

The best-represented vectors are those closest to the radius of size 1 (maximum correlation) (Santos et al., 2019). The closer a variable is to the circle of correlations, the better to reconstruct it from the first two components. Also, the closer to the origin of the axes, the less relevant the variable is for the first two components (Abdi &

Williams, 2010). The vector orientation and its length indicate the direction towards which the variable increases and the rate of change in that direction, respectively. Thus, a long vector indicates a gradual rate of change, while a short vector represents a faster rate of change (Kent, 2012).

For the graphical interpretation, the following assumptions were considered. The principal components 1 (PC1 or Dim. 1) and 2 (PC2 or Dim. 2) were represented on the abscissa and ordinate axis, respectively. Thus, comparisons involving the PC1 were made horizontally, while comparisons with the PC2 were made vertically (Teixeira et al., 2012).

The highest percentage of the total data variance is usually explained by Dim. 1, followed by Dim. 2 (Fraga et al., 2015). Therefore, in the present study, only these two components were considered, given that the others do not add relevant information (Tobar-Tosse et al., 2015). Most studies only use the first two axes, which besides sufficiently explaining the data, can be easily interpreted through a bi-dimensional graph (Gomes et al., 2004).

The PCA was performed using the statistical packages FactoExtra (Kassambara, 2017) and FactoMiner (Lê et al., 2008) run within the statistical program R version 4.0.4 (R CoreTeam, 2021) and RStudio version 1.3.1093.

3. Results

The sample universe for the directional felling analyses included 1,075 trees represented by 17 species (Table 1). Four species accounted for 56.9% of the number of trees sampled: tauari (221), maçaranduba (167), jarana (119), and jatobá (105). The diameter of the felled trees ranged from 50.61 to 197.35 cm, and half of them had DBH values ≤ 76. Of the felled trees, 75% were in the commercial height, measuring between 7 and 26 m (Table 2). On average, the species tauari (24.9 m), jatobá (28.71 m), and muiracatiara (29.02 m) had the highest commercial height. The median stem and branch volumes of the trees were 5.44 m^3 and 3.07 m^3, respectively.

The analyzed variables presented asymmetry and kurtosis values different from zero, indicating a non-normal distribution (Table 2). The Kolmogorov-Smirnov test ($\alpha = 0.05$) rejected the normality hypothesis confirming the data pattern distribution.

Among the species that were felled and evaluated in this study, the basic wood density varied from 0.48-0.91 g cm^{-3}, with the highest and lowest values corresponding to the species quarubarana and cumarú, respectively. The median planning and cutting times were six minutes each, while the median tree felling time was 13 minutes. Planning and cutting times were as short as nine minutes for 75% of the felled trees. On the other hand, the total directional felling time lasted up to 18 minutes.

In general, a median of two trees was damaged per felling. However, this variable corresponded to a median of three damaged trees per felling for the species angelim pedra (AngePedra), quaruba (Quaru), and sapucaia (Sapu). On the other hand, the felling of the trees garapeira (Garap), jarana (Jara), and mandioqueira rosa (ManRosa) damaged less the nearby standing vegetation, with a median of one tree affected per felling.

Independently of the tree species, the median values for the variables QPE%, QNP%, QNE% indicated a correspondence higher than 80% between the angles (Figure 4).

The planning and cutting times had median values lower than 15 minutes, with a total median time for the whole tree felling process of up to 25 minutes.

From all the variables involved in the process of directional tree felling, basic density (Db) had the lowest correlation value (Figure 5).

Table 1. Mean values of variables per species observed in the directional felling of trees in the *Tapajós* National Forest, Belterra, Pará, Brazil.

Species code	No. trees	Db (g cm^{-3})	Planning (min)	Cutting (min)	Felling (min)	QNP (%)	QPE (%)	QNE (%)	Damage (No. ind.)	DBH (cm)	Height (m)	Stem Vol. (m^3)	Basal (m^2)	Branch Vol. (m^3)
AngePedra	11	0.59	8.09	8.00	16.09	83.03	92.72	89.44	2.64	102.58	22.64	10.27	0.86	6.00
CedroRa	26	0.49	7.69	7.77	15.46	79.72	85.86	84.17	2.00	99.82	23.31	10.81	0.87	5.99
Cuia	15	0.80	10.27	8.80	19.07	87.33	85.05	80.67	2.13	83.65	21.73	6.50	0.56	3.89
Cuma	49	0.91	5.96	8.86	14.82	88.06	85.42	83.62	1.92	77.52	17.37	4.94	0.49	3.67
Cupiu	15	0.71	7.33	4.73	12.07	83.19	74.27	68.59	1.93	75.97	12.33	3.60	0.46	3.64
FavaTimb	45	0.69	8.09	7.69	15.78	85.72	85.80	80.32	2.14	76.37	16.71	4.61	0.47	3.54
Garap	16	0.75	10.25	8.69	18.94	93.54	87.50	85.83	1.38	86.14	18.50	6.20	0.60	4.42
Itau	69	0.70	6.17	7.17	13.35	85.10	83.95	79.86	1.53	80.93	23.67	6.82	0.53	3.53
Jara	119	0.85	6.26	6.71	12.97	82.99	85.07	78.73	1.51	71.30	19.18	4.48	0.41	2.93
Jato	105	0.76	7.03	9.46	16.49	82.97	86.41	82.39	1.82	90.75	28.71	9.91	0.68	4.08
JutaiMi	65	0.90	6.22	6.97	13.18	84.37	87.56	84.60	1.91	75.65	22.60	5.60	0.46	3.09
MacaRan	167	0.87	7.06	6.75	13.81	81.78	82.84	77.65	1.84	71.30	19.63	4.60	0.41	2.93
ManRosa	11	0.54	8.36	6.36	14.73	90.40	86.97	91.01	1.91	80.04	19.64	5.61	0.51	3.67
Muira	47	0.79	6.91	8.23	15.15	84.82	84.10	80.33	2.04	82.30	29.02	8.17	0.55	3.18
Quaru	61	0.48	7.38	8.16	15.54	82.81	86.41	79.35	2.68	101.43	19.66	9.14	0.86	6.25
Sapu	33	0.84	7.61	7.55	15.15	79.11	84.30	77.02	2.24	81.13	17.73	5.57	0.54	3.99
Taua	221	0.52	6.90	7.70	14.60	81.73	84.63	76.51	1.86	78.38	24.89	6.69	0.50	3.23
Mean	63.23	0.72	6.98	7.61	14.59	83.27	84.92	79.59	1.88	80.08	22.15	6.45	0.53	3.60
Total	1075	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. Species code, vernacular and scientific names: AngePedra: angelim pedra (*Hymenolobium petraeum*); CedroRa: cedrorana (*Vochysia maxima*); Cuia: cuiarana (*Terminalia amazonia*); Cuma: cumaru (*Dipteryx odorata*); Cupiu: cupiúba (*Goupia glabra*); FavaTimb: fava timborana (*Pseudopiptadenia psilostachya*); Garap: garapeira (*Apuleia leiocarpa*); Itau: itaúba (*Mezilaurus itauba*); Jara: jarana (*Lecythis lurida*); Jato: jatobá (*Hymenaea courbaril*); JutaiMi: jutai mirim (*Hymenaea parvifolia*); MacaRan: maçaranduba (*Manilkara elata*); ManRosa: mandioqueira rosa (*Qualea dinizii*); Muira: muiracatiara (*Astronium lecointei*); Quaru: quaruba (*Erisma uncinatum*); Sapu: sapucaia (*Lecythis pisonis*); Taua: tauari (*Couratari guianensis*).

Variables: No. trees: Number of trees, Db (g cm^{-3}): Basic wood density expressed in g cm^{-3}, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Damage (No. ind.): Number of trees damaged after the conclusion of the felling operation, DBH (cm): Diameter at breast height, expressed in centimeters, Height (m): Commercial tree height expressed in meters, Stem Vol (m^3): Stem volume expressed in m^3, Basal (m^2): Basal area expressed in m^2, Branch Vol. (m^3): Branch volume expressed in m^3.

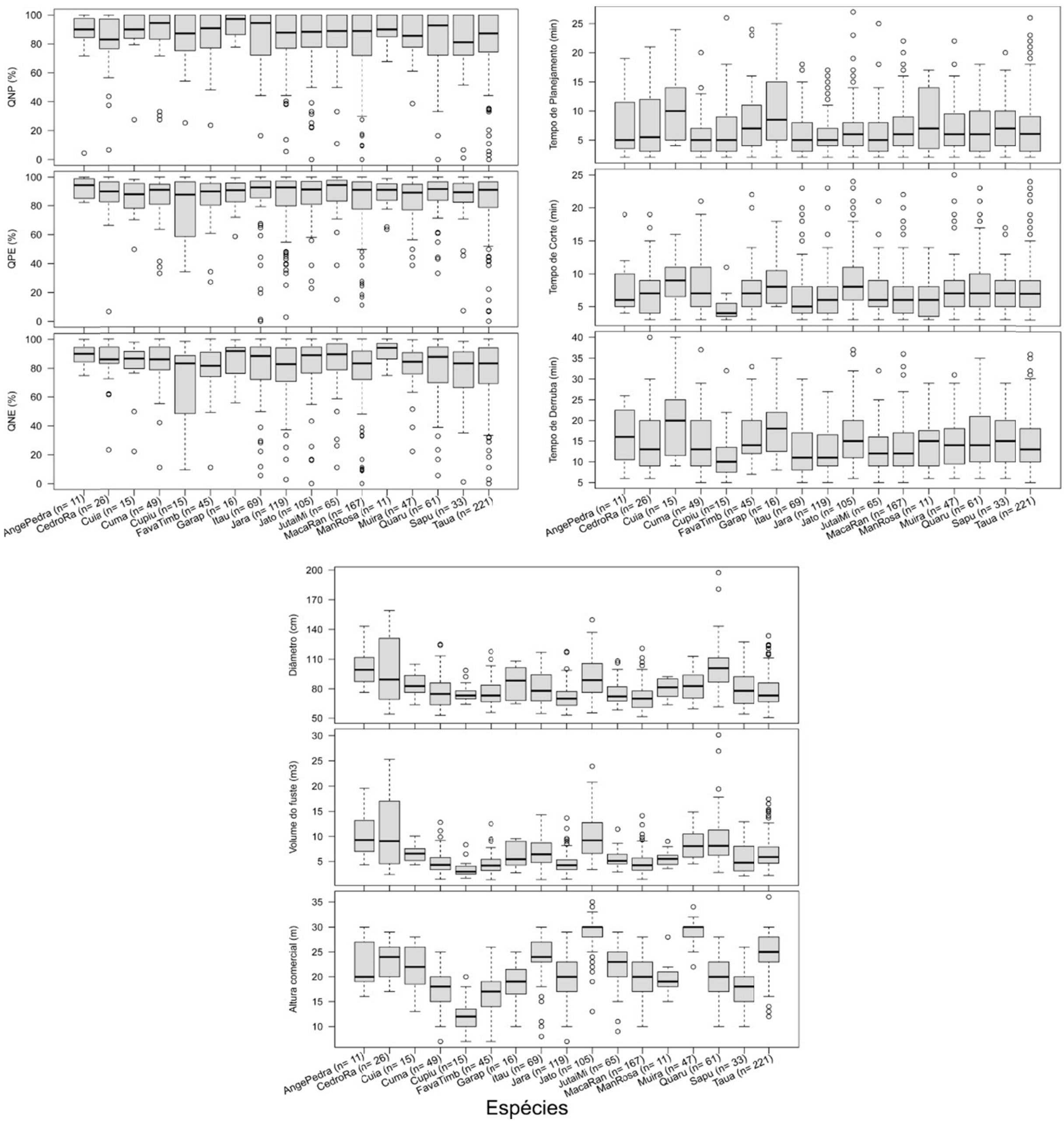

Figure 4. Graphical representation of the distribution of the variables measured in the tree species logged through directional felling in the Tapajós National Forest, Belterra, Pará, Brazil. Variables: QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, DBH (cm): Diameter at breast height, expressed in centimeters, Stem Vol (m^3): Stem volume expressed in m^3, Height (m): Commercial tree height expressed in meters. Species code, vernacular and scientific names: AngePedra: angelim pedra (*Hymenolobium petraeum*); CedroRa: cedrorana (*Vochysia maxima*); Cuia: cuiarana (*Terminalia amazonia*); Cuma: cumaru (*Dipteryx odorata*); Cupiu: cupiúba (*Goupia glabra*); FavaTimb: fava timborana (*Pseudopiptadenia psilostachya*); Garap: garapeira (*Apuleia leiocarpa*); Itau: itaúba (*Mezilaurus itauba*); Jara: jarana (*Lecythis lurida*); Jato: jatobá (*Hymenaea courbaril*); JutaiMi: jutai mirim (*Hymenaea parvifolia*); MacaRan: maçaranduba (*Manilkara elata*); ManRosa: mandioqueira rosa (*Qualea dinizii*); Muira: muiracatiara (*Astronium lecointei*); Quaru: quaruba (*Erisma uncinatum*); Sapu: sapucaia (*Lecythis pisonis*); Taua: tauari (*Couratari guianensis*)

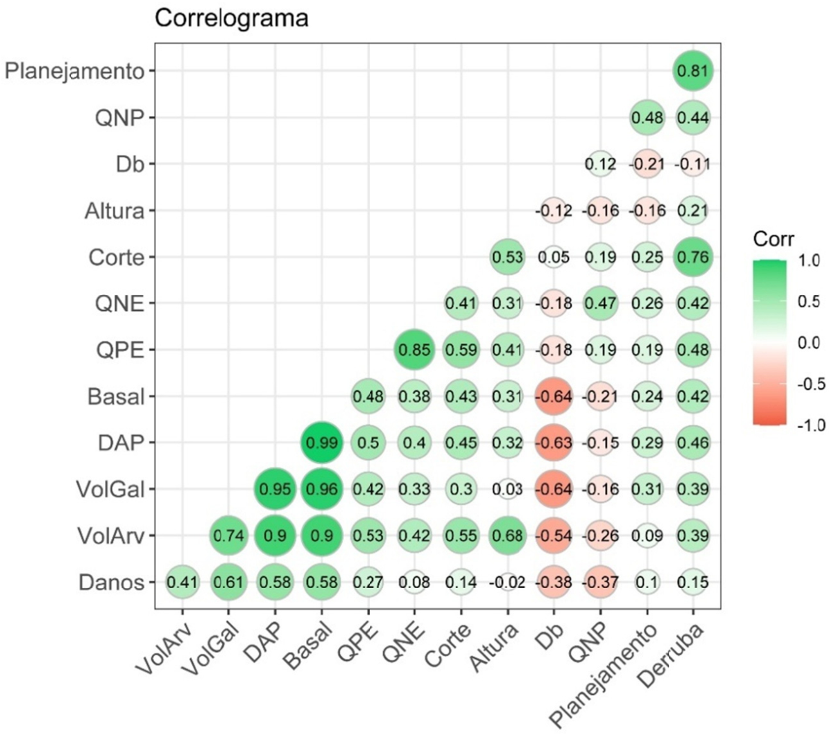

Figure 5. Pearson's correlation analysis (α ≤ 0,05) using the variables measured during the process of directional tree felling in the Tapajós National Forest, Belterra, Pará, Brazil. Variables: QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, DBH (cm): Diameter at breast height, expressed in centimeters, Stem Vol (m^3): Stem volume expressed in m^3, Height (m): Commercial tree height expressed in meters

Table 2. Descriptive statistics of the variables measured during the process of directional tree felling in the Tapajós National Forest, Belterra, Pará, Brazil

Variable	n	Mean	Minimum	1°Quartile	Median	3°Quartil	Maximum	Amplitude	Asymmetry	Kurtosis
Db (g cm^{-3})	1075	0.72	0.48	0.52	0.76	0.87	0.91	0.43	-0.43	-1.41
Planning (min)	1075	6.98	2.00	3.00	6.00	9.00	27.00	25.00	1.29	1.53
Cutting (min)	1075	7.61	3.00	5.00	6.00	9.00	25.00	22.00	1.55	2.37
Felling (min)	1075	14.60	5.00	9.00	13.00	18.00	40.00	35.00	0.95	0.57
QNP (%)	1059	83.27	0.00	76.11	88.89	100.00	100.00	100.00	-1.80	3.60
QPE (%)	996	84.92	0.00	80.56	91.67	96.67	100.00	100.00	-2.18	5.04
QNE (%)	1059	79.59	0.00	73.89	85.00	94.44	100.00	100.00	-1.77	3.15
Damage (No. ind.)	1063	1.89	0.00	0.00	2.00	3.00	9.00	9.00	0.69	0.35
DBH (cm)	1075	80.08	50.61	66.85	76.08	89.13	197.35	146.74	1.35	3.06
Height (m)	1075	22.15	7.00	19.00	23.00	26.00	36.00	29.00	-0.31	-0.50
Stem Vol. (m^3)	1075	6.45	1.35	4.04	5.44	7.92	30.14	28.79	1.81	4.97
Basal area (m^2)	1075	0.53	0.20	0.35	0.45	0.62	3.06	2.86	2.53	12.17
Branch Vol. (m^3)	1075	3.60	1.05	2.33	3.07	4.27	23.61	22.56	2.88	16.38

Note. Db (g cm^{-3}): Basic wood density expressed in g cm^{-3}, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Damage (No. ind.): Number of trees damaged after the conclusion of the felling operation, DBH (cm): Diameter at breast height, expressed in centimeters, Height (m): Commercial tree height expressed in meters, Stem Vol (m^3): Stem volume expressed in m^3, Basal (m^2): Basal area expressed in m^2, Branch Vol. (m^3): Branch volume expressed in m^3.

Table 3. Variation and proportion of the eigenvalues within the dimensions used to form the principal components. Dim.: Dimensions present in the principal components

Dimension	Eigenvalue	Variance (%)	Cumulative variance (%)
Dim.1	5.916106E+00	4.550851E+01	45.50851
Dim.2	2.582603E+00	1.986618E+01	65.37468
Dim.3	1.714391E+00	1.318762E+01	78.56231
Dim.4	1.003370E+00	7.718228E+00	86.28054
Dim.5	7.931747E-01	6.101344E+00	92.38188
Dim.6	4,298263E-01	3.306356E+00	95.68824
Dim.7	2.819414E-01	2.168780E+00	97.85702
Dim.8	2.171935E-01	1.670720E+00	99.52774
Dim.9	5.574702E-02	4.288233E-01	99.95656
Dim.10	3.710315E-03	2.854089E-02	99.98510
Dim.11	1.775584E-03	1.365834E-02	99.99876
Dim.12	1.605888E-04	1.235298E-03	99.99999
Dim.13	8.512454E-07	6.548041E-06	100.00000

Table 4. Values of the correlations/coordinates of the variables found in the dimensions of the principal components

Variable	Dim.1	Dim.2	Dim.3	Dim.4
Db	-0.5760521	0.3905703	0.3052262	0.2741640
Planning	0.3884945	0.5216313	-0.6326676	0.2348286
Cutting	0.6297079	0.4503300	0.3474362	0.4028270
Felling	0.6363357	0.6176027	-0.2133728	0.3976256
QNP	-0.0094782	0.8348518	-0.2743767	-0.2610988
QPE	0.7032070	0.3592726	0.2917482	-0.3533211
QNE	0.5896531	0.4994523	0.1698037	-0.5700969
Damage	0.5377906	-0.4503199	-0.2308387	0.0616097
DBH	0.9457188	-0.2431977	-0.1024269	0.0173193
Height	0.4398519	0.0512934	0.7794778	0.1483198
Stem Vol.	0.8985885	-0.2273666	0.2925007	0.0744219
Basal	0.9314890	-0.2966728	-0.0870262	0.0078690
Branch Vol.	0.8587202	-0.3065087	-0.3177944	-0.0544956

Note. Dim.: Dimensions of the principal components, Db (g cm^{-3}): Basic wood density expressed in g cm^{-3}, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Damage (No. ind.): Number of trees damaged after the conclusion of the felling operation, DBH (cm): Diameter at breast height, expressed in centimeters, Height (m): Commercial tree height expressed in meters, Stem Vol (m^3): Stem volume expressed in m^3, Basal (m^2): Basal area expressed in m^2, Branch Vol. (m^3): Branch volume expressed in m^3, Correlation: Values of the Pearson's correlation.

Table 5. Variables most significantly associated with a given principal component.

Dim.	Variable	Correlation	p value
1	DBH	0.9457188	1.013670E-08
	Basal	0.9314890	5.572577E-08
	Stem Vol.	0.8985885	9.573546E-07
	Branch Vol.	0.8587202	1.020477E-05
	QPE	0.7032070	1.637501E-03
	Felling	0.6363357	6.027524E-03
	Cutting	0.6297079	6.750034E-03
	QNE	0.5896531	1.273058E-02
	Damage	0.5377906	2.597124E-02
	Db	-0.5760521	1.551591E-02
2	QNP	0.8348518	3.058955E-05
	Felling	0.6176027	8.248270E-03
	Planning	0.5216313	3.174940E-02
	QNE	0.4994523	4.122614E-02

Note. Dim.: Dimensions of the principal components, Db (g cm^{-3}): Basic wood density expressed in g cm^{-3}, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Damage (No. ind.): Number of trees damaged after the conclusion of the felling operation, DBH (cm): Diameter at breast height, expressed in centimeters, Stem Vol (m^3): Stem volume expressed in m^3, Basal (m^2): Basal area expressed in m^2, Branch Vol. (m^3): Branch volume expressed in m^3, Correlation: Values of the Pearson's correlation.

The PCA resulted in the formation of two groups of variables (G1 and G2). The first, G1, consisted of dendrometric variables, such as diameter (DBH), basal area (Basal), stem volume (Stem Vol.), and branch volume (Branch Vol.). The correlation value between these variables and the principal components surpassed 0.8 (Table 4), and their proximity evidenced a higher correlation with each other (Figure 6).

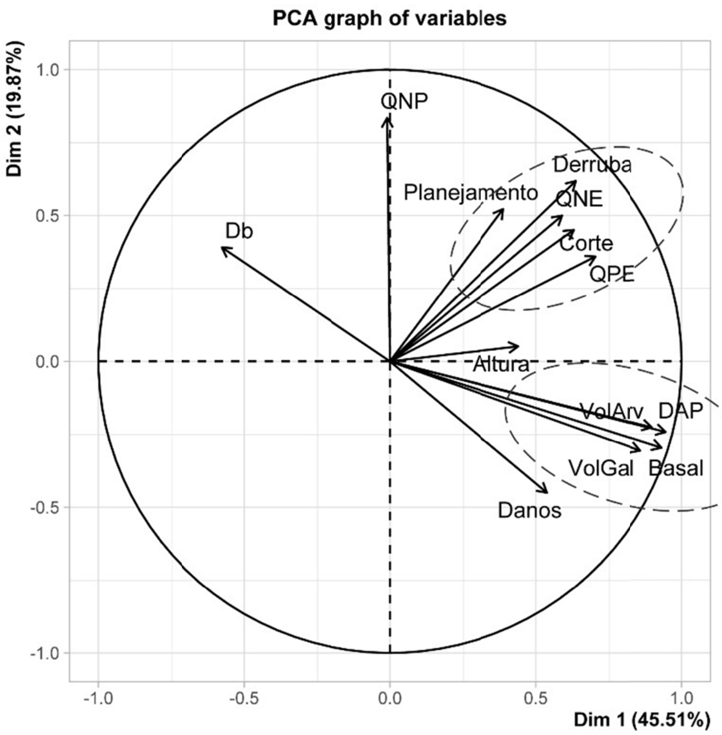

Figure 6. Biplot graph representing the projections of the variables on the axis of the principal components. Dim.: Dimensions of the principal components, Db (g cm^{-3}): Basic wood density expressed in g cm^{-3}, Planning (min): Time, expressed in minutes, used to plan the felling, Cutting (min): Time, expressed in minutes, used to cut the tree, Felling (min): Total time, expressed in minutes, used to complete the tree felling process, QNP (%): Angle difference, expressed in percentage, between the tree natural lean and the intended felling direction, QPE (%): Angle difference, expressed in percentage, between the intended and the effective felling direction, QNE (%): Angle difference, expressed in percentage, between the tree natural lean and the effective felling direction, Damage (No. ind.): Number of trees damaged after the conclusion of the felling operation, DBH (cm): Diameter at breast height, expressed in centimeters, Height (m): Commercial tree height expressed in meters, Stem Vol (m^3): Stem volume expressed in m^3, Basal (m^2): Basal area expressed in m^2, Branch Vol. (m^3): Branch volume expressed in m^3

On the other hand, the second group, G2, was formed, basically, by variables that depended on the directional felling activity. These included the times used to plan the felling (Planning) and execute the cutting (Cutting) and the felling itself (Felling), and the percentage of correspondence between the angles of natural lean and effective felling (QNE%), and the intended felling and the effective felling direction (QPE%). Among these variables, QPE% had a correlation value of 0.7. This value was 0.63 and 0.61 for the variable felling time (Felling) in the first (Dim.1) and second (Dim.2) dimensions of the principal components, respectively (Table 4). The latter explains the increased length of the vector of this variable compared to the other vectors of the group (Figure 6).

The number of standing trees damaged with the process of directional felling (Damage), the commercial height (Height), the percentage of correspondence between the angles of natural and planned felling direction (QNP%), and the wood density (Db) lacked a direct relationship with the groups and appeared isolated (Figure 6).

The commercial height of the trees had correlation values of 0.43 and 0.05 in Dim.1 and Dim.2, respectively (Table 4), and positioned between the two formed groups (G1 and G2) (Figure 6).

In general, the variable QNP% remained distant from G1 and G2 and the variables Db and Damage (Figure 6). In Dim. 2, the variable QNP% had a correlation value of 0.83, reinforcing an inversely proportional correlation with the groups G1 and G2.

The basic wood density (Db) had correlation values of -0.57 and 0.39 in Dim. 1 and Dim. 2, respectively. The latter is reinforced by the opposite direction of this variable in relation to the groups of variables G1 and G2. Therefore, Db is inversely proportional to the variables of these two groups, especially when it comes to the number of nearby trees damaged by the directional felling.

Correlation values regarding the variable number of nearby trees damaged by the directional felling (Damage) were 0.53 and -0.45 in Dim.1 and Dim.2, respectively. The latter suggests an inversely proportional relationship with the variables QNP% and Db. However, the opposite pattern occurs between this variable and the dendrometric variables of G1 since they share the same quadrant. This implies a higher correlation within the same direction, and therefore, covariation with the variables of the group.

The variable QNE% had an intermediate correlation with the variables QNP% and QPE%, but higher with QPE%. This tends to occur when the natural lean of a tree is the only option for directing its fell.

The variable QPE% was more correlated with the first principal component and, therefore, with the dendrometric variables, showing a directly proportional correlation. The larger the dimension of a tree, the better it is for the chainsaw operator to achieve the intended felling direction, even if it is in its natural lean.

The times used for planning (Planning), cutting (Cutting), and felling (Felling) the trees had each correlation values of 0.38, 0.62, and 0.63 in Dim.1., and 0.52, 0.45, and 0.61 in Dim. 2, respectively.

The highest correlation involving the cutting time was with the variable QNE%. On the other hand, the planning time showed a direct correlation with the variable QPE%.

The species jatobá, muiracatiara, itaúba, maçaranduba, jutai mirim, jarana, fava timborana, angelim pedra, cedronara, quaruba, and cupiúba were more correlated with the first dimension (Dim.1), while the species mandioqueira rosa, cuiarana, garapeira, cumaru, sapucaya, and tauari did so with the second dimension (Dim.2) (Figure 7).

In Dim. 1, the species jatoba was directly influenced by the commercial height. Contrary to this, the species muiracatiara was poorly influenced by the variables involved in the analysis. The closer a sample is to the origin of the principal component axes, the less influence it will have. The species maçaranduba, itaúba, jutaí mirim, jarana and fava timborana were more affected by the variable Db.

The species cedrorana and quaruba were directly influenced by the dendrometric variables of G1. However, the variables Diameter and Volume were closer to the species angelim pedra. The species cupiúba was inversely proportional to the operational variables, suggesting probable complications involved in its felling.

In Dim. 2, the species mandioqueira rosa and garapeira were directly influenced by QNP%. Despite being close to this variable, the species cuiarana was more influenced by the operational variable Planning time. The species cumaru was more affected by the basic wood density. Finally, tauari and sapucaia had the same pattern as cupiúba regarding the operational variables.

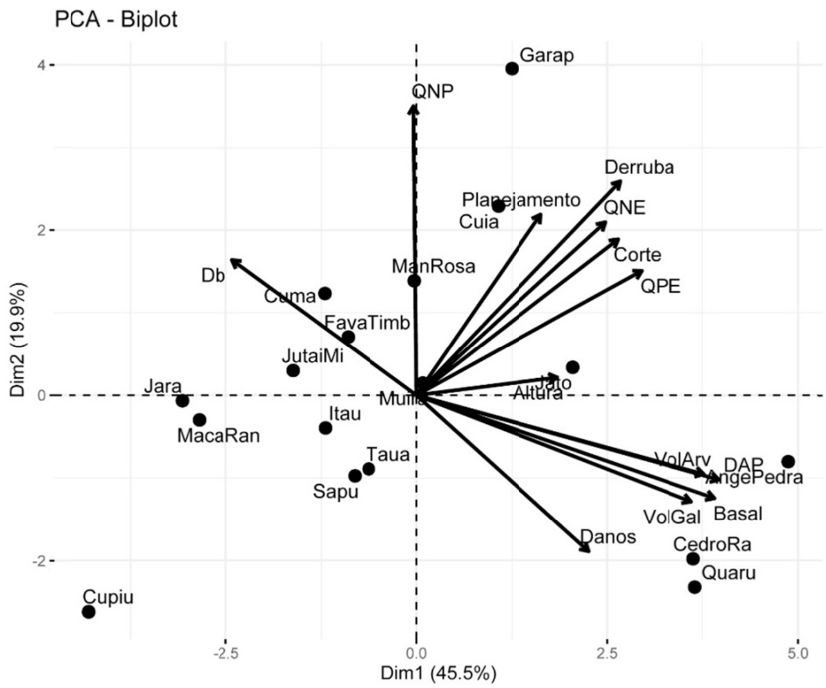

Figure 7. Projections of the observations (species) and variables in the axis of the principal components. AngePedra: angelim pedra (*Hymenolobium petraeum*), CedroRa: cedrorana (*Vochysia maxima*), Cuia: cuiarana (*Terminalia amazonia*), Cuma: cumaru (*Dipteryx odorata*), Cupiu: cupiúba (*Goupia glabra*), FavaTimb: fava timborana (*Pseudopiptadenia psilostachya*), Garap: garapeira (*Apuleia leiocarpa*), Itau: itaúba (*Mezilaurus itauba*), Jara: jarana (*Lecythis lurida*), Jato: jatobá (*Hymenaea courbaril*), JutaiMi: jutai mirim (*Hymenaea parvifolia*), MacaRan: maçaranduba (*Manilkara elata*), ManRosa: mandioqueira rosa (*Qualea dinizii*), Muira: muiracatiara (*Astronium lecointei*), Quaru: Quaruba (*Erisma uncinatum*), Sapu: sapucaia (*Lecythis pisonis*), Taua: tauari (*Couratari guianensis*)

4. Discussion

In general, the angular differences between the intended and effective felling directions showed that 75% of the felled trees had a 96.67% success rate of correspondence regarding the planned felling angle. A higher error concerning the intended felling direction was verified for just 25% of the trees, which had less than a 20% success rate of correspondence regarding the planned felling angle. A similar pattern was observed between the natural lean and the intended felling direction. Total correspondence between these two angles represents 100% of correspondence with the effective felling direction, as confirmed for 75% of the trees. On the other hand, the intended felling direction equaled the effective felling direction in 96.67%. The felling angle changed up to 15% for 25% of the trees.

Considering the angular differences QPE%, QNP% and QNE%, more than 50% of the trees were felled towards their natural lean or close.

The PCA explained 65.37% of the total variation in the original data, with 45.51% and 19.87% corresponding to Dim. 1 and Dim. 2, respectively. In general, the variables involved in the directional felling had moderate to strong correlation values (Cohen, 1978; Dancey & Reidy, 2019).

The groups of variables G1 (dendrometrics: DBH, basal area, volumes) and G2 (felling-related time and felling directions) correlated more with the principal components, given their proximity to Dim. 1. The vectors of G1 were near each other, indicating greater intercorrelation between the variables. The higher length of the vectors within this first group (G1) compared to the second (G2) suggests a good representation in the first dimension of the principal components. The higher the length of a variable vector, the greater its importance (Pereria et al., 2010).

Positive and negative correlation values indicate a direct or inversely proportional relationship between the variables, respectively (Becker, 2015). Variables with the same sign act together, increasing or decreasing in the same direction. On the other hand, variables with opposite signs act inversely, meaning that as the first increases, the second decreases (Tobar-Tosse et al., 2015).

For instance, the dendrometric variables DBH, stem, and branch volume were inversely correlated with the variables felling time and direction. The proximity of these variables with the number of trees damaged by directional felling (Damage) allows inferring a direct relationship between them. Therefore, the higher the values of diameter (DBH), basal area (Basal), and volume (Stem Vol. and Branch Vol.) of the tree species, the greater the damage caused by their felling. According to Rocha and Pereira (2015), the distribution of variables by principal components allows verifying relationships between variables through the angular distance between their vectors, defined as intercorrelation.

The opposite representation between the variables damage and Db indicates the lack of a direct relationship between them. This result shows that the number of trees damaged by directional felling is not related to the wood density of the felled trees but their dendrometric characteristics.

Within G1, the level of damage increased in the same direction as the dendrometric variables, indicating that the higher the diameter, basal area, and volume (stem and branches) of a tree, the greater the damage caused by its directional felling. Jackson et al. (2002) reported similar results in a survey concerning the damage caused by the logging activity in Bolivia. According to the authors, the diameter of the felled trees significantly correlated with the number of damaged trees.

Higher values concerning the dendrometric variables imply a reduced difference between the natural lean and the intended felling direction since trees with larger dimensions usually have a smaller amplitude in the felling direction. Consequently, it is possible to infer that the larger the tree, the more its intended felling angle will tend to its natural lean. Tree dimensions constitute the main characteristic that influences tree felling (Câmpu & Ciubotaru, 2017). In Bolivia, Krueger (2004) observed that the error associated with tree felling direction increases with diameter classes. However, the latter cannot be completely confirmed since it occurs more frequently just in some species. While researching the factors affecting directional felling in a forest in Iran, Nikooy et al. (2013) verified that diameter and tree volume influence the error in directional felling given their high correlation.

These authors also observed that the highest errors in directional felling occurred most clearly in two tree species with large stem dimensions (diameter and volume) and asymmetric crowns. These characteristics complicate evaluating the process of directional felling. In a study involving cutting angles used for directional felling in the Appalachian region of the United States, Koger (1983) observed that tree diameter significantly influenced the determination of these angles through regression equations.

Trees with large dimensions tend to have lower QNP% values. Given the high cross-sectional areas, stem and branch volumes, and reasonable heights of these trees, they usually have less inclined stems and better-distributed branches.

In a forest, dominant and canopy trees characterize by their large stem and branch dimensions in the crown and a robust growth without competition for light. On the other hand, asymmetric crowns respond to changes in the canopy level through gaps that open successively above and beside the crown, favoring a faster growth rate (Halle et al., 1978). Smaller trees tend to concentrate their branches on a particular side of the crown to optimize the use of the luminosity that comes from possible gaps in the forest canopy. Tree crown asymmetry is quite common in tropical forests (Young & Hubbell, 1991) and smaller trees. In contrast, emergent trees have crowns with more well-distributed branches (Turner, 2004).

The size of the QNP% vector suggests a good representation of this situation in the principal components coordinate system. The correlation value between QNP% and the second principal axis indicates an inversely proportional correlation with the G1 and G2 variables. This is especially true for G1 since the distance between QNP% and G1 variables surpasses 90°. The angle between the vectors is a measure of the correlation between the groups. Accordingly, highly correlated variables tend to be together and in the same direction (Kent, 2012). Therefore, small angles between two variables indicate high positive correlations. On the other hand, angles close to 90° and 90°-180° define lack and negative correlations, respectively (Santos et al., 2019).

The vectors of the variables QNE% and QPE% were proximate, indicating a higher correlation when compared to the variable QNP%. When it comes to the commercial height, its vector was shorter than those of G1 and G2 variables. The commercial height measured up to the first bifurcation instead of the total height up to the crown possibly affected this correlation. Nevertheless, in general, trees with a diameter of 50 cm or more have reached their maximum altitude and, thus, stem height does not vary much among them (d'Oliveira & Braz, 1995).

The planning time is highly variable since it includes all the activities that precede the execution of the directional felling. However, in the present study, the highest variation corresponded to the felling time and the lowest to the planning time. Regarding the correlations, the planning time correlates more with the tree felling time than with the cutting time. The felling time considers all the operations until the tree falls to the ground, and therefore, the longer the planning time, the longer it takes to cut a tree. Analyzing the time of the tree felling activity plays a crucial role in identifying its limiting factors and technical and technological measures that lead to an increase in the productivity level (Câmpu & Ciubotar, 2017).

The variable felling time (Felling), composed of the variables planning time and cutting time, was directly influenced by the G1 variables, which indicates that the higher the values regarding the variables diameter (DBH), basal area (Basal), and volume (Stem Vol.), the higher the cutting time.

Previous research aimed at studying productivity costs of chainsaw logging has confirmed the influence of DBH on the cutting and total felling time. Some of these studies were conducted in forests of Arkansas (Lortz et al., 1997), the Appalachian Mountain, USA (Wang et al., 2004), the Caspian Forests, Iran (Behjou, 2012; Jourgholami et al., 2013), and the state of Mato Grosso, Brazil (Acosta et al., 2018). However, comparing the time involved in directional felling operations is difficult given the differences in the execution methodologies (Câmpu & Ciubotaru, 2017).

The vectors of the variables planning, cutting, and felling time increased in the same direction, proportionally to their participation in the directional felling activity. That is, the planning time was shorter than the cutting time.

The shorter the cutting time of a tree, the more likely it is to fall towards its natural lean. On the other hand, a longer cutting time with a more careful execution may favor the tree to fall in the intended falling direction. In general, the longer the planning time, the greater the chance of the tree falling in the direction planned by the chainsaw operator. These results indicate the wisdom of applying appropriate techniques when felling trees since higher planning and cutting times imply increased chances of the tree falling in the desired direction.

The species cedrorana (CedroRa), quaruba (Quaru), and angelim pedra (AngePedra) were more associated with Dim. 1 and, consequently, with the variables diameter (DBH), basal area, and volume (stem and branches). Specifically, angelim pedra correlated more with the variables volume (Stem Vol.) and diameter (DBH). The position of the variable number of trees damaged by the directional felling (Damage) indicates a direct relationship between this variable and the ones previously mentioned. These results confirm that felling these tree species, with higher values of diameter (DBH), basal area (Basal), and volume (Stem Vol. and Brach Vol.), affect more the nearby standing trees. The opposite position between the variables Damage and basic wood density (Db) indicates the absence of a direct relationship between them. The latter shows that the number of trees damaged by directional felling is not related to the wood density of the felled trees but rather to their dimensions. These results corroborate the findings of Nikooy et al. (2013), who reported that large-sized trees increase the error associated with directional felling and consequently imply higher damage values.

The highest correlation values of commercial height corresponded to the species muiracatiara (Muira) and jatobá (Jato). Therefore, the commercial height of these trees influences their directional felling.

The species mandioqueira rosa (ManRosa), cuiarana (Cuia), and garapeira (Garap) were more correlated with the Dim. 2, where the QNP% variable stood out. At the same time, these species correlated with the variable planning time, suggesting a possible correspondence between the intended fall direction and the tree natural lean.

The species fava timborana (FavaTimb), cumaru (Cuma), jutai mirim (JutaiMi), and muiracatiara (Muira) correlated more with the Dim. 1. The latter is explained by the direct influence of the wood density on the directional felling process. Other species, such as itaúba (Itau), jarana (Jara), maçaranduba (MacaRan), and cupiúba (Cupiu), showed a similar pattern, although with less influence of the wood density variable (Db). In general, the results confirmed a marked effect of their wood density and smaller dimensions (diameter, volume, and basal area) for these species.

In trees of the abovementioned species, the combination of higher wood density and smaller dimensions implies damaging less the nearby standing trees. In this case, achieving the intended felling direction might be less complicated. On the other hand, directing the fell of trees with larger diameters and lower wood densities may be more challenging given their increased susceptibility to the actions of possible external interferences.

The species tauari (Taua) and sapucaia (Sapu) correlated more with Dim. 2, and along with the species muiracatiara (Muira), itaúba (Itau), and cupiúba (Cupiu) were less correlated with the planning, cutting, and felling times. The same occurred for the vectors of the variables QNE% and QPE%, indicating that these species do not follow a defined pattern associated with the application of directional felling techniques. It is important to note that, except for itaúba, these species characterize by forming predominant buttress roots.

5. Conclusion

The Principal Components Analysis formed two groups of variables: the dendrometric and the operational variables. The dendrometric variables include diameter (DBH), basal area (Basal), stem (Stem Vol.), and branch volume (Branch Vol) and have high correlation values with the principal components. On the other hand, the operational variables include time (Planning, Cutting, and Felling) and the percentages of correspondence between the felling angles (QNP%, QPE%, QNE%). Regarding these angles, in more than 50% of the observations, the trees are felled towards their natural lean or proximate.

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