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A model for roundwood of planted forests

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ABSTRACT: Forest harvesting is quantified in stereo volume. Therefore, there is no information on the types and quantities of products that can be extracted from trees. Information on timber products, as well as their evaluation, can assist forestry producers in trading. Another purpose is to provide support information for companies that purchase forests, such as the amount of most sold pieces and the amount of wood residue. In this work, a model to segment trees into roundwood pieces in the dimensions provided by the user was developed and validated. The required data are the diameter at breast height (DBH), total height of the trees, taper data, and the diameter and length dimensions of the roundwood pieces selected by the user. The validation was performed on the harvest of 8-year-old eucalyptus clone I224 and VM1, in an ILPF system and monoculture. The number of errors greater than 20% for the dimensions of pieces selected and calculated by the algorithm did not exceed 8% of the frequency distribution.

Um modelo para madeira roliça de florestas plantadas

RESUMO: A colheita florestal é quantificada em volume estereo. Desta forma, não se tem informação dos tipos e quantidades de produtos que podem ser extraídos das árvores. Informações sobre os produtos madeireiros, bem como sua valoração, podem auxiliar na fase de comercialização para o produtor florestal. Outra finalidade são informações de suporte para empresas compradoras de florestas, como a quantidade de peças mais vendidas e a quantidade de madeira destinada ao resíduo. Neste trabalho um modelo para segmentar árvores em peças roliças nas dimensões fornecidas pelo usuário foi testado e validado. Os dados necessários foram o diâmetro à altura do peito (DAP), altura total das árvores, os dados de taper, e as dimensões de diâmetro e comprimento das peças roliças selecionadas pelo usuário. A validação foi realizada na colheita de clones I224 e VM1 de eucalipto com 8 anos de idade, em Sistema ILPF e monocultivo. A quantidade de erros maiores que 20% das dimensões de peças selecionadas e calculadas pelo algoritmo não ultrapassou 8% da distribuição de frequência.

Introduction

Brazil is a major producer of wood, ranking fifth in the world for both production and consumption of roundwood, with an average production of 150 million cubic meters annually (FAO, 2019). A significant portion of this production comes from the planting of Eucalyptus and Pinus species, with approximately 70% being Eucalyptus species (Barreiros et al., 2023).

The supply of planted forests with homogeneous dimensions facilitates the development of business models to support wood management and processing. As a result, reporting information on roundwood per tree (number, volume, volumetric yield, and potential revenue), provides suppliers with the opportunity to market their wood in more profitable markets (Soares et al., 2003; Vergara et al., 2015, Costa et al., 2016).

For wood treatment companies, roundwood (Fig. 1) is classified and sold based on diameter and length for applications such as fence posts, beams, components for rustic structures, roofs, and poles. The market dictates the distribution of quantities by the dimensions of these products, meaning that buyers must classify and assess the forest based on wood products with higher demand.

For example, 2.2-meter-long fence posts with diameters between 8–10 cm and 10–12 cm are currently the most sought-after, representing approximately 80% of treated wood sales (Pereira JC, oral communication, 10/02/2023). Older forests tend to offer these dimensions from the upper sections of trees, closer to the tips, which are typically of lower quality due to branch insertions. In this case, younger forests may have a higher market value. However, this evaluation is typically performed visually, without quantitatively assessing the distribution of pieces by dimension.

On the other hand, producers who have invested in small forest stands or crop-livestock-forest systems (Silva et al., 2023) to generate income face difficulties in selling wood due to various factors, especially the small scale of production, which often does not justify mechanized harvesting. However, a financial analysis of the project may reveal that harvesting is viable if the wood is quantified in terms of roundwood and sawn wood, which generally have greater added value.

There are computational tools available to estimate multiproduct outputs from trees, aiming to optimize volumes for charcoal, pulp, and logs (Leite, 1994; Soares et al., 2003; Oliveira, 2011; Oliveira et al., 2011; Binoti, 2012), or to optimize products from sawn and roundwood (Murara et al., 2013; Nunes, 2013; Binoti, 2012; Oliveira, 2011; Leite, 1994). Additionally, scanning methods (Halabe et al., 2011) improve cutting processes, and simulation tools assess operations in sawmills (Lin et al., 1995; Heinrich, 2010; Maturana et al., 2010; Vergara et al., 2015).

Most studies evaluating computational tools focus on comparing conventional and optimized procedures, with or without associated economic evaluations of one or more wood products (usually pulp, energy, and lumber). However, they often fail to validate their success in actual forestry operations.

This study aims to apply a computational tool to forest exploitation and assess its accuracy in relation to the harvested products (Costa et al., 2022; Costa et al, 2023). The software is designed for simplicity, requiring minimal user input to calculate the information for roundwood pieces from a forest (Fig. 2).

Therefore, the hypotesis is: The application of the computational tool to estimate the quantity and dimensions of roundwood pieces in logging area will provide accurate estimates, comparable to the results obtained through direct field measurement.

The objective of this work is to present the roundwood model and its field validation, comparing the accuracy of the number of pieces obtained in a logging area with those calculated by the algorithm.

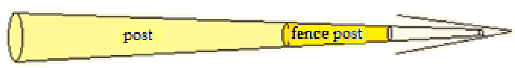

Figure 1: Segmentation of the stem into roundwood pieces.

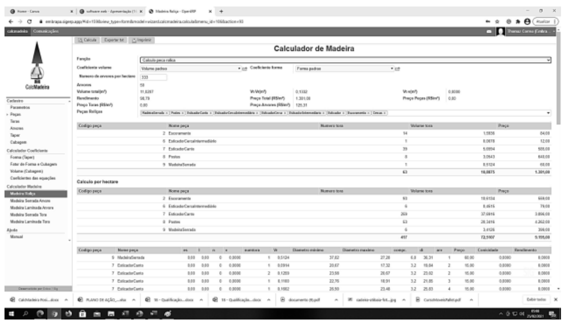

Figure 2: Web to calculate roundwood.

Material and Methods

The model

The software is a Web service in an ERP system/Python language, to support producers of planted forests, wood treatment companies, lumber companies, and sawmills in calculating the quantity and volume of roundwood, sawn and laminated wood that a set of individual trees or logs can provide.

First, the algorithm adjusts the tapering function (Kozak et al., 1969) and volumetric function (Schumacher & Hall, 1933; Silva et al., 2009), based on data from tree taper (Fig. 3). It is also capable of calculating the commercial height based on a limit diameter.

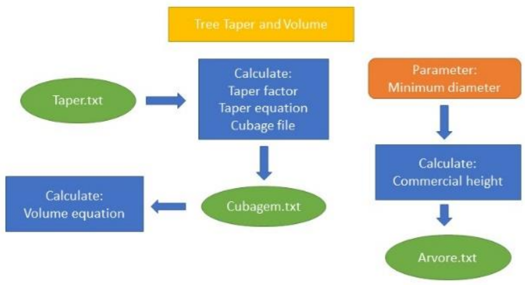

Figure 3: Chart of use cases to taper model.

For the selection of roundwood pieces, the algorithm's logic is to iterate through the trunk diameter until it fits the largest piece registered in a list of pieces. If this is not possible, it moves to the second piece on the list, and so on, until a piece fit. From this point on, the smallest diameter, calculated by the tapering function, becomes the trunk diameter for the next piece. If by the end of the list the trunk does not meet the required dimensions (diameter and length) for the listed pieces, the tree is discarded. In piece selection, up to the last piece, the tip of the tree is considered residual volume.

Additional information includes the proportion of bark, the stump height, spaces between trees and lines (Fig. 4). The parameters file for roundwood (DimRolica.txt) contains the minimum and maximum diameters of the pieces, their lengths, and, optionally, their price, which can represent either the operational cost or the sale value. Lastly, the forest inventory data (diameter at breast height and total tree height) are stored in the Arvore.txt file. Synthetic and detailed results are then generated, providing information on the number of pieces, volume, residue, and gross revenue or operational cost, per 10,000 m² (Fig. 2).

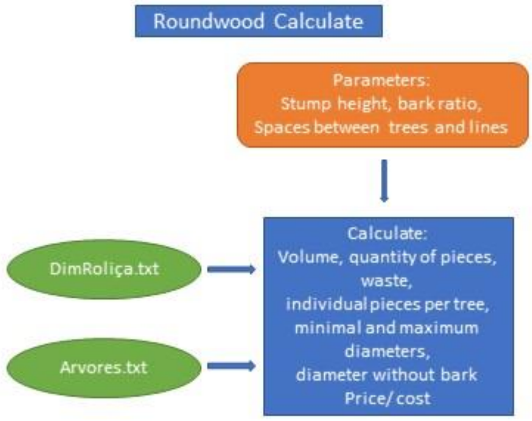

Figure 4: Use cases to calculate roundwood.

Validation

The algorithm was applied in a charcoal production area and roundwood harvesting. Three tests were conducted: two at the "Lagoa dos Currais" farm in Codisburgo, MG, in a plot planted with the I224 clone at a 3 x 12 m spacing within a crop-livestock-forest system (Costa et al., 2023), and one at "Cidade do Boi" farm in Pitangui, MG, in a plot planted with the VM1 clone at a 3 x 2 m spacing. Both plantations were 8 years old at the time of harvesting.

Defects observed during harvesting included tortuosity at the base and intermediate points, bifurcations, and branch insertions. For Test 3, the base defect was removed. We measured it in 30 trees (Tab. 1), and the average was calculated to be added to the stump height. The criteria for selecting roundwood pieces in the harvesting area were as follows.

T1 - Attempt to select a piece of 7, 6, 5, 4, 3.2, or 2.2 meters from the base of the tree. If intermediate tortuosity is present in the trunk, it is considered residue. In this case, the minimum and maximum diameters and the length of the piece are recorded. The next selection is made from the minimum diameter of the residual section. This process was applied in all tests. After the first selection, it proceeds with a new attempt, limiting the commercial height and diameter to ≥ 10 cm, continuing until all usable pieces are selected.

T2 - From the base of the tree, attempt to select a 7-meter piece with a minimum diameter of ≥ 19 cm. If this is not possible, select pieces of 3.2 m or 2.2 m until the minimum diameter reaches ≥ 9 cm. After the first selection, it proceeds with a new tentative, limiting the commercial height and diameter to ≥ 9 cm, continuing until all usable pieces are selected.

T3 - Cut the trees at a stump height of 10 to 15 cm, and remove any residue based on imperfections at the tree base. For the algorithm, a stump height of 35.2 cm (10 cm + 25.2 cm) was used, with 25.2 cm being the average length of the base imperfections in 30 trees (Tab. 1). Next, 3.2-meter pieces are cut until the diameter reaches 13 cm. After this, pieces are cut to 2.2 meters in length. The cutting limit for the tree tip is a diameter of 4 cm. Roundwood pieces must be within the diameter range of 19 cm to 9 cm, and any remaining material down to 4 cm in diameter is designated for firewood or charcoal.

Tab. 2 provides information on the number of trees measured and cubed in each test, the taper model applied (Eq. 1), the stump height, and the criteria used for selecting roundwood pieces. Diameter at breast height (DBH), total height, and trunk diameters were measured to ensure accurate volume calculations and to guide the selection of roundwood pieces based on the established criteria for each Tests.

Table 1: Length of sawn waste at the base of the trunk.

Tree	L(cm)	Tree	L(cm)	Tree	L(cm)
1	32	11	19.7	21	46
2	32.5	12	26.5	22	24
3	21.5	13	33	23	39
4	23	14	22.5	24	14
5	26	15	18	25	17.5
6	26.5	16	22	26	20.4
7	19.5	17	12.5	27	38
8	39	18	22.5	28	23
9	22	19	34.5	29	19.3
10	22	30	17.7	30	21.2
Average					25.2

Table 2: Number of cubed and measured trees, taper model, stump height and criterion for selection of roundwood pieces for treatment.

Test	Cub. Tree*	Measur. Tree	Stum.height (cm)	Pieces criterion
T1	12	60	0	7, 6, 5, 4, 3.2, 2.2 m until diam. >=10 cm
T2	17	33	0	7 m until diam. >=19 cm 3.2, 2.2 m with diam. < 19 and >=9 cm
T3	19	50	35.2	3.2 m until diam. >=13 cm 2.2 m until diam. < 13 and >= 9 cm 2.2 m until diam. < 9 and >=4 cm

$$*(d_i/dbh)^2 = b_0 + b_1*h_i/ht + b2*(h_i/ht)^2 \quad (1)$$

The percentage relative error (Eq. 2) was used to evaluate the deviation between the values obtained during harvest and those calculated by the algorithm.

$$E\% = \left(\frac{\text{calculated -observed}}{\text{observed}}\right) \text{ x } 100 \quad (2)$$

To evaluate the adherence between distributions by diameter class and by length of the observed and calculated roundwood pieces, the bilateral Kolmogorov-Smirnov (K-S) test was used, a non-parametric test that consists of measuring the discrepancy between the observed values and the values estimated under a probability model.

Results and Discussion

The total number of pieces observed and calculated, along with the predominant per test (7, 3.2, and 2.2 meters), are shown in Tab. 3, along with the relative error. The relative errors did not exceed 16%, except for the Test 3 charcoal/firewood class, where diameters ranged between 4 and 9 cm. In the observed data, it was noted that the minimum diameter of some pieces was not close to 4 cm, with values of 5, 6, and even 7 cm, while the calculated pieces were closer to 4 cm.

Tab. 4 compares the volumes of roundwood pieces per hectare (vr/ha), along with the respective relative errors, and the volumetric yield of roundwood pieces in relation to the total volume per hectare. The highest error (9%) occurred in Test

1, except for the charcoal/firewood class, which showed an error of 68.4%.

Table 3: - Total and predominant roundwood pieces in each test (with 7, 3.2 and 2.2 m in length) and their respective percentage errors (E%).

Test	Piece	n. piece obs.	n. piece calc.	E%
T1	total	168	161	-4.0
T2	total	175	191	9.0
T3	total	377	437	15.9
T1	7	120	113	-6.0
T2	3.2	141	125	-11.0
T3	3.2	119	104	-12.6
T3	2.2	138	139	0.7
T3 coal/firewood		120	194	61.7

Table 4: Total volume (m^3) per hectare (vt/ha), volume (m^3) of pieces per hectare (vr/ha), percentage error of the estimate (E%) and volumetric yield (vy) for the test

	vt/ha*		vr/ha	E%	vy
T1	145.6	Observed	119.4		0.82
		Calculated	130.0	9.0	0.89
T2	145.6	Observed	137.8		0.94
		Calculated	134.5	-2.0	0.92
T3	433.3	Observed	371.1		0.82
		Calculated	366.1	-1.3	0.82
coal/firewood		Observed	34.5		
		Calculated	58.1	68.4	

* Calculation without mortality (1666 trees/ha) and with border trees in the sample (larger dimensions).

Figs 5, 6 and 7 show the relationship between the percentage error and the minimum and maximum diameter of pieces for Tests 1, 2 and 3.

In Test 1, there was a serial correlation of the error with the maximum diameter of the pieces, starting at approximately 20 cm (Fig. 5A). This indicates that the model tended to underestimate the diameter as the pieces became thicker. This trend reveals a bias in the Kozak function for the thicker sections of the stem, particularly near the base. Since the trees were cut close to the ground, small buttresses at the base were included in the measurement of the first diameter.

In Test 1, the number of errors greater than 20% for the maximum and minimum diameters selected and calculated by the algorithm did not exceed 4.1% and 3.3% of the frequency distribution, respectively (calculations not shown).

In Test 2, the error trend relative to the larger diameter was less pronounced (Fig. 6), and the number of errors greater than 20% for the maximum and minimum diameters selected and calculated by the algorithm did not exceed 5.9% and 2.4% of the frequency distribution, respectively (calculations not shown).

Test 3 exhibited a bias with overestimations in the diameters near the tree tips. Underestimations were also noted for diameters around 15 cm, although this trend was less pronounced for the minimum diameters of the pieces (Fig. 7B). The number of errors greater than 20% for the maximum and minimum diameters selected and calculated by the algorithm did not exceed 4.0% and 7.3% of the frequency distribution, respectively (calculations not shown).

Across the three tests, relative errors were predominantly within the 20% range. In Test 3, even accounting for an average residual base, there was a slight loss in consistency, with most errors being negative. The roundwood model considered the first piece starting at 35.2 cm from the base of the trunk. In some trees, the observed section was measured between 14 and 46 cm from the trunk base, leading to some maximum and minimum diameters being smaller than those calculated.

An observation regarding clones is that, despite being from the same genetic material, differences in size and even shape were observed. When measuring diameters along the trunk at Lagoa dos Currais farm (Test 1 and Test 2), different rates of diameter reduction were noted both between trees and at different positions along the trunk.

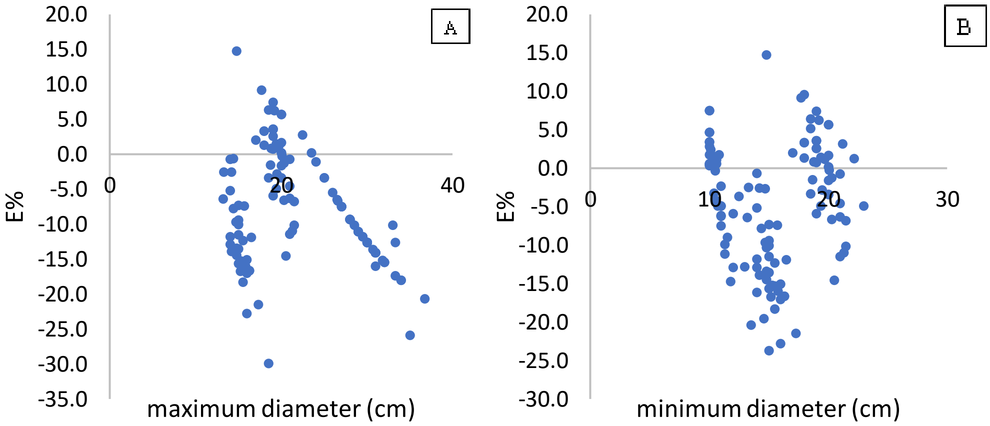

Figure 5: (A) E% as a function of the maximum diameter, and (B) E% as a function of the minimum diameter of the part in Test 1

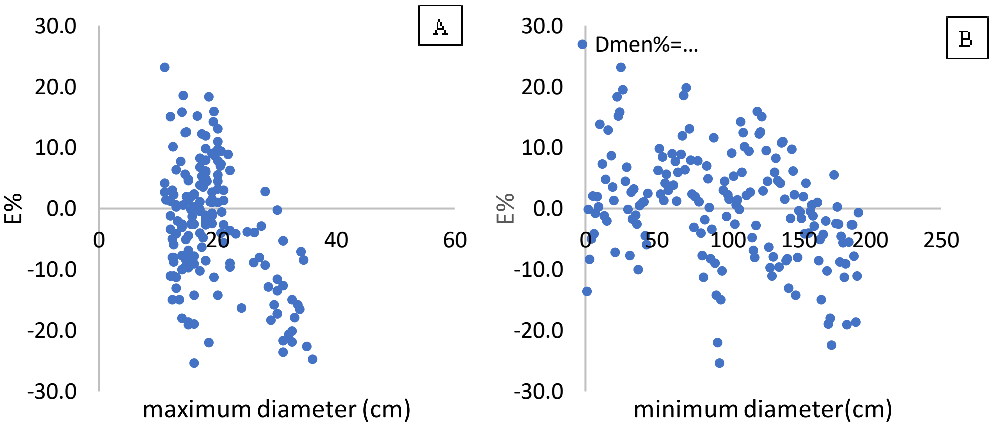

Figure 6: (A) E% as a function of the maximum diameter, and (B) E% as a function of the minimum diameter of the part in Test 2

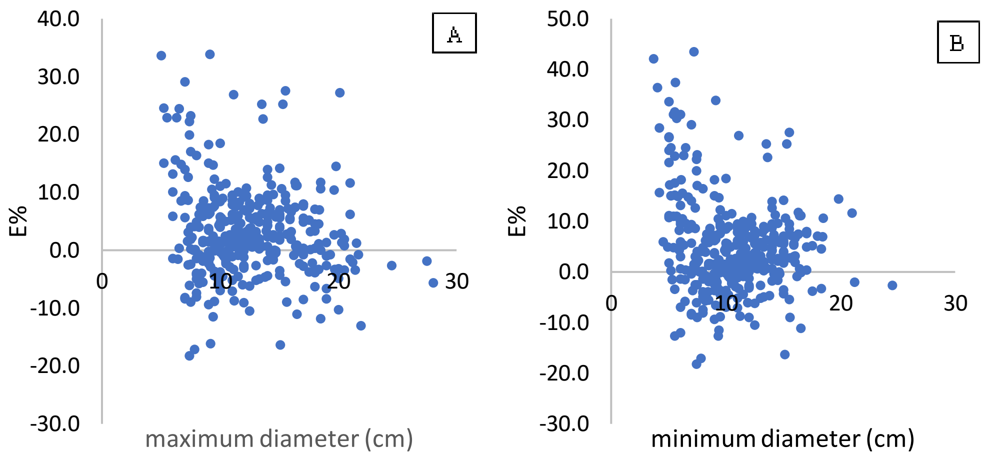

Figure 7: (a) E% as a function of the maximum diameter, and (b) E% as a function of the minimum diameter of the part in Test 3

Tab. 5 shows the differences between the calculated and observed number of pieces per tree. Deviations were predominantly within one piece more or less, except for the charcoal/firewood class. On average, 3 pieces were obtained per tree in Test 1, 6 pieces in Test 2, and 5 pieces in Test 3 (data not shown).

Tabs 6 and 7 present the statistics for the K-S (Kolmogorov-Smirnov) adherence test between the calculated and observed marginal probability distributions of minimum diameter (Dmin) and length (L). The results indicate adherence between all curves, showing they are statistically equal.

Tab. 8 displays the distribution of observed and calculated pieces by class of minimum diameter (Dmin) and length (L) for the total pieces across the three tests, and Figs 8 and 9 compare the marginal distributions of diameters and lengths. Residuals at the base and intermediate sections in some trees, as well as the precision of the taper equations, were the main factors contributing to the poor adherence in some results.

Table 5. Distribution of the difference between the number of observed and calculated pieces per tree in each test.

Diference	T1	T2	T3	T3 Coal/firewood
-4	0	0	0	1
-3	0	0	0	1
-2	0	0	1	17
-1	1	15	8	23
0	52	16	30	5
1	7	2	11	3
2	0	0	0	0

Table 6: Kolmogorov-Smirnov test (K-S) with 95% probability for comparison between observed and calculated distributions of pieces by minimum diameter (Dmin).

T1		T2		T3	
Dmin Class	K-S	Dmin Class	K-S	Dmin Class	K-S
10	n.s. 0.119	9	0.051	9	0.050
13	0.068	11	n.s. 0.096	13	0.058
16	0.018	13	0.083	16	0.024
19	0.035	15	0.059	19	0.008
22	0.006	17	0.013	20-24	n.s. 0.012
25	0.000	19	0.048		
		21	0.001		

		23	0.000

n.s. not significant at 0.05. K-S tab. = 0.519 (n=6) for T1, K-S tab=0.454 (n=8) for T2, and K-S tab=0.0.563 (n=5) for T3

Table 7: Kolmogorov-Smirnov test (K-S) with 95% probability for comparison between observed and calculated distributions of pieces by length (L)

	T1		T2		T3
L Class	K-S	L Class	K-S	L Class	K-S
2.2	0.026	2.2	n.s. 0.172	2.2	n.s. 0.045
3.2	0.097	3.2	0.021	3.2	0.000
4.0	n.s. 0.148	5.0	0.015		
5.0	0.126	6.0	0.009		
6.0	0.012	7.0	0.000		
7.0	0.000				

n.s. not significant at 0.05. K-S tab. = 0.519 (n=6) for T1, and K-S tab=0.563 (n=5) for T2, and K-S tab=0.8419 (n=2) for T3.

Table 8: Double entry of total pieces (T1 + T2 + T3), observed (field) and calculated by the algorithm

			L(m)				
Class	2.2	3.2	4	5	6	7	total
Dmin (cm)			Observed				
9	143	67	2	5	15	19	251
13	11	127	1	1	0	37	177
16	3	53	0	2	0	22	80
19	0	22	2	2	5	61	92
Total	157	269	5	10	20	139	600
			Calculated				
9	189	48	13	4	0	21	275
13	7	117	0	0	0	32	156
16	0	51	0	0	0	16	67
19	0	33	0	1	0	63	97
Total	196	249	13	5	0	132	595

Note. disregarding the class for charcoal/firewood.

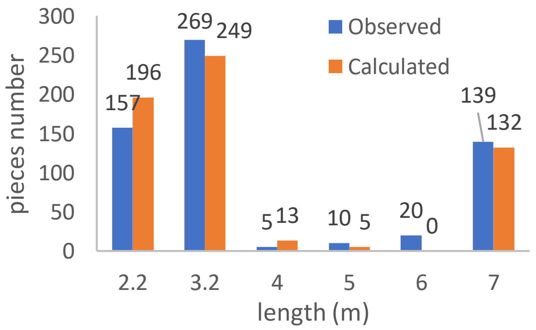

Figure 8: Distribution of calculated and observed pieces by length for all tests.

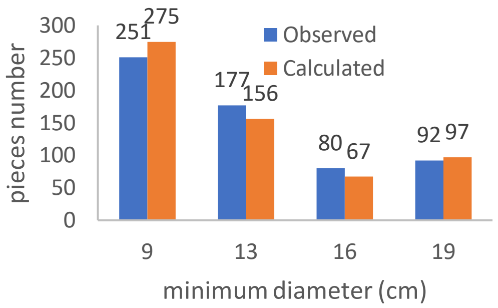

Figure 9: Distribution of calculated and observed pieces by minimum diameter for all tests.

The first observation regarding the differences is the presence of intermediate imperfections in the trunk, which are not detectable through the algorithm. The roundwood model identifies residuals above the commercial height or estimates them based on averages when these imperfections occur at the base of the tree.

The second observation, after evaluating each tree, is that Kozak's model slightly deviated from the actual trunk shape of I224 clone, which often exhibits a "bottle" shape in most trees. In some cases, measurements showed a larger diameter compared to previous measurements along the trunk, as if the tree had thickened in a higher section. The presence of thick branches, common in crop-livestock-forest systems, further complicates the model's accuracy by causing irregularities in the trunk's diameter.

The irregularity at the base of I224 clone trees becomes even more pronounced, with small buttresses and very large diameters that do not correspond to the trunk's diameter higher up, making modeling particularly challenging, especially since the trees were cut near the ground. In the case of clone VM1, the largest imperfections occurred at the base, where residual sections up to 50 cm in length were removed. In contrast, in clone I224, imperfections occurred in the intermediate portion of the trunk, with some small tortuous segments.

These factors contribute to the errors and trends observed in the model's performance. There are many others taper models (Andrade et al., 2022) that could be implemented, including neural networks, but this type of error is generally unpredictable and impossible to correct.

Despite the imperfections noted in the trees, the highest probabilities in the error distributions between diameters are close to zero (data not shown). This work shows a hit level with respect to the results of the algorithm so that the users can judge if this level is satisfactory or not for their application.

Approaches related to multi-product optimization focus on solutions aimed at increasing revenue and reducing waste—two key interests for forest managers. The solution presented by the roundwood model tested in this study is up to date, allowing managers to define criteria based on the products demanded by both industry and end consumers. They can assign and simulate various dimensions according to the desired product specifications and use this tool to determine the optimal production strategy.

Conclusions

The validation of the timber estimation model for clone I224 in the ILPF system and for clone VM1 showed promising results, with most of the percentage errors below 20% for both the number of pieces and the total estimated volume. In addition, a statistically significant equality was observed between the number of pieces per diameter class and the width of the pieces, confirming the accuracy of the model in different cutting categories.

The distribution of errors between the diameters of the pieces was, for the most part, consistent, and the variations in the number of pieces per tree were limited, for the most part, to just one error unit, which establishes a level of reliability for the model, indicating that the computational tool presented is an alternative for estimating the quantities and dimensions of the timber to be harvested with a level of precision, with great potential for application in forestry production.

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