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Scientific Article

MODELING AS A TOOL FOR PREDICTING THE PRODUCTIVE CAPACITY OF WOOD HARVESTING: APPROACH OF FELLER-BUNCHER AND HARVESTER

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ABSTRACT

Carrying out an assertive planning in logistics and forest harvesting is essential to reduce the operational costs, as well as guaranteeing a constant supply of wood for the manufacturing unit, without compromising the integrity of the fleet of machinery in the field. This study addressed the analysis of the productive capacity of two important wood harvesting machines, the Feller-Buncher, and the Harvester, with an objective to propose a technical modeling to optimize the logistics associated with these machines. Eight machines were analyzed in planted forests with different productivity (0.08 to 0.58 m³/tree). Machinery productivity was also evaluated for each forest condition. Regression analysis, means tests, and statistical inferences were carried out to present the results. The relationship between machinery productivity and forest productivity obtained through regression analysis was explained with up to 97% accuracy. The productivity curves indicated stabilization with the increase of the mean individual volume per tree (MIV). The forest being harvesting machines evaluated showed a reduction in cost per cubic meter harvested, as forest productivity increased. The productive capacity of the harvester dedicated exclusively to processing, although superior, presents a disadvantage in practical terms, mainly due to the requirement for a new machine in the felling process, therefore increasing the production cost.

Keywords: Forestry operations; Wood harvesting; Operational income; Productivity of forestry machines

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MODELAGEM COMO FERRAMENTA PARA A PREDIÇÃO DA CAPACIDADE PRODUTIVA DA COLHEITA FLORESTAL: UMA ABORDAGEM DO FELLER-BUNCHER E HARVESTER

RESUMO Realizar um planejamento assertivo na logística e na colheita florestal é essencial para reduzir os custos operacionais, bem como garantir o fornecimento constante de madeira para a unidade fabril, sem comprometer a integridade da frota de máquinas em campo. Este estudo abordou a análise da capacidade produtiva de duas importantes máquinas de colheita de madeira, o Feller-Buncher e o Harvester, com o objetivo de propor uma modelagem técnica para otimizar a logística associada a essas máquinas. Oito maquinários foram analisados em florestas plantadas com diferentes níveis de produtividades (0,08 a 0,58 m³/árvore). A produtividade das máquinas foi avaliada para cada condição florestal. Os resultados foram apresentados por meio de análises de regressão, testes de médias e inferências estatísticas. A relação entre a produtividade das máquinas e a produtividade florestal, obtida através da análise de regressão, foi explicada com até 97% de precisão. As curvas de produtividade dos maquinários indicaram estabilização com o aumento do Volume Médio Individual (VMI). As máquinas florestais avaliadas apresentaram redução no custo por metro cúbico colhido com o aumento da produtividade florestal. A capacidade produtiva do Harvester dedicado exclusivamente ao processamento, embora superior, apresenta desvantagens em termos práticos, principalmente pela necessidade de uma nova máquina para o processo de derrubada, o que aumenta o custo de produção.

Palavras-Chave: Operações florestais; Colheita de madeira; Rendimento operacional; Produtividade de máquinas florestais

1. INTRODUCTION

The Brazilian forestry sector has 9.94 million hectares of planted trees, being 76% composed by eucalyptus plantations. In 2022, the sector was accounted for 6.3% of Brazilian GDP, with gross revenue of BRL 260.0 billion, with 25 million tons of cellulose being produced (Indústria Brasileira de Árvores, 2023). Such aspects highlight the relevance of the forestry segment for the Brazilian economy.

The aforementioned scenario drives the mechanization process in forestry operations, with a focus on increasing productivity and reducing production costs, mainly in technical, operational, and economic aspects. This approach is crucial to providing reliable information that supports planning and decision-making in planted forests (Lima et al., 2023). Technological progress is essential to make this commercial forestry production viable, as well as to promote improvements in the overall efficiency of the system (Lima et al., 2019).

One of the most important steps in the production chain is forest harvesting, which can represent up to 60% of the total costs of wood that arrives at the factory. In paper and cellulose companies, mainly because a large part of forestry operations are mechanized and carried out by high-performance machinery that operates in continuous shifts (Rocha et al., 2022).

Harvesting is the forestry activity that benefits the most from technological advances, as it uses self-propelled machines in all stages of the operational cycle, ensuring increased productivity and optimization of processes (Suhartana et al., 2022; Lima et al., 2023). Santos et al. (2017) reports the importance of the operational efficiency of machinery in the wood harvesting process, mainly due to the high cost of the operation, therefore requiring great control and efficiency in the process.

According to Gomes et al. (2021), meticulous planning of logistics and forest harvesting is essential to reduce operational and economic costs, in addition to ensuring a constant supply of wood to the manufacturing unit, without compromising the integrity of the machinery fleet in the field. The wood harvesting emerges as a costly and complex activity, subject to several variables that directly influence machine productivity and operating costs (Shadbahr et al. 2021).

In Brazil, the most common cutting machines are the Harvester and Feller-Buncher, used in cut-to-length and full-tree systems, respectively. These consists of a highly mobile and stable powertrain, consisting of a head and a hydraulic arm. In the case of the harvester, this head carries out the complete processing of each tree individually, while the Feller-Buncher cuts the trees, grouping them into bundles for subsequent manipulation (Schettino et al., 2021).

According to Silva et al. (2022) harvester operation performance is affected by forest productivity, operational efficiency, and quality of operation. According to Pereira et al. (2020) Feller-Buncher costs also vary according to these variables and can be explained by several reasons, being those: the technical characteristics of the machine and cutting head, angle of arrangement of the tree bundles, length of professional experience of operators, terrain conditions, terrain slope, species harvested, individual volume of trees, forestry plantation mortality rate, among others, which justify the constant monitoring of productivity per effective hour, to optimize the operation. Such factors are, therefore, inseparable from the "man-machine" analysis in a forest harvesting system (Schettino et al. 2022; Soranso et al. 2022).

With this context in mind, this work aimed to analyze the productive capacity of forest harvesting machinery, Feller-Buncher, and harvester, concerning various forest productivity scenarios, as well as to highlight the production cost (USD.m^{-3}) associated with the mean individual volume per tree (MIV).

2. MATERIAL AND METHODS

2.1 Study area

The research was carried out in a forestry company located in the northeast region of Brazil, in the state of Bahia, located between the meridians of 39º34'30" to 40º34'48" longitude west of Greenwich and the parallels of 16º22'23" to 17º22' 00" latitude south of the Equator. The mechanized wood harvesting operations are limited to up to 10º of slope, carried out seven days a week in two shifts of eight hours each, through the cut-to-length system, in which processing is carried out inside the plots, with the wood extracted in the form of logs.

The assessments were carried out between August and May 2016, in forest plantations of *Eucalyptus* spp. with an average age of seven years, being those located in similar soil and climate conditions. Although the data were collected nearly ten years ago, the machinery used at that time still features technology levels comparable to those of current Feller-Bunchers and Harvesters. Furthermore, operational conditions of the Cut-to-Length system in Brazil have remained largely similar, as demonstrated by recent studies involving other types of machinery (Lima et al., 2025; Ferreira, 2025).

2.2 Machinery specifications and sampling procedures

The treatments and plots with harvester and Feller-Buncher were composed of 8 forest harvesting machines (Table 1, Figure 1).

The determination of forest productivity originated from the pre-cut inventory, in which the area occupied by each tree totaled 12 m² with a spacing of 4 x 3 meters, resulting in a density of 833 trees per hectare. Subsequent cutting and felling operations were analyzed in five distinct scenarios, each one representing different mean individual volume per tree (MIV): 0.08; 0.16; 0.30; 0.48, and 0.58 m³ without bark. In the Feller-Buncher study, data from the MIV class of 0.08 m³ without bark were not used to establish the model. To enable the development of regression models and the estimation of machine productivity based on MIV classes, three intermediate classes were arbitrarily defined between the minimum and maximum observed MIV values.

Table 1. Description and specification of the evaluated wood harvesting machines
Tabela 1. Descrição e especificações das máquinas de colheita florestal avaliadas

Number of machines	Type	Tires	Brand	Model	Head	Power
6	Harvester	Rigid Track	Volvo	EC210Bf	Ponsse, H77	165 HP
2	Feller-Buncher	Rigid Track	John Deere	903k and 909k	John Deere	330 HP

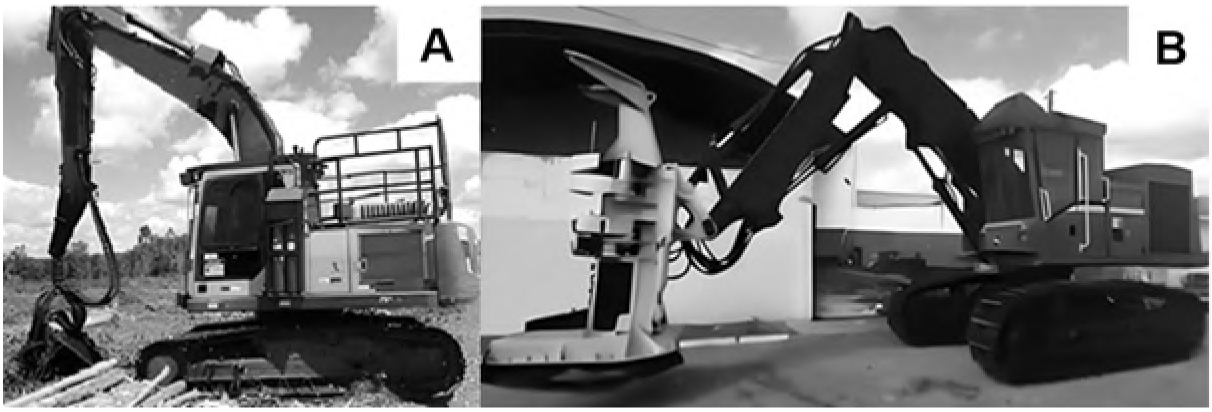

Figure 1. Harvester (A) and Feller-Buncher (B) models used in the study
Figura 1. Modelos de Harvester (A) e Feller-Buncher (B) utilizados no estudo

To establish the minimum number of cycles that would satisfy a maximum allowable sampling error of 5%, thus guaranteeing a confidence of 95% (Equation 1), the methodology proposed by Barnes (1977) was adopted.

$$n \geq (t*CV) / e^2 \quad \text{(Eq.1)}$$

Where n is the minimum number of cycles required; t is the t value, for the desired probability level and (n-1) degrees of freedom; CV is the variation coefficient t, (%); e is the permissible sampling error at 95% probability.

The study information, covering the felling processes with the Feller-Buncher, cutting and processing with the harvester, and only the processing activity with the harvester machine, are specified below (Table 2).

2.3 Study of production capacity and operational cycles

The machines operated in flat areas with operators of the same technical level, with the activity carried out simultaneously in three planting lines. In the experiment, the border areas of the plot were excluded. The productivity of the machines was determined in cubic meters of wood processed per effective hour of work ($m^3.hw^{-1}$).

A time study was carried out considering three levels of forest productivity, being: low (0.16 m³ without bark), medium (0.31 m³ without bark for felling and processing activities and 0.30 m³ without bark in processing), and high productivity (0.46 for felling and processing activity and 0.48 or 0.58 m³ without bark in processing). The multi-moment method was used with 15-second intervals, evaluating the following stages of the operational cycle: displacement, search and positioning, peeling, tracing, and waste movement. Personal breaks were also factored into the study. Personal breaks were also factored into the study. The variability associated with individual operator performance was statistically controlled by selecting operators with experience and similar productivity levels, as confirmed through company data, thereby minimizing sampling error and ensuring the reliability of the study's findings.

Table 2. Summary of Harvester and Feller-Buncher plot information
Tabela 2. Resumo das informações das parcelas avaliadas com Harvester e Feller-Buncher

MIV* (m^3 without bark)	DHB** (cm)	Height (m)	Plot	Minimum number of required cycles	Collected Cycles
Harvester (cutting and processing)					
0.08	13.90	18.90	5	64	375
0.16	15.50	21.70	5	63	375
0.20	16.00	24.00	5	75	375
0.31	18.20	26.90	5	80	375
0.36	19.90	30.50	5	54	375
0.46	21.30	31.70	5	69	375
0.58	22.90	35.50	5	76	375
		Total	35	481	2625
Harvester (Processing)					
0.08	13.90	18.90	5	92	375
0.16	15.50	21.70	5	105	375
0.30	18.80	26.90	5	89	375
0.48	21.50	32.30	5	63	375
0.58	22.90	35.50	5	60	375
		Total	25	409	1875
Feller-Buncher					
0,08	13,90	18,90	5	61	244
0,16	15,50	21,70	5	63	241
0,30	16,00	24,00	5	59	348
0,46	21,60	32,00	5	34	291
0,58	22,90	35,50	5	38	276
		Total	25	255	1400

Note: *MIV: Mean individual volume per tree without bark. **DHB: Diameter at Breast Height (DHB)
Nota: *MIV: Volume individual médio por árvore sem casca (VMI). **DHB: Diâmetro à Altura do Peito (DAP)

The activities were recorded through video recordings from cameras installed, both internally and externally to the machines. This methodology avoided interference with operators' productivity, since there was no presence of evaluators in the field. Furthermore, it enabled accurate identification of operational activities, also contributing to reducing the time needed to collect the data.

2.4. Statistical analysis

For regression analysis, mean tests, inferences from descriptive statistics, and presentation of results, the software GraphPad Prism 8, Statistical 7.0, and SPSS 11.0 were used. For the statistical analysis of the equations, the selection of productivity equations with the highest coefficient of determination (R^2) was adopted as a criterion, followed by the lowest number of variables.

The average operational cycle times were subjected to a comparative analysis using the Tukey test, with a significance level of 5%. This statistical analysis was performed using Statistical 7.0 and GraphPad Prism 8 software. The Tukey test is especially useful for identifying significant differences between multiple groups, allowing an accurate and detailed comparison of averages. This statistical approach provides a deeper understanding of variations in machinery operational cycle times, contributing to decision-making.

To investigate the relationship between MIV, expressed in cubic meters (m^3), and the productivity of forestry machines, measured in cubic meters processed per effective working hour ($m^3.hw^{-1}$), linear and parabolic models were adopted using linear regression, using Statistical 7.0 software. The performance of the Harvester and Feller Buncher machinery was evaluated according to the forest productivity classes (low, medium, and high). The adjusted models, according to Burnham and Anderson (1998), were then compared using the Akaike Information Criterion (AIC), to determine which model best describes the relationship between MIV, in the respective classes, and forestry machine productivity.

To relate dependence, the Stepwise regression method was established, at a 5% level of significance. The tested variables that did not present a significant statistical influence were excluded from the model.

3. RESULTS

3.1 Evaluation of wood harvesting machines

The productivity curves of the Feller-Buncher in felling, Harvester in cutting and processing, and Harvester only in processing (productivity in $m^3.hw^{-1}$), were adjusted according to the function of the Mean Individual Volume per tree (MIV) (Figure 2). It is noteworthy that the adjusted models presented a high coefficient of determination (R^2), which guarantees the accuracy of the data estimated according to the proposed model.

The descriptive statistics of the models (Table 3) show that the mean and median productivity values ($m^3.hw^{-1}$) are close to each other. This alignment suggests a symmetric distribution of the data. The high coefficient of determination (R^2) indicates a good correspondence between the technical statistical models and the observed data, suggesting that they are capable of explaining a large part of the data variability.

The significant improvement in the productivity of forest harvesting operations with the increase in the mean individual volume per tree (MIV) therefore becomes

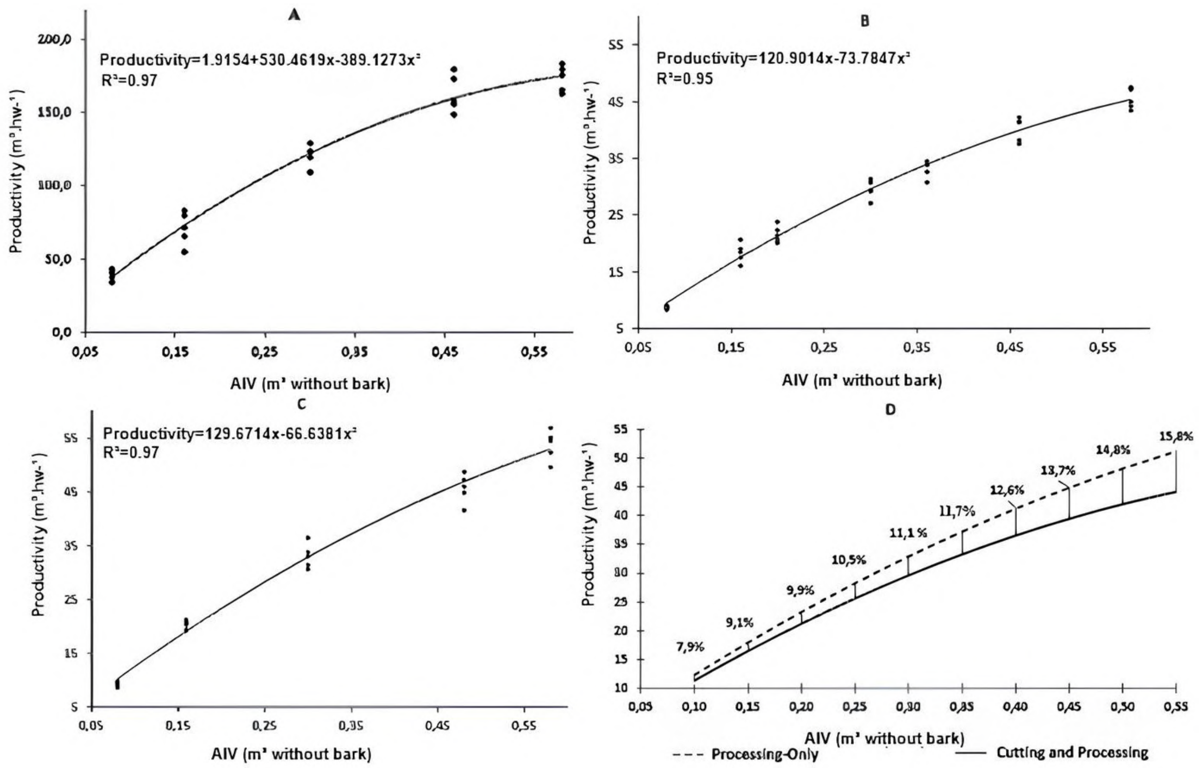

Figure 2. Productivity function models for forestry operations as a function of MIV: (A) Felling with a feller-buncher, (B) Cutting and processing with a harvester, (C) Exclusive wood processing with a harvester, (D) Difference between harvester models in evaluated situations

Figura 2. Modelos de função de produtividade para operações florestais em função do VMI: (A) Corte com Feller-Buncher, (B) Corte e processamento com Harvester, (C) Processamento exclusivo da madeira com Harvester, (D) Diferença entre os modelos de Harvester nas situações avaliadas

Table 3. Analysis of descriptive statistics of productivity (m³.hw⁻¹) of forestry machinery operations in the extreme south region of Bahia
Tabela 3. Análise das estatísticas descritivas da produtividade (m³.hw⁻¹) das operações de máquinas florestais no extremo sul da Bahia

Variable	Average	Median	σ (Standard Deviation)	CV (%)	N	R²
Feller-Buncher	110.18	102.11	65.80	59.74	25	0.97
Harvester cutting and processing	28.08	29.35	12.03	42.85	35	0.95
Harvester processing-only	32.30	32.93	16.30	50.49	25	0.97

evident. An increase in operational efficiency is noted, especially in the case of the harvester dedicated exclusively to processing, as felling takes more time in highly productive forests. Based on technical modeling, an estimate of the productivity of forestry machinery was made with a variation in MIV of 0.01 m³ without bark.

The income between the harvester cutting and processing and just processing shows a difference in productivity of around 15% when evaluating the largest MIVs. Although the harvester presents greater productivity, when it operates exclusively in processing, it must be considered that in this situation it would be necessary to adopt a new machine for the felling process.

To understand where the greatest time losses occur during the operation in order to optimize the process, it is necessary to evaluate the production capacity between the different operational cycles by machinery and by MIV classes.

3.2 Assessment of production capacity and operational cycles

The analysis of the productive capacity of the Feller-Buncher and harvester reveals the distribution of time dedicated to each activity per operational cycle, as well as the statistical relationship between the activities categorized by MIV classes.

The average percentage values of the operational cycles were categorized into MIV classes, divided into low, medium, and high productivity forests (Figure 3).

The cutting and accumulation activity with the Feller-Buncher required the longest time in all operating conditions, followed by the displacement/unloading activity. In low productivity forests, the Feller-Buncher took 47 seconds to complete a cycle, resulting in 5.7 trees, and reaching a productivity of 71.15 m³.hw⁻¹, totaling 445 trees per hour. In conditions of average productivity, the Feller-Buncher needed 39 seconds to complete a cycle, processing 4.32 trees, with average productivity of 120.94 m³.hw⁻¹, which totaled 403 trees per hour of effective work. For high productivity forests, on average, the Feller-Buncher required 32 seconds to complete a cycle, with 3.15 trees, resulting in an average productivity of 162.82 m³.hw⁻¹, totaling 354 trees per working hour.

The Feller-Buncher time analysis demonstrated a significant correlation ($p < 0.05\%$) between the Mean Individual Volume per tree (MIV) and the reduction in cutting and felling time. The increase in the diameter of the trees results in greater efficiency in the cutting and accumulation process, requiring a smaller number of trees to reach the head capacity.

The study carried out with the harvester covered the investigation of the machinery in felling/processing and exclusive processing operations. In low-productivity forests, both operations showed that the debarking activity required more time, followed by search and positioning. The harvester involved in cutting and processing took 32.9 seconds to complete a cycle, resulting in approximately 109 trees per effective working hour. In the exclusive processing activity, the average time per cycle was 30.3 seconds, totaling around 119 trees per hour.

Revista ÁRVORE
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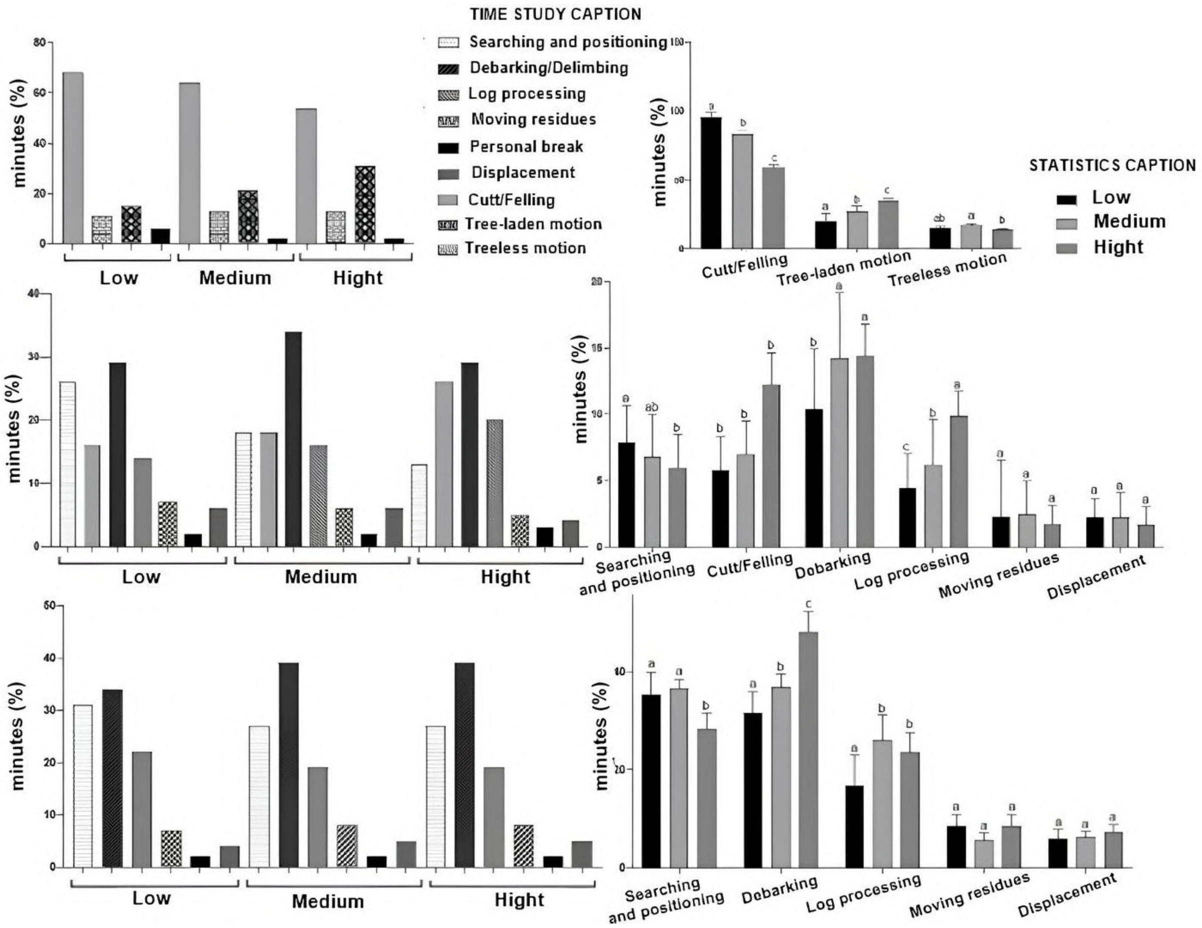

Figure 3. Time distribution during the operational cycle: Feller-buncher time studies (A1); Comparison between Feller-Buncher operating cycles (A2); Harvester time studies with cutting and processing (B1); Comparison between harvester operational cycles with cutting and processing (B2); Time studies of the Harvester acting only in processing (C1). Comparison between the operational cycles of the Harvester working exclusively in processing (C2). Means followed by a different letter within the same graph are statistically different by the Tukey test at the significance level of p <0.05%

Figura 3. Distribuição do tempo durante o ciclo operacional: Estudos de tempo do Feller-Buncher (A1); Comparação entre ciclos operacionais do Feller-Buncher (A2); Estudos de tempo do Harvester com corte e processamento (B1); Comparação entre ciclos operacionais do Harvester com corte e processamento (B2); Estudos de tempo do Harvester atuando apenas no processamento (C1); Comparação entre os ciclos operacionais do Harvester atuando exclusivamente no processamento (C2). Médias seguidas por letras diferentes no mesmo gráfico diferem estatisticamente entre si pelo teste de Tukey ao nível de significância de p < 0,05%

The study conducted with harvesters for cutting and processing operations revealed a statistically significant correlation ($p < 0.05\%$) between the increase in MIV and processing capacity. However, no statistically significant differences ($p < 0.05\%$) were observed during the study with harvesters dedicated exclusively to processing in forests with MIV greater than 0.30 m^3 without bark. In both operations with harvesters, lower processing, delimbing, and debarking capacity was recorded in forests with low productivity ($p < 0.05\%$).

For medium productivity forests, the average values of the operational cycles in both operations with the harvester showed that the debarking activity was the one that required the most of the time, followed by search, positioning, cutting, and felling in the case of the combined operation. On average, the harvester required 37.8 seconds to carry out the cutting and processing activities, resulting in approximately 95 trees per hour, while the exclusive processing activity took 32.7 seconds per cycle, totaling approximately 110 trees per hour.

For high-productivity forests, debarking and cutting activities took the most time, at 29% and 26%, respectively. When evaluated only in processing, the most significant activities were peeling and search and positioning, with 39% and 27%, respectively. In average, the harvester required 41.22 seconds per cycle for the cutting and processing activities, totaling approximately 87 trees per hour, while the exclusive processing activity required 38.35 seconds per cycle, totaling approximately 94 trees per effective hour.

In the context of operations in high-productivity forests, a statistically significant reduction ($p<0.05\%$) in harvester search and positioning time was observed. There was, however, an increase in search and positioning time during the processing activity. In some cases, operators found it difficult to locate trees on the ground after felling by the Feller-Buncher, since the harvester head, when opening the knives to search for the tree, often caught more than one, making it necessary to open them again and pick them up individually. Furthermore, the beams were located far from the pile formation site, requiring excessive turning to process the tree into the pile. This resulted in a significant loss of time gained in felling, in other words, even without carrying out the felling operation, the difficulty in searching and positioning trees on the ground for processing ended up impacting the time of the harvester machine dedicated only to processing.

The considerable time spent in the search and positioning stages to carry out the operation indicates the need for improvements to improve the efficiency of working with the harvester machine. These challenges highlights the need to improve the work routine of the exclusive harvester in the processing activity, to maximize operational gains.

3.3 Production cost

The increase in MIV per tree, from 0.08 to 0.58 m³, promoted percentage reductions in production costs of around 78.07; 79.18, and 80.72, respectively for felling activities (Feller-Buncher), cutting and processing (Harvester) and only processing with the harvester machine (Table 4).

It is evident that the increase in Mean Individual Volume (MIV) had a direct impact on machine productivity and consequently on the reduction of operational costs per cubic meter harvested. As MIV increased from 0.08 m³ to 0.58 m³ per tree, the productivity of the Feller-Buncher rose from 38.0 $m^3 \cdot hw^{-1}$ to 172.1 $m^3 \cdot hw^{-1}$, resulting in a significant decrease in unit cost from USD 4.15 to USD 0.91. A similar trend was observed for the Harvester, both in combined cutting and processing operations and in processing alone. In the case of the Harvester dedicated exclusively to processing, the cost dropped from USD 10.27 to USD 1.98, representing a percentage reduction of 80.72%. These results demonstrate that stands with higher MIV allow for better utilization of harvesting equipment, reducing fixed operational costs and enhancing overall harvesting efficiency.

4. DISCUSSION

In Brazil, the two most used forest harvesting systems are cut-to-length and full-tree (Amorim et al., 2021). The cut-to-length system is the most adopted in the harvesting of eucalyptus for the cellulose industry, where the tree is processed individually and sectioned into a specific standardized size at the harvesting site by the harvester (Silva et al., 2022; Holzleitner & Kanzian, 2022). However, there are variations adopted to maximize production. By adopting a Feller-Buncher cutting system for further processing with a harvester in the area, production capacity is increased, but the productivity curve is more sensitive and does not grow at the same rate. It is worth noting that in these conditions a new machinery is required in the process (Feller-Buncher), which brings an economic impact on the activity, despite the increase in the harvester's production capacity.

Understanding machine productivity is crucial for managing the costs of mechanized

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Table 4. Influence of MIV on the production cost of feller-buncher and harvester machines (USD.m^{-3})
Tabela 4. Influência do VMI no custo de produção das máquinas Feller-Buncher e harvester (USD.m^{-3})

	Feller-buncher			Harvester cutting and processing			Harvester only processing		
MIV (m³ without bark)	Productivity (m³.hw^{-1})	Cost USD.m^{-3}	Cost (%)	Productivity (m³.hw^{-1})	Cost USD.m^{-3}	Cost (%)	Productivity (m³.hw^{-1})	Cost USD.m^{-3}	Cost (%)
0.08	38.0	4.15	----	9.20	11.05	----	9.90	10.27	----
0.09	42.70	3.69	11.08	10.30	9.87	10.67	11.10	9.16	10.80
0.54	171.10	0.92	77.83	43.80	2.32	79.00	50.60	2.01	80.42
0.55	172.10	0.91	78.07	44.20	2.30	79.18	51.20	1.98	80.72

forest harvesting, as this aspect directly influences sustainable planning, especially when taking into account the significant contribution of this activity to the total cost of wood production (Ferreira et al., 2024). However, mechanized timber harvesting operations are challenging and complex due to the interaction of several factors that directly influence productivity, including forest density, operator skills, work techniques, and characteristics of forestry machines (Kamarulzaman et al., 2022; Aworka et al., 2022).

The harvester productivity curves indicate that as the volume per tree increases, the productivity of the machinery also increases, however, the equation reveals a tendency to stabilize as the MIV reaches high values. This pattern of curve stabilization is also observed with the feller-buncher in this study. Studies carried out by Ferreira et al. (2024) corroborate these results. The same authors observed a diminishing increase in machine productivity as the classes of Mean Individual Volume (MIV) increased, meaning that productivity grows at progressively smaller rates with increasing tree volume, resulting in a stabilization of production costs. As the volume per tree increases, operational productivity rises and costs decrease; however, with larger tree sizes, there is a gradual additional time consumption required to complete operational processes, which tends to affect productivity and, consequently, production costs.

The same phenomenon is observed with other types of forest harvesting machinery, as reported by Lima et al. (2025), where the costs of forest loading operations using log loaders tend to stabilize as machine productivity increases. This reinforces the understanding that, despite productivity gains with increasing tree size or operational efficiency, production costs reach a plateau due to additional time demands or operational constraints.

The findings of this study demonstrate that increasing the Mean Individual Tree Volume (MIV) significantly enhances the productivity of forest harvesting operations, leading to substantial reductions in unit production costs. However, it is observed that beyond certain MIV thresholds, these gains tend to plateau. This phenomenon can be attributed to the additional time required for operational activities such as processing and positioning of trees, particularly in high-productivity forests. This trend of production cost stabilization with increasing MIV was previously noted by Holtzscher and Lanford (1997), who highlighted that although productivity increases with tree size, unit costs tend to stabilize due to operational limitations imposed by the additional processing time.

Moreover, studies like that of Parajuli et al. (2020) emphasize that factors such as tree size, stand density, and operator technical efficiency directly influence the productivity and costs of harvesting operations. In the present study, analyzing operations across different MIV classes revealed that although increasing tree volume contributes to reducing unit costs, there is an inflection point beyond which additional gains become marginal. This observation reinforces the importance of balancing the increase in tree volume with associated operational limitations to optimize production costs in forest harvesting operations.

Similarly, a more recent study involving another type of forest harvesting equipment, the log loader, identified that operational limitations associated with boom movements for organizing timber both inside and outside trucks reduced the expected gains in scenarios with higher volume per tree (Lima et al., 2025).

To mitigate this operational plateau effect and continue promoting productivity gains, it is recommended to adopt integrated solutions, such as the use of more efficient processing heads, optimized logistical planning for the execution of the operational cycle of harvesters and Feller Bunchers, and operator training strategies aimed at maintaining operational efficiency even in high-productivity areas. These aspects can be explored in future research to further enhance the efficiency of forest harvesting operations.

The variables linked to MIV and machine operators are significant factors that affect the productivity of this machinery could explain more than 80% of the variation in productivity (Purfürst & Erler, 2011; Liski et al., 2020).

By analyzing the operations of machines in different MIV classes (0.08 to 0.58 m^3), it becomes possible to generate curves to predict the incomes of these machines in different conditions, which helps in the economic planning of the activity. Studies carried out by Ferreira et al. (2024) showed that the increase in the average volume per tree from 0.16 m^3 to 0.58 m^3 promoted a 58.43% reduction in the production cost of mechanized harvesting.

It is worth noting that other variables influence the performance of machinery. Diniz et al. (2018) highlighted the influence of varying terrain slopes on the time required to carry out the elements of the Feller-Buncher operational cycle. Alam et al. (2013) observed that the time for executing the cutting element was affected by the variation in the slope of the terrain, however, for the displacement element, no significant variations were found concerning the slope.

As highlighted by Schettino et al. (2022) in addition to MIV, factors related to the interaction between man and machine may influence the Harvester's productivity in mechanized forest harvesting. This study reveals deficient ergonomic standards and an average safety level, which implies in risks that can contribute to work accidents and the emergence of occupational diseases among operators, in addition to affecting the productivity of operations (Schettino et al., 2022; Soranso et al., 2023).

The production costs of the machinery ($USD.m^{-3}$) were obtained by the ratio between the total operating cost and the productivity of the respective machines, which varied according to the MIV of the forests. The operating costs for the same machinery models evaluated in this study were also determined by Rocha et al. (2022), which are in the order of USD 101.75 and USD 157.76 per effective working hour, respectively for the harvester and Feller -Buncher machines. In this sense, the work of Munis et al. (2024) highlighted that productivity and the cost components of labor, lubricating oil, maintenance, and economic depreciation were positively correlated, in other words, these cost components vary depending on the variation in productivity. Therefore, as evidenced by this work, as productivity increases, labor, lubricating oil, maintenance, and economic depreciation costs tend to increase.

Finally, it is essential to recognize the need for similar studies in different operating and soil-climatic conditions, this fact promotes productive adjustments and enables specific uses of forest harvesting machinery with a focus on gaining operational efficiency (Melchiori et al., 2022; Silva et al., 2023; Ghotb et al., 2024).

5. CONCLUSION

The technical modeling methodology adopted allowed to explain with 97% of accuracy the relationship between the machinery productivity and forest productivity. The productivity curves demonstrate a stabilization trend as the Average Individual Volume (MIV) reaches higher values.

The peeling activity required more time in the operations evaluated with the harvester, while the cutting and accumulation activity was the most impactful in terms of time in the Feller-Buncher operations.

The time study for the Feller-Buncher demonstrates that with the increase in forest productivity, occurs a reduction in the time of the operational cycle activity related to cutting and accumulation of trees, mainly due to the greater volume of logs.

An increase in harvester productivity was observed when its operation is exclusively focused on processing, especially in high-productivity forests. However, more in-depth studies are needed to optimize the productive capacity of the machinery in this exclusive processing activity, even considering the productivity gain.

In both operations with the harvester, in cutting and processing activities and processing only, a lower yield in processing, delimbing, and debarking was recorded in forests with low productivity.

The productive capacity of the harvester dedicated exclusively to processing, although superior, presents a disadvantage in practical terms, mainly due to the requirement for a new machine in the felling process, therefore increasing the production cost. However, studies are recommended under different soil-climatic and operating conditions to provide operational gains greater than those of the present work.

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AUTHOR CONTRIBUTIONS

F.A.C.F.; C.F.L.; L.J.M.: Conceptualization, Methodology, Project Administration, Writing – Original Draft. R.C.A.L.; L.C.F.; F.A.L.; B.L.S.S.; A.A.S.; L.F.S.; E.S.L.: Project Administration, Writing – Review & Editing. L.M.R.S.; P.P.A.J.; L.C.F.O.: Writing – Review & Editing.

7. REFERENCES

Alam, M., Acuna, M., & Brown, M. (2013). Self-levelling feller-buncher productivity based on LiDAR-derived slope. *Croatian Journal of Forest Engineering, 34*(2), 273–281.

Amorim, E. P., Pimenta, A. S., & Souza, E. C. de. (2021). Aproveitamento dos resíduos da colheita florestal: estado da arte e oportunidades [Using forest harvesting residues: state of the art and opportunities]. *Research, Society and Development, 10*(2), 1–20. https://doi.org/10.33448/rsd-v10i2.12175

Aworka, R., Cedric, L. S., Adoni, W. Y. H., Zoueu, J. T., Mutombo, F. K., Kimpolo, C. L. M., Nahhal, T., & Krichen, M. (2022). Agricultural decision system based on advanced machine learning models for yield prediction: Case of East African countries. *Smart Agricultural Technology, 2*, 100048. https://doi.org/10.1016/j.atech.2022.100048

Barnes, R. M. (1977). Estudos de movimentos e de tempos: projeto e medida do trabalho [*Motion and time studies: design and measurement of work*]. Edgard Blucher.

Burnham, K. P., & Anderson, D. R. (1998). Practical use of the information-theoretic approach. In *Model selection and inference* (pp. 75–117). Springer.

Diniz, C. C. C., Nakajima, N. Y., Robert, R. C. G., Dolácio, C. J. F., & Silva, F. A. da. (2018). Desempenho de um feller buncher em extrema variação da declividade do terreno [Performance of a feller buncher in extreme variations in terrain slope]. *Advances in Forestry Science, 5*(3), 381–384.

Ferreira, F., Freitas, L., Leite, E., Silva, M., Santos, S., Simões, D., Fiedler, N., Silva, L., Rocabado, J., Carmo, F., & Souza, J. (2025). Forwarder machine performance in eucalyptus forests in Brazil with different productivity levels: An analysis of production costs. *Forests, 16*(4), 646. https://doi.org/10.3390/f16040646

Ferreira, F. de A. C., Freitas, L. C. de, Leite, E. da S., Santos, S. L. M. dos, & Rocabado, J. M. A. (2024). Work efficiency and harvester costs in Brazilian eucalyptus plantations. *International Journal of Forest Engineering, 35*(1), 21–28. https://doi.org/10.1080/14942119.2023.2276577

Ghotb, S., Sowlati, T., & Mortyn, J. (2024). Scheduling of log logistics using a metaheuristic approach. *Expert Systems with Applications, 238*, 122008. https://doi.org/10.1016/j.eswa.2023.122008

Gomes, V. de S., Monti, C. A. U., Silva, C. S. J. e, & Gomide, L. R. (2021). Operational harvest planning under forest road maintenance uncertainty. *Forest Policy and Economics, 131*, 102562. https://doi.org/10.1016/j.forpol.2021.102562

Holtzscher, M. A., & Lanford, B. L. (1997). Tree diameter effects on cost and productivity of cut-to-length systems. *Forest Products Journal, 47*(3), 1–6.

Holzleitner, F., & Kanzian, C. (2022). Integrated in-stand debarking with a harvester in cut-to-length operations – Processing and extraction performance assessment. *International Journal of Forest Engineering, 33*(1), 66–79. https://doi.org/10.1080/14942119.2021.2013049

Indústria Brasileira de Árvores. (2023). Relatório Anual 2023 [Annual Report 2023]. IBÁ.

Kamarulzaman, A. M. M., Wan Mohd Jaafar, W. S., Abdul Maulud, K. N., Saad, S. N. M., Omar, H., & Mohan, M. (2022). Integrated segmentation approach with machine learning classifier in detecting and mapping post selective logging impacts using UAV imagery. *Forests, 13*(1), 48. https://doi.org/10.3390/f13010048

Lima, C. F., Lima, R. C. A., Souza, A. P. de, Minette, L. J., Schettino, S., Vieira, M. P. L., & Nascimento, G. S. P. (2019). Occupational noise and vibration assessments in forest harvesting equipment in north-eastern Brazil. *Journal of Experimental Agriculture International, 40*(5), 1–9. https://doi.org/10.9734/jeai/2019/v40i530379

Lima, R. C. A., Minette, L. J., Simões, D., Rocha, Q. S., Miyajima, R. H., Fritz, G. F., Schettino, S., Soranso, D. R., Nascimento, G. S. P., Vieira, M. P. L., Schettini, B. L. S., & Silva, A. A. (2023). Measurement time in the evaluation of whole-body vibration: The case of mechanized wood extraction with grapple skidder. *Forests, 14*(8), 1551. https://doi.org/10.3390/f14081551

Lima, C. F., Silva, L. F., Souza, C. M. A., Ferreira, F. A. C., Minette, L. J., Mendieta, F. M. P., Lima, R. C. A., Freitas, L. C., Vieira, J. K. M., Oliveira, V. C., Schettini, B. L. S., & Silva, A. A. (2025). Analysis of operational performance and costs of log loaders under different conditions. *Forests, 16*(6), 913. https://doi.org/10.3390/f16060913

Liski, E., Jounela, P., Korpunen, H., Sosa, A., Lindroos, O., & Jylhä, P. (2020). Modeling the productivity of mechanized CTL harvesting with statistical machine learning methods. International Journal of *Forest Engineering, 31*(3), 253–262. https://doi.org/10.1080/14942119.2020.1820750

Melchiori, L., Nasini, G., Montagna, J. M., & Corsano, G. (2022). A mathematical modeling for simultaneous routing and scheduling of logging trucks in the forest supply chain. *Forest Policy and Economics, 136,* 102693. https://doi.org/10.1016/j.forpol.2022.102693

Munis, R. A., Camargo, D. A., Rocha, Q. S., Pandolfo, P. T., da Silva, R. B. G., & Simões, D. (2024). Economic analysis of the feller buncher in Brazilian eucalyptus plantations: Modeling with time series. *International Journal of Forest Engineering, 35*(2), 296–302. https://doi.org/10.1080/14942119.2023.2290800

Parajuli, M., Hiesl, P., Smidt, M., & Mitchell, D. (2020). *Factors influencing productivity and cost in the whole-tree harvesting system.* Clemson Cooperative Extension, Land-Grant Press by Clemson Extension, 1079, 1–8.

Pereira, G., Fenner, P. T., Batistela, G. C., & Simões, D. (2020). Análise técnica-econômica da derrubada de *Eucalyptus* sp. com Feller-Buncher: Uma abordagem estocástica [Technical-economic analysis of the felling of *Eucalyptus* sp. with feller-buncher: A stochastic approach]. *Scientia Forestalis, 48*(126), 1–13. https://doi.org/10.18671/scifor.v48n126.14

Purfürst, F. T., & Erler, J. (2011). The human influence on productivity in harvester operations. *International Journal of Forest Engineering, 22*(2), 15–22. https://doi.org/10.1080/14942119.2011.10702606

Rocha, Q. S., Lima, R. C. A., Munis, R. A., Pereira, G., & Simões, D. (2022). Economic viability of the whole tree harvest under conditions of uncertainty: A study in southeastern Brazil. *International Journal of Forest Engineering, 33*(3), 181–188. https://doi.org/10.1080/14942119.2022.2029316

Santos, L. N. dos, Fernandes, H. C., Silva, R. M. F., Silva, M. L. da, & Souza, A. P. de. (2017). Evaluation of cost of harvester in cut and processing of eucalyptus wood. *Revista Árvore, 41*(5), e170005. https://doi.org/10.1590/1806-90882017000500001

Schettino, S., Minette, L. J., Lima, R. C. A., Nascimento, G. S. P., Caçador, S. S., & Vieira, M. P. L. (2021). Forest harvesting in rural properties: Risks and worsening to the worker's health under the ergonomics approach. *International Journal of Industrial Ergonomics, 82*, 103087. https://doi.org/10.1016/j.ergon.2021.103087

Schettino, S., Minette, L. J., Soranso, D. R., & Lima, R. C. A. (2022). Influência de fatores ergonômicos na produtividade do sistema homem-máquina na colheita florestal mecanizada [Influence of ergonomic factors on the productivity of the man-machine system in mechanized forest harvesting]. S*cientia Forestalis, 50*, e20. https://doi.org/10.18671/scifor.v50.20

Shadbahr, J., Bensebaa, F., & Ebadian, M. (2021). Impact of forest harvest intensity and transportation distance on biomass delivered costs within sustainable forest management: A case study in southeastern Canada. *Journal of Environmental Management, 284*, 112073. https://doi.org/10.1016/j.jenvman.2021.112073

Silva, A. A., Machado, C. C., Gomes, R. R. M., Schettini, B. L. S., Minette, L. J., Nunes, Í. L., & Villanova, P. H. (2022). Forest extraction management with the indicator of Overall Efficiency of Forest Machines (OEFM). *Revista Árvore, 46,* e000018. https://doi.org/10.1590/1806-908820220000018

Silva, A. A., Machado, C. C., Gomes, R. R. M., Schettini, B. L. S., Minette, L. J., Nunes, Í. L., & Villanova, P. H. (2023). Indicador eficiência global de máquinas florestais (EGMF) na gestão do corte florestal [Global efficiency indicator of forestry machines (EGMF) in forest felling management]. *Scientia Forestalis, 50,* e43. https://doi.org/10.18671/scifor.v50.43

Soranso, D. R., Minette, L. J., Lima, R. C. A., Schettino, S., Nascimento, G. S. P., Bermudes, W. L., & Campos, J. C. C. (2023). Biomechanical analysis of wood processing work in tropical forest regions: A study in Midwest Brazil. *Journal of Occupational and Environmental Hygiene, 20*(10), 452–459. https://doi.org/10.1080/15459624.2023.2241536

Soranso, D. R., Minette, L. J., Marçal, M., Marins, J. C. B., Schettino, S., Lima, R. C. A., & Oliveira, M. (2022). Thermography in ergonomic assessment: A study of wood processing industry workers. *PeerJ, 10*, e13973. https://doi.org/10.7717/peerj.13973

Suhartana, S., Yuniawati, Gandaseca, S., Dulsalam, Soenarno, & Ratnasingam, J. (2022). Potential of wood harvesting residues and residual stand damage due to timber harvesting: A case study at PT Austral Byna in Central Kalimantan, Indonesia. *International Journal of Forestry Research, 2022,* 3251945. https://doi.org/10.1155/2022/3251945