Revista
ÁRVORE
ISSN 1806 - 9088

Scientific Article

INFLUENCE OF HARVESTER AND FORWARDER OPERATOR EXPERIENCE ON FOREST HARVESTING ACTIVITIES IN NORTHEAST BRAZIL

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1 Received on 06.04.2024 accepted for publication on 14.08.2025. Editors: Carlos Moreira Miquelino Eleto Torres.
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ABSTRACT

The forestry sector has experienced continuous growth in investments and technological innovations, particularly in harvesting operations, which have been significantly enhanced by these advancements. In this context, the systematic monitoring of operator performance is an essential tool for assessing individual progress over time, based on the experience acquired in machine operation. This approach enables managers to track learning curves, plan targeted training actions, and promote the continuous improvement of operational efficiency. The objective of this study was to evaluate the productivity evolution of Harvester and Forwarder operators as a function of field experience in a forestry company in the southwestern region of the Maranhão state, Brazil. The average time consumption for performing operational cycles and their elements was assessed, correlating the time spent with experience duration and the average individual volumes of the harvested areas. A time and motion study was used to evaluate operators without prior experience. The time consumed in each element of the operational cycle and the effective working time for cutting and extraction operations were determined. In the Harvester cycle, the "Processing" element accounted for the highest percentage of time consumption, whereas in the Forwarder cycle, the "Loading" stage was the most time-consuming, regardless of the operators' level of experience. Correlation analysis showed that, for the Harvester, the average individual volumes of the harvested areas had a greater influence on the evolution of cycle time consumption than operator experience. Conversely, for the Forwarder, field experience showed a more significant correlation. The practical experience of operators showed a significant impact on productivity, with percentage gains of 71.0% for the Harvester and 84.6% for the Forwarder. These results demonstrate that the accumulation of operational experience is directly related to performance improvement, highlighting the importance of continuous monitoring of operator performance over time.

Keywords: Reforestation; Forestry operator learning; Forestry machinery

How to cite:
Teles, M. T. de A., Souza, A. P. de, Minette, L. J., Schettini, B. L. S., Silva, A. A., Lacerda, P. H. G. A., Resende, J. H. D., Silva, K. A. P., & Lima, C. F. (2025). Influence of Harvester and Forwarder operator experience on forest harvesting activities in northeast Brazil. *Revista Árvore, 49*(1). https://doi.org/10.53661/1806-9088202549263798

INFLUÊNCIA DA EXPERIÊNCIA DE OPERADORES DE HARVESTER E FORWARDER NAS ATIVIDADES DE COLHEITA FLORESTAL NO NORDESTE BRASILEIROS

RESUMO O setor florestal tem vivenciado uma constante expansão em investimentos e inovações tecnológicas, com destaque para a modernização das operações de colheita florestal, amplamente beneficiadas por esse avanço. Nesse contexto, o acompanhamento sistemático do desempenho dos operadores torna-se uma ferramenta essencial para avaliar a evolução individual ao longo do tempo, em função da experiência adquirida na operação. Essa prática permite aos gestores identificar o ritmo de aprendizagem, planejar ações de capacitação específicas e promover a melhoria contínua da eficiência operacional. O objetivo do estudo foi avaliar a evolução do rendimento dos operadores de Harvester e Forwarder, em função da experiência de campo, em uma empresa florestal do sudoeste do estado do Maranhão. Foi avaliado o consumo do tempo médio para a realização dos ciclos operacionais e seus elementos, correlacionando à evolução do tempo gasto com o tempo de experiência e os volumes médios individuais das áreas colhidas. O estudo de tempo e movimento foi utilizado para avaliação dos operadores sem experiência prévia. Foram determinados os tempos consumidos em cada elemento do ciclo operacional e o tempo de trabalho efetivo das operações de corte e extração. No ciclo do Harvester, o elemento “Processamento” foi o que consumiu maior percentual do tempo, enquanto no ciclo do Forwarder, o “Carregamento” representou a etapa mais demorada, independentemente do tempo de experiência dos operadores. A análise de correlação demonstrou que, para o Harvester, os volumes médios individuais das áreas colhidas obtiveram uma influência maior do que o tempo de experiência dos operadores sobre a evolução no consumo de tempo para realização do ciclo operacional. Ao contrário, para o Forwarder, o tempo de experiência em campo demonstrou uma correlação mais significativa. A experiência prática dos operadores demonstrou impacto significativo, com ganhos percentuais de 71,0% para o Harvester e 84,6% para o Forwarder. Esses resultados evidenciam que o acúmulo de experiência operacional está diretamente relacionado ao aprimoramento do desempenho, destacando a relevância do monitoramento contínuo da performance ao longo do tempo de operação.

Palavras-Chave: Reflorestamento; Aprendizado de operadores florestais; Máquinas florestais

1. INTRODUCTION

The Brazilian forestry sector encompasses more than 10.2 million hectares of commercial forest plantations and holds a significant position in the national economy, representing approximately 0.9% of the country’s GDP. It is responsible for producing 24.3 million tons of pulp and generating a gross revenue of R$ 202.6 billion in 2023 (Iba, 2024).

Such a magnitude of production results from the integration of advanced technologies, responsible forest management practices, and continuous improvements in the wood production chain, which collectively enable high productivity (Ferraz et al., 2024; Leonello et al., 2024; Lima et al., 2025a).

Among these processes, forest harvesting stands out, defined as a set of operations aimed at preparing and extracting timber to the transport location using established techniques and standards (Titus et al., 2021). This set of activities is highly complex, requires substantial investment, and plays a crucial role in supplying forest-based industries, particularly those producing pulp and paper. Therefore, forest harvesting operations are frequently the focus of studies that seek to identify the main factors affecting their performance and efficiency (Eufrade-Junior et al., 2020; Santos et al., 2020).

The mechanization of forest harvesting through high-performance machinery has been widely adopted to enhance efficiency and reduce costs (Lima et al., 2025a).

However, despite this extensive adoption, operational performance still varies significantly, primarily due to human factors arising from the human–machine system interaction, such as operator experience (Linhares et al., 2012; Schettino et al., 2022).

In Brazil, the main system used in the pulp industry is the cut-to-length method, in which the tree is processed at the harvest site by a Harvester and then extracted to the roadside by a Forwarder (Magagnotti et al., 2020). The productivity of these machines is a key indicator of operational efficiency, as it measures the volume harvested or transported per unit of effective working time. This indicator is widely employed by forest managers as a basis for strategic decision-making (Hakamada et al., 2022).

The Harvester, responsible for the felling stage, and the Forwarder, for timber extraction, have their performances influenced by multiple factors, such as stand characteristics, environmental conditions, technical specifications of the machines, operational organization, and human characteristics, particularly those of the operators (Schettino et al., 2022; Noordermeer et al., 2021). These factors highlight the complexity of the human–machine interaction in forest harvesting, which demands attention to operator qualification and training (Lima et al., 2019).

The relationship between practical experience and operational performance is a widely discussed topic across various productive sectors. In the forestry sector, this dynamic assumes specific characteristics due to the operational and technological complexity of harvesting activities.

Several international studies demonstrate that performance improvements are directly related to the time of use of forest machinery, the experience acquired by the operator over time, and the corresponding learning curve for the required operation (Björheden, 2001; Purfürst, 2010; Wenhold et al., 2019; Polowy et al., 2024). According to Purfürst (2010), novice Harvester operators double their operational performance over time, within approximately eight months of practice, starting from 50–60% of the average performance, with considerable individual variation. Forwarder operators, in turn, are more sensitive to the technical variations of the operation, with productivity influenced by structural variables such as the Mean Individual Volume of the stand and the machine's travel distance (Björheden, 2001; Belisario et al., 2022).

An important tool used in performance management during the learning process of forest machine operators is the study of experience gained in relation to operational performance (Glock et al., 2019; Lima et al., 2025b). The analysis of experience and operational performance is widely applied in sectors such as metallurgy, civil construction, and other industries involving human labor, contributing primarily to performance improvement in production processes and learning gains (Lee et al., 2024; Ferrari et al., 2025). Expanding its use to different industrial and service contexts, experience analysis enables performance monitoring in repetitive tasks, based on the principle that the time required to complete a task tends to decrease as learning occurs (Stroieke et al., 2012).

Currently, the use of learning tools in simulated virtual environments represents the main trend in technological advancement, as it enables accelerated, safe, and cost-effective training — particularly useful for operators of forest machines such as Harvesters and Forwarders (Polowy et al., 2024). Studies such as that of Lopes et al. (2008) demonstrated average productivity gains of approximately 41.3% in felling operations after training with a virtual reality simulator. Moreover, although interpersonal variability must be considered, the greatest operator development tends to occur after approximately 10 hours of experience in a virtual environment (Polowy et al., 2024).

Gaining experience allows for the analysis and scheduling of productive tasks, reducing losses resulting from worker inexperience during the initial production cycles, assigning tasks according to workers' performance characteristics, and monitoring costs associated with the learning process (Anzanello & Fogliatto, 2007). Furthermore, production efficiency analysis enables the assessment of the impact of experience time on operator performance, supporting decision-making regarding training and continuous improvement strategies across different sectors, including forestry (Stroieke et al., 2012; Glock et al., 2019; Lee et al., 2024; Ferrari et al., 2025).

Several authors state that there is a relationship between the experience time of forest machine operators and their operational performance (Anzanello & Fogliatto, 2007; Leonello et al., 2012; Glock et al., 2019). As operators accumulate experience, the time required to complete operational cycles decreases, resulting in significant efficiency gains and productivity increases (Leonello et al., 2012). This relationship is particularly relevant in the forestry sector, where productivity optimization is directly linked to cost reduction and increased operational efficiency.

However, little is known about the evolution of operational performance among forest machine operators under real working conditions in northeastern Brazil, particularly regarding the relationship between experience time, average harvested volume, and specific productivity gains throughout the learning period. Few studies assess performance improvement under actual field conditions, from the beginning of experience to operational stability. In the Brazilian context, studies conducted in the Northeast region report average operational efficiencies of 73% for Harvesters and 82% for Forwarders, based on time and motion analysis (Linhares et al., 2012). Nevertheless, there is still a lack of investigations directly relating operators' practical experience time, average harvested volume, and specific productivity gains under real field conditions.

Therefore, the present study aimed to evaluate the evolution of the performance of Harvester and Forwarder operators as a function of field experience time. This investigation seeks to provide concrete insights for operational management by quantifying productivity gains throughout the learning period, thereby enabling the definition of optimized strategies for personnel allocation, team sizing, training planning, and operational cost reduction, contributing to greater efficiency and sustainability of harvesting operations.

2. MATERIAL AND METHODS

2.1 Study area characterization

The study was conducted in a forestry company located in the southwestern region of the Maranhão state, Brazil (Figure 1). According to the Köppen climate classification, the region's climate is Aw, tropical hot and humid with a dry season. The average temperature ranges between 24°C and 25°C, and the mean annual precipitation is approximately 1,400 mm. The terrain is predominantly flat, with soils classified as Yellow Argisol, Red-Yellow Argisol, and Yellow Latosol, according to the Brazilian Soil Classification System (Embrapa, 2018).

The forest stands evaluated in this study were not homogeneous plantations; instead, they consisted of stands of different ages and Mean Individual Volumes (MIV), ranging from 0.23 to 0.76 cubic meters, according to pre-harvest inventory data.

2.2 Data collection and operator analysis

The machines used in this study operated under the cut-to-length forest harvesting system, in which the Harvester performs the felling operation. The model employed consisted of a Tigercat H845C base machine, equipped with a 194 kW engine and a tracked undercarriage system. The harvesting head was an SP Maskiner model 591 LX G2. The extraction process was performed using a Forwarder, specifically the Tigercat CB1075B model, equipped with a 205 kW engine, a tandem-wheel drive system, and a crane with a reach of 7.83 meters (Figure 2).

Data collection was carried out under real operational conditions, covering different work shifts and environmental situations. An observational design was adopted, involving systematic recording of operator performance over time. A total of ten Harvester operators and six Forwarder operators were randomly evaluated, corresponding to 18.5% and 33.3% of the company's total operators, respectively.

The 16 operators selected for the study had successfully completed the company's theoretical and practical selection and training process, had no previous experience with forest machinery, and exhibited a homogeneous profile in terms of age —

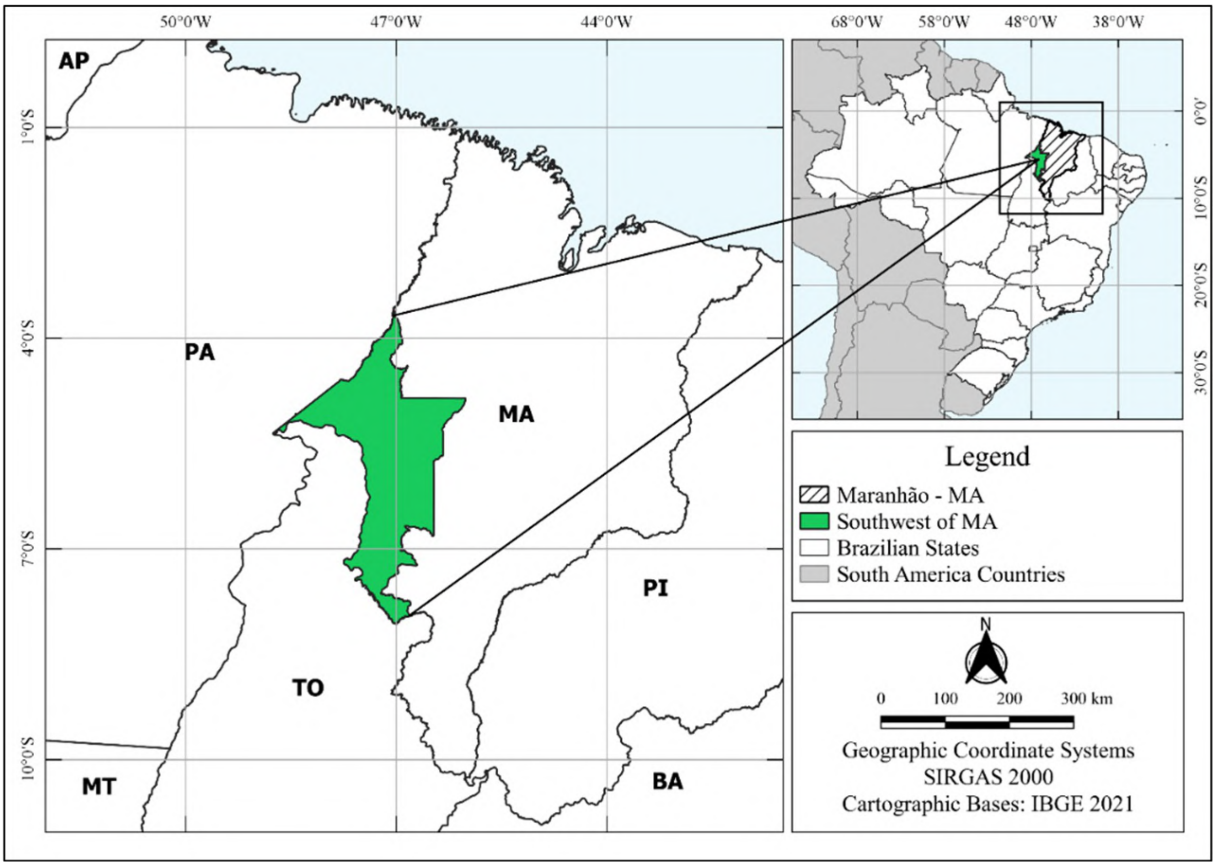

Figure 1. Location of the stands where operational data were collected, in the Maranhão state
Figura 1. Localização dos talhões onde foram coletados os dados da operação, no estado do Maranhão

Figure 2. Forest harvesting machines used in the study: Harvester (A) and Forwarder (B)
Figura 2. Máquinas de colheita florestal utilizadas no estudo, Harvester (A) e Forwarder (B)

averaging 26.5 years, ranging from 22 to 31 years — and educational background (all had completed high school).

To quantify operational times, a time and motion study was conducted using the continuous timing method, with a maximum sampling error of 5%, following the criteria described by Barnes (2001). Data collection was performed using a digital stopwatch in thousandth mode and specific data sheets. The duration of each element within the operational cycle was recorded, allowing subsequent statistical analysis of operational performance and operator experience.

The operational cycle elements considered in this study for the Harvester were as follows: felling – from the boom movement toward the tree to be felled until the activation of the feed rollers; processing – from the activation of the rollers, causing the tree to slide through the harvester head, until the completion of delimbing, debarking, and bucking; traveling – from the beginning to the end of the machine's movement along the working trail; and operational interruptions – including stump leveling, cleaning, and stops.

For the Forwarder, the analyzed operational cycle elements were: travel without load – from movement at the roadside to the first pile to be loaded and the crane being removed from the load bunk; loading – from the beginning of crane movement until the bunk is completely filled; travel with load – from the crane repositioning on the bunk until arrival at the roadside; unloading – from the beginning of crane movement to pick up the first log bundle until the crane is repositioned on the bunk; and operational interruptions – including maneuvers along the skid trail, log stacking to continue pile formation, adjusting logs in the pile after unloading, collecting fallen logs along the trail, and stops.

2.3 Correlation analysis

The correlation analysis was conducted to assess the relationship between operator experience time and their effective operational performance. For this purpose, the Pearson correlation coefficient (r) was used, applying a 1% significance level, following the methodology described by Furtado Lima et al. (2024). The variables Mean Individual Volume (MIV) classes and operator experience were compared with the time spent by the forest machines during operation.

The database used comprised a total of 4045 cycles (161 for the Forwarder and 3884 for the Harvester). However, additional data collections were conducted depending on the company's availability during the study period, distributed among the evaluated operators. Operational times were recorded through a time and motion study and subsequently analyzed statistically. The variability of the recorded times was verified using dispersion measures, ensuring data representativeness for the analysis.

The Pearson correlation coefficient measures the intensity and direction of the linear relationship between two variables, assuming values between -1 and +1. When $r > 0$, it indicates a positive correlation, meaning that as X increases, Y also increases. When $r < 0$, it indicates a negative correlation, meaning that X increases while Y decreases. The magnitude of the coefficient defines the strength of the association, with values close to ±1 indicating a strong correlation and values near 0 indicating a weak or nonexistent linear association (Bussab & Morettin, 2004). The interpretations attributed to the respective correlation values are defined as follows:

2.4 Evaluation of operator experience and operational performance

To assess the experience acquired by the operators, their effective performance was analyzed at three specific four-month intervals: 4, 8, and 12 months of experience. These development points were selected based on the company's standard model, which considers these periods as milestones in the technical development of the operators.

This approach calculates the Effective Productivity (EP) of each machine, expressed in cubic meters (m^3) per effective operational

Table 1. Correlation coefficients and their interpretation
Tabela 1. Valores de correlação e como devem ser interpretados

Correlation Value (+ or -)	Interpretation
(0.00 a 0.19]	Very weak correlation
(0.20 a 0.39]	Weak correlation
(0.40 a 0.69]	Moderate correlation
(0.70 a 0.89]	Strong correlation
(0.90 a 1.00]	Very strong correlation

hour, allowing comparison between the operators' actual performance and the reference values established by the company for each phase of the learning process. For example, in a stand with a Mean Individual Volume (MIV) class of 0.27 m³, the expected productivity for the Harvester and Forwarder was 26.68 and 53.13 m³ per hour, respectively. It is observed that, as the MIV class of the forest increases, the expected productivity of both machines also tends to rise, since the work becomes operationally more efficient.

2.4.1 Harvester

Effective productivity was calculated using the following data: Mean Individual Volume (MIVwb) without bark in cubic meters, obtained from the company's pre-harvest inventory; the number of trees processed; and the effective working time in hours, determined from the time and motion study. Therefore, the total number of cycles required to process the trees during the considered period is expressed by the following equation:

$$EP = \frac{VMI_{sc}(m^3) * N}{he} \quad \text{(Eq.1)}$$

Where: EP = Effective Productivity (m³ he⁻¹); MIVwb = Mean Individual Volume without bark, in m³; N = Number of cycles performed, determined by the number of trees processed; he = Effective working hours (total time minus operational interruptions, machine downtime).

2.4.2 Forwarder

Effective productivity was calculated considering the load bunk volume in cubic meters (m³), the number of cycles (or trips) performed, and the effective working time in hours, according to the following equation:

$$EP = \frac{LB(m^3) * N}{he} \quad \text{(Eq. 2)}$$

Where: EP = Effective Productivity (m³ he⁻¹); LB = Load bunk volume, in m³; N = Number of cycles performed, determined by complete loading and unloading trips; he = Effective working hours (total time minus operational interruptions, machine downtime).

2.5 Study of operator operational performance

To assess operational performance and standardize the data for comparison over time, the company's reference table of desired productivity was used. This table related the Mean Individual Volume (MIV) of the stand to the operator's expected performance targets for that volume. Accordingly, the data were expressed as percentages relative to the values expected by the company.

Graphs for each operator scenario were generated based on field observations and subsequently compared to the performance targets established for Harvester and Forwarder operators by the company during the first 12-month learning cycle. The graphs were constructed showing the difference, in percentage points, between the operators' effective and expected performance.

3. RESULTS

The analysis of the operational performance of Harvester and Forwarder machines considered operator experience time and the Mean Individual Volume (MIV) classes of the harvested areas. The analyzed data allowed evaluation of the evolution of time spent on operational cycle activities, as well as the influence of operator learning over the first 12 months in the field. Additionally, correlations between experience time, cycle time, and MIV were analyzed to understand how these factors affect the efficiency of mechanized forestry operations.

3.1 Evolution of time spent by operators

For the Harvester, processing was the cycle element consuming the largest portion of total cycle time, regardless of operator experience. Felling was the second most time-consuming element, followed by traveling (Figure 3A). For the Forwarder, loading consumed the largest portion of the cycle time, also independently of operator experience, followed by unloading (Figure 3B).

To analyze the relationship between both machines, the evolution of cycle time, operator field experience, and MIV classes of the harvested stands were examined. An inversely proportional relationship was

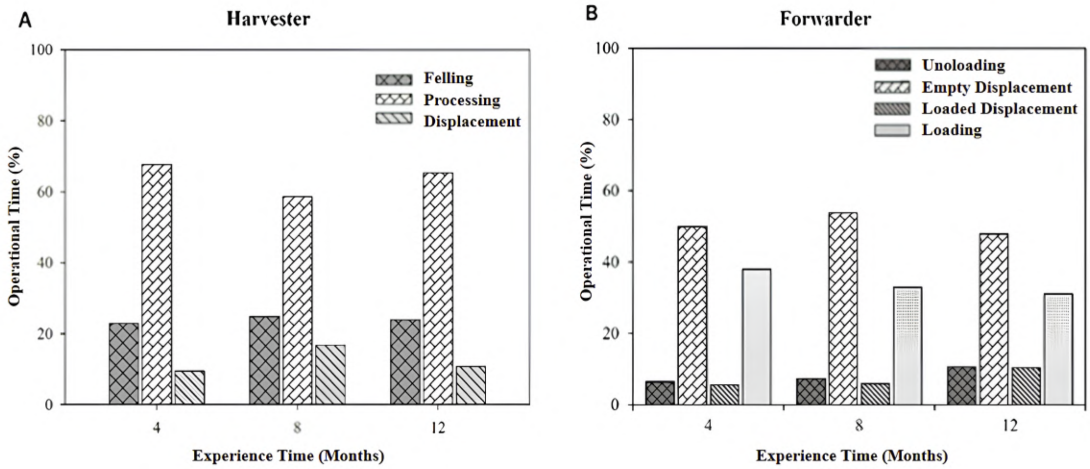

Figure 3. Time consumed for all operational stages for the Harvester (A) and Forwarder (B)
Figura 3. Tempo consumido para todas as etapas para o Harvester (A) e Forwarder (B)

observed between operator experience and total cycle time as well as the duration of each activity. This finding suggests that as operators gain experience, they tend to perform tasks with greater speed and efficiency.

Regarding the Mean Individual Volume (MIV) classes, a directly proportional correlation was observed between MIV and Harvester cycle time, whereas for the Forwarder, this relationship was inversely proportional. This behavior indicates that as the MIV class of the stands increases — reflecting more productive forests — the Harvester operations become more efficient, with reduced time required for tree processing. In contrast, for the Forwarder, the influence of MIV on cycle time was classified as "very weak," suggesting low sensitivity of this machine to variations in forest productivity. Nevertheless, further studies exploring different MIV levels and operational strategies are recommended to deepen the understanding of how these factors influence wood extraction and transportation dynamics.

An inversely proportional correlation was found for the Harvester between the evolution of total cycle time and operator experience; that is, as experience increased, the time required to complete the cycle decreased. However, this correlation was moderate (-0.418). Conversely, Mean Individual Volumes showed a strong and directly proportional correlation (0.868) with the evolution of time spent.

For the Forwarder, increased experience presented a very strong negative correlation (-0.911) with the total time required to complete the cycle, indicating that as operator experience increased, cycle time decreased.

3.2 Analysis of operator performance

For both machines, Harvester and Forwarder, operator operational capacity during the first learning cycle (12 months) showed a linearly inversely proportional correlation with experience time, indicating that as operators accumulated field experience, they performed tasks with greater speed and efficiency. However, a conservative approach is recommended at the beginning of field operations, as operators tend to exhibit lower operational performance during the first two months. In this initial period, observed results remained below the maximum expected potential due to the adaptation process to task requirements, machine handling, and familiarization with specific field conditions.

In this context, operator performance relative to the company's established targets evolved as follows: for the Harvester, from 69.43% at 4 months to 89.10% at 12 months; and for the Forwarder, from 74.27% at 4 months to 98.30% at 12 months (Figure 4). It is important to note that forest productivity characteristics varied throughout the first operator training and monitoring cycle, covering the 12 months analyzed in this

Table 2. Pearson correlation analysis between the evolution of machine cycle time, operator field experience, and the Mean Individual Volume (MIV) classes of the harvested stands
Tabela 2. Análise da correlação de Pearson entre a evolução do tempo de ciclo das máquinas, o tempo de experiência dos operadores em campo e as classes de Volume Médio Individual (MIV) dos talhões colhidos

	Harvester Time		
	Total	**Processing**	**Felling**
Operator Experience	-0.418 Inversely proportional, Moderate	-0.450 Directly proportional, Moderate	-0.390 Inversely proportional, Weak
MIV Class	+0.868 Directly proportional, Strong	+0.920 Directly proportional, Very Strong	+0.860 Directly proportional, Strong
	Forwarder Time		
	Total	**Loading**	**Unloading**
Operator Experience	-0.911 Inversely proportional, Very Strong	-0.850 Inversely proportional, Strong	-0.949 Inversely proportional, Very Strong
M Mean Individual Volume V Class	-0.086 Inversely proportional, Very Weak	-0.244 Inversely proportional, Weak	0.119 Directly proportional, Very Weak

Note: Operator Experience (Months); MIV Class (m³); Time (Minutes)
Nota: Experiência do Operador (Meses); Classe Volume Médio Individual (MIV) (m3); Tempo (minutos)

study. At 4 months, the MIV class of the stands was 0.65 m³; at 8 months, 0.19 m³; and at 12 months, 0.31 m³.

4. DISCUSSION

The process of knowledge acquisition has been extensively studied, particularly in repetitive tasks such as those in the forestry sector (Campbell & Bergelson, 2022; Wenhold et al., 2019). The analysis of experience acquired by operators constitutes a strategic tool for monitoring operational performance, allowing the assessment of individual development over time and the identification of learning patterns. This approach significantly contributes to the

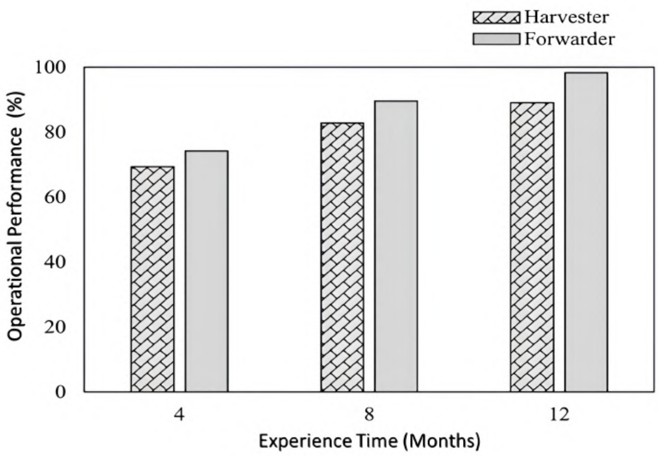

Figure 4. Relationship between operational performance (%) and operator experience for Harvester and Forwarder during the first training cycle (12 months) – Operational performance in relation to operator experience for Harvester and Forwarder
Figura 4. Relação entre o desempenho operacional (%) e o tempo experiência dos operadores de Harvester e Forwarder durante o primeiro ciclo de treinamento (12 meses) – Desempenho operacional em relação à experiência dos operadores de Harvester e Forwarder

optimization of forestry activities, particularly by enabling the reduction of productivity losses, increasing efficiency, and correcting deviations resulting from lack of practical knowledge or inadequate prior training.

The analysis indicates that for the Harvester, operational time remained practically constant, even with the significant reduction in Mean Individual Volume (MIV) class from 0.65 to 0.31 cubic meters. This result suggests that forest productivity — represented by the MIV class — had a more relevant impact on cycle time than the experience accumulated by the operators. This finding is consistent with recent studies.

For example, Stadler et al. (2022) evaluated the impact of MIV in Pinus taeda plantations and concluded that, although the total felling and processing cycle time does not change substantially between different volume classes, specific cycle elements — such as processing — vary significantly, reflecting productivity differences from 36.8 to 74.1 cubic meters per hour depending on the individual tree volume. Similarly, Rodrigues et al. (2019) reported that forest MIV has a strong correlation with Harvester processing time, with classes ranging from 1.21 to 1.61 cubic meters per tree showing a significant increase in machine operational performance.

This result is further supported by the statistical analysis presented in Table 2, which revealed a strong and directly proportional correlation between MIV class and Harvester cycle time. In contrast, for Forwarder cycle time, MIV showed a weak and inversely proportional correlation, indicating that other logistical factors — such as extraction distance, route efficiency, and average travel speed — tend to have a more significant influence on machine performance (Minette et al., 2004; Nurminen et al., 2006).

Although the time required to complete the Harvester cycle elements did not show a significant decrease with increasing operator experience, this may be attributed to variations in the MIV of the stands during data collection. As noted, the strongest correlation was with the MIV of the harvested stands, highlighting that this factor had a more pronounced impact on time consumption than the accumulation of operator experience.

Operator experience demonstrated a significant impact on performance, with percentage gains for Harvester operators (71.0%) and Forwarder operators (84.6%) exceeding those reported in previous studies. It was observed that for the Harvester, more experienced operators performed 23.6% better than novices (Maline et al., 2018). This increase is noteworthy, especially when compared to studies involving virtual reality simulator training, such as Lopes et al. (2008), which reported a 41.3% gain after 14 months of training. This suggests that, although virtual training is beneficial, real-field gains tend to be more substantial, possibly due to factors such as adaptation to the real environment and the complexity of actual operations.

The analysis in this study confirms that MIV class exerts a substantial influence on Harvester operational performance, even more so than the increase in operator experience over 12 months. These results align with the study by Schwegman et al. (2023), which evaluated nine operators in Eucalyptus plantations and found that approximately 40% of the variation in cycle time was attributable to individual performance, while around 25% was explained by differences in the MIV of the harvested trees. Thus, even under training conditions, the average tree size directly affects processing time, reinforcing the notion that silvicultural factors can play a significant role in machine productivity.

The evolution of operational performance with experience is greatest during the initial months on the job, as evidenced in this study. However, according to the literature, it is important to note that this expected potential tends to decrease over the years (Leonello et al., 2012). Monitoring observed and expected parameters determines the operation’s performance. Additionally, potential points for improvement can be identified through questionnaires applied to machine operators (Kymäläinen et al., 2021).

According to Pagnussat et al. (2020), operator productivity grows rapidly until the sixth month but tends to stabilize afterward, while machine availability may vary. Similarly, the study by Lima et al. (2025) with forestry machines highlighted that, beyond operator experience, variables such as tree density, MIV, topography, and soil characteristics significantly influence productivity and operational costs. This suggests that after the initial learning phase, factors such as stand volume distribution and operational mechanics become decisive. Our results corroborate this interaction between operator experience and forest characteristics, with MIV emerging as a predominant factor in Harvester performance throughout the 12-month operational cycle.

In summary, the results of this study demonstrate that although operator experience significantly contributes to improved operational performance — particularly during the initial months — the Mean Individual Volume (MIV) class proved to be the most determinant factor for Harvester productivity over the 12-month cycle. In the case of the Forwarder, further studies are needed to understand the low influence of MIV on cycle time, suggesting that logistical factors — such as extraction distance, route layout, and average travel speed — exert a greater impact on its productivity.

Thus, the need for integrated management approaches is reinforced, combining the enhancement of operator training with technical-operational planning of wood harvesting and extraction operations.

5. CONCLUSION

Operator experience influences the productivity of forestry machines, but the impacts differ between Harvester and Forwarder. For the Harvester, MIV was the main factor affecting operational cycle time, surpassing the influence of experience. For the Forwarder, variables such as extraction distance and terrain conditions had greater influence, highlighting the importance of logistical planning.

The most critical stages of the cycles were tree processing for the Harvester and log loading for the Forwarder, indicating the need for machine-specific optimization strategies.

After 12 months, operators had not yet fully achieved performance targets, emphasizing the importance of continuous training and performance monitoring.

This study demonstrates that efficiency in mechanized forestry operations depends on the integration of operator training and adaptation to working environment conditions. Future research should investigate the evolution of operator performance over periods longer than 12 months to more accurately understand the limits and potential for continuous improvement.

6. ACKNOWLEDGEMENTS

The authors would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, and by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais – FAPEMIG.

AUTHOR CONTRIBUTIONS

M.T.A.T.; A.P.S.; L.J.M.; B.L.S.S.; A.A.S.; C.F.L.: Conceptualization, Methodology, Project Administration, Writing – Original Draft. P.H.G.A.L.; J.H.D.R.; K.A.P.S; C.F.L.: Writing – Review & Editing, Supervision.

DATA AVAILABILITY

The entire dataset supporting the findings of this study has been published within the article.

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