

EFFECT OF WORKING RANGE ON PRODUCTIVITY AND COSTS OF HARVESTING MACHINES IN A EUCALYPTUS STAND

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Resumo

Efeito da faixa de trabalho na produtividade e custos de máquinas de colheita em povoamento de Eucalyptus. A colheita de madeira deve ser planejada para reduzir os impactos ambientais com minimização do tráfego de máquinas, aumento de produtividade e redução dos custos. Nesse contexto, objetivou-se avaliar o efeito da largura da faixa de trabalho sobre o desempenho operacional do *harvester* e *forwarder* em povoamento de *Eucalyptus saligna* sob corte raso. O estudo foi realizado no Paraná, Brasil, em um sistema de toras curtas nas operações de corte e extração de madeira em duas faixas de trabalho: T₁ - largura de 12 m com corte de quatro linhas de plantio; e T₂ - largura de 18 m com cortes de seis linhas de plantio. Um estudo de tempos e movimentos foi realizado para determinar tempos de ciclos de trabalho, produtividade e custos, bem como a trafegabilidade das máquinas, sendo as faixas de trabalho comparadas pelo teste t ($\alpha = 0,05$) para amostras independentes. Os resultados mostraram que os elementos processamento e carregamento consumiram o maior tempo do ciclo no corte e extração de madeira. O *harvester* apresentou maior produtividade ($61.05 \text{ m}^3 \text{ PMH}_0^{-1}$) na faixa de trabalho T₁, enquanto o *forwarder* foi maior ($48.32 \text{ m}^3 \text{ PMH}_0^{-1}$) na faixa de trabalho T₂. Quanto ao sistema, observou-se que T₂ permitiu redução de 1% no custo de produção, sendo importante quando considerada a larga escala de produção da empresa, enquanto houve uma redução de 33,4% na trafegabilidade. Portanto, o aumento na largura da faixa de trabalho poderá proporcionar benefícios operacionais e ambientais nas operações de colheita de madeira em florestas plantadas.

Palavras-chave: Planejamento operacional; sustentabilidade; colheita de madeira.

Abstract

Wood harvesting should be planned to reduce environmental impacts by minimizing machine traffic, increase productivity and reduce costs. In this context, the aim of this study was evaluate the effect of working range on operational performance of a harvester and forwarder in a *Eucalyptus saligna* stand under a clear cutting regime. The study was carried out in Paraná State, Brazil, in a cut-to-length system in cutting and wood extraction operations in two working ranges: T₁ - width of 12 m with a cut of four planting lines; and T₂ - width of 18 m with a cut of six planting lines. A time and motion study was performed to determine work cycle times, productivity, production costs, and machine traffic, with working ranges compared by the t-test ($\alpha = 0.05$) for independent samples. The results showed that the wood processing and loading elements consumed the longest operating cycle time in cutting and wood extraction. The harvester machine presented higher productivity ($61.05 \text{ m}^3 \text{ PMH}_0^{-1}$) in the T₁ working range, while the forwarder was superior ($48.32 \text{ m}^3 \text{ PMH}_0^{-1}$) in the T₂ working range. Regarding the wood harvesting system, it was observed that the T₂ working range enabled a reduction of 1% in production costs, which is important when considering the large scale production of the company, while there was a 33.4% reduction in traffic. Therefore, an increase in machines' working range can provide operational and environmental benefits to wood harvesting operations in forest plantations.

Keywords: Operational planning; sustainability; wood harvesting.

INTRODUCTION

The Brazilian planted tree sector has significantly contributed to social, economic, and environmental development of the country through 3.7 million direct and indirect employment contracts, 6.2% of the Gross Domestic Product (GDP), and natural forest preservation, occupying approximately 1% of the national territory (IBÁ, 2017). Among the production cycle stages, wood harvesting and transportation represent the highest final wood costs (TIERNAN *et al.*, 2007; HOLZLEITNER *et al.*, 2011). Therefore, planning studies are important to carry out harvesting operations with high productivity, quality, safety, and sustainability.

There are two predominant wood harvesting systems in *Eucalyptus* stands in Brazil: cut to length and full tree (MACHADO *et al.*, 2014). The first system is characterized by tree felling and processing, followed by log

extraction to the field edge; and the second one is characterized by tree cutting and stacking, followed by dragging to the field edge for wood processing.

Cut-to-length wood harvesting systems can be composed by a harvester and forwarder for wood cutting and extraction execution, respectively (MACHADO *et al.*, 2014). Machines typically move inside fields by cutting systematic tree lines and using the same traffic trails which can lead to variability in soil compaction in the fields, along with greater intensity in places close to roads (RODRIGUES *et al.*, 2015). In this context, one way for minimizing environmental impacts on the soil in wood harvest operation would be to reduce machines' traffic inside the forest stands (NIEMI *et al.*, 2017).

In addition, technological development in wood harvesting machines with greater stability and crane reach can enable cutting tree lines with greater width from the same machine position (SHEN *et al.*, 2017). Greater working range width in forest stands has the potential to reduce machine traffic on the ground, with consequent reductions in environmental impacts and increases in forest production sustainability (LINDROOS *et al.*, 2008).

In this respect, it was hypothesized that harvester productivity would be at its maximum when it operated at a lower working range width, whereas the productivity for the forwarder would be higher in the lesser working range due to the greater amount of wood stacked. Furthermore, the effects of operational modifications on productivity and the system production costs (harvester + forwarder) are unknown, and investigations must be carried out to enable better decision-making by forest managers.

In view of the above, the aim of this study was to evaluate the working range effect on productivity and cost of harvesting machines in a *Eucalyptus* sp. stand, aiming to improve harvesting operation planning, to reduce environmental impacts and increase forest production sustainability.

MATERIAL AND METHODS

This study was carried out in operational areas located in Paraná State, Brazil, at the coordinates 23°33'04" S and 50°33'13" W. The region's climate is characterized as wet temperate (Cfa) according to the Köppen-Geiger classification, with average temperatures of 22 °C and 18 °C in hot and cold months, respectively (ALVARES *et al.*, 2013). The measurements were taken in the shift from 7 a.m. to 4 p.m. in October, with no influence from climatic variables.

The experiment was carried out in a *Eucalyptus saligna* Smith stand implanted in 3 m x 2 m spacing under a clear cutting system. The statistical population was evaluated at 10 years old in areas with homogeneous soil, relief and site characteristics, presenting mean tree variables of: 43 cm of diameter at 1.3 m; 23 m of total height; and 0.42 m³ whole stem individual volume. The cut-to-length wood harvesting system was evaluated and composed by a harvester for tree cutting and a forwarder to perform pulpwood extraction with 7.2 m length (Figure 1).



Figure 1. Machines evaluated in this study. (a) harvester; and (b) forwarder. Source: authors.
Figura 1. Maquinas avaliadas neste estudo. (a) harvester; e (b) forwarder. Fonte: Os autores.

The harvester was composed of a base machine with 205 kW engine power; eight-wheel drive, stated as 8WD; 21.5 t operating weight; 8,973.0 hours average equipment life-cycle; 18 t operating weight; and 11 m maximum crane reach. The forwarder was composed of a base machine with 205 kW engine power; eight-wheel drive, stated as 8WD; 23.7 t operating weight; 9,734.8 hours average equipment life-cycle; 18 t load capacity; and 9.5 m maximum crane reach, with this machine being evaluated to the distance of 410 m of the road.

Two working ranges (treatments) were studied in the wood harvesting, as shown in Figure 2: 12 m working range with cutting of four planting lines - T1; and 18 m working range with cutting of six planting lines - T2.

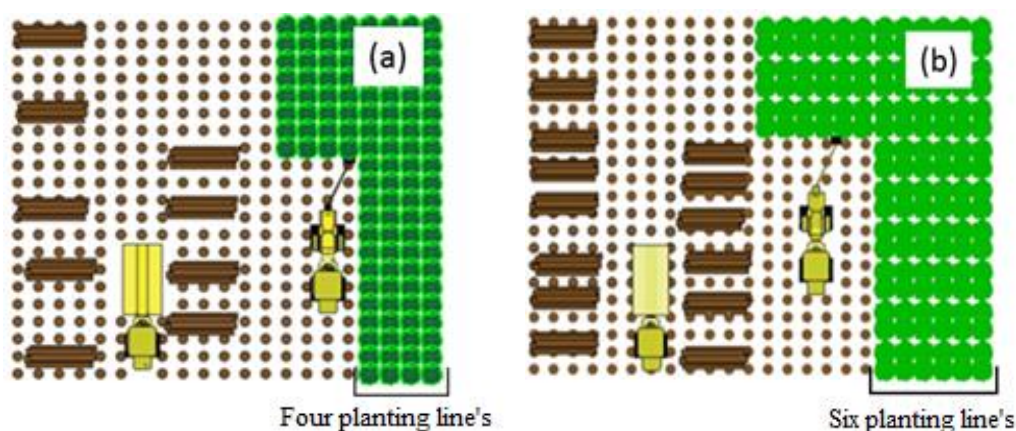


Figure 2. Working ranges evaluated in the wood harvesting; (a) width of 12 m with cutting of four planting lines; and (b) width of 18 m with cutting of six planting lines. Source: authors.

Figura 2. Faixas de trabalho avaliadas na colheita de madeira; (a) largura de 12 m com corte de quatro linhas de plantio; e (b) largura de 18 m com corte de seis linhas de plantio. Fonte: Os autores.

A time and motion study of wood cutting and extraction operations was carried out using a continuous timing method. The sampling procedure was defined by a pilot study to define the minimum number of working cycles, according to the methodology proposed by Barnes (1977), providing 5% maximum sampling error. The number of operational cycles evaluated in the T₁ and T₂ working ranges for the harvester was 1,150 and 1,092, respectively, with 87 and 104 cycles being required; while 33 and 58 cycles were evaluated for the forwarder, respectively, with 26 and 48 cycles being required. Moreover, two operators were evaluated with a single operator for each machine. These operators had 10 years of experience. The machines' working cycles in both working range treatments were subdivided into partial elements, as shown in Table 1.

Table 1. Description of the partial working cycle elements for the harvester and forwarder.
Tabela 1. Descrição dos elementos parciais dos ciclos de trabalho do harvester e do forwarder.

Machine	Partial elements	Description
<i>Harvester</i>	Displacement and Search (DS)	Time between machine motion between trees and searching for the tree to be felled.
	Cutting (C)	Time between saber activation for felling execution, ending with trees separated from the stump.
	Processing (PR)	Time between head drive to perform tree processing, ending with wood stacking.
	Interruptions (I)	Time the machine did not perform any of the previous activities.
<i>Forwarder</i>	Empty Trip (ET)	Time between starting the machine shift from the edge of the stand to the first log pile to be loaded inside the stand.
	Loading (L)	Time between initial crane motion to load the logs and final grapple positioning in the machine's bunker.
	Loaded Trip (LT)	Time between grapple positioning in the bunker and machine positioning beside log piles located on the stand edge.
	Unloading (U)	Time between the initial crane motion for log unloading and grapple positioning in the empty bunker, including necessary maneuvers to start the next cycle.
	Interruptions (I)	Time the machine did not perform any of the previous activities.

Machine utilization (Util%) refers to the portion of workplace time when a machine was used to conduct the intended function of the machine, being determined by equation (1). It should be noted that the interruption data of both evaluated treatments were grouped in order to calculate Util%. This is due to the inexistence of the treatments' influence on interruptions during the study.

$$\text{Util\%} = \frac{\text{PMH}}{\text{SMH}} \times 100 \quad (1)$$

In which: Util% = Machine utilization (%) = productive machine hours (hours); and SMH = scheduled machine hours (hours).

Productivity (PPMH_0^{-1}) was determined in wood cubic meters per effective working time (hours) by multiplying the number of cut trees or logs extracted by the average tree or log scaling volume through the Smalian method, and divided by the productive machine hours without delay time, according to equation (2) as proposed by Simões and Fenner (2010a).

$$\text{PPMH}_0^{-1} = \frac{N \times v_i}{\text{PMH}_0^{-1}} \quad (2)$$

In which: PPMH_0^{-1} = productivity ($\text{m}^3 \text{PMH}_0^{-1}$); N = number of operational cycles evaluated; v_i = tree volume for harvester or log volume for forwarder (m^3); and PMH_0 = productive machine hours.

Operational cost was determined by the methods proposed by Miyata (1980), considering fixed costs (depreciation, interest, and insurance), variable costs (fuels, lubricants, grease, hydraulic oil, tires, maintenance, repairs, and transportation of personnel), and personnel costs (salary and social benefits). An interest rate of 12% per year was considered for the calculations. The operational cost data was provided by the company and obtained by the historical data of the last six months.

The production cost was obtained by the ratio of operating costs and the machines' productivity, according to equation (3).

$$\text{PC} = \frac{\text{OC}}{\text{PPMH}_0^{-1}} \quad (3)$$

In which: PC = production cost ($\text{US\$ m}^{-3}$); OC = operating cost ($\text{US\$ PMH}_0^{-1}$); and PPMH_0^{-1} = productivity ($\text{m}^3 \text{PMH}_0^{-1}$).

Traffic was represented by the number of cutting ranges in one hectare and calculated for each operational procedure, according to equation (4).

$$\text{TR} = \frac{A}{L \times C} \quad (4)$$

In which: TR = traffic; A = area corresponded to one hectare ($10,000 \text{ m}^2$); L = width of working range (m); and C = length of working range (100 m).

The mean values for both working ranges (treatments) were compared using the Wilcoxon-Mann-Whitney test ($\alpha = 0.05$) for independent samples, in which the replicates were the operational cycles evaluated for both the elements of the operational cycles, productivity and production costs. The variance homogeneity was evaluated by the Levene test ($\alpha = 0.05$), while the Kolmogorov-Smirnov test ($\alpha = 0.05$) was used to verify absence of normality, even after data analysis.

RESULTS

The results show the working range effect of the harvester's working cycle (Table 2). The total absolute values of the working cycles were 26.6 and 27.6 seconds in the T₁ and T₂ working ranges, respectively, with significant statistical difference ($\alpha = 0.05$). This statistical difference in total time was directly influenced by the displacement and search time. In relation to the forwarder, the total average times of the working cycles were 1,721.6 and 1,553.1 seconds in the T₁ and T₂ working ranges, respectively, using a statistically significant difference ($\alpha = 0.05$).

There was a slight reduction in loading and unloading times in the T₂ working range (Table 3), explained by the higher wood volume piles along the working range. The distance between the woodpiles was the highest in the T₁ working range, and consequently the machine's time consumed in displacement and wood loading were increased, with a statistical difference between the working ranges ($\alpha = 0.05$). In addition, there was a significant statistical difference between the load volumes of the forwarder between the evaluated treatments.

Table 2. Average times of partial elements by the harvester operating cycle evaluated in the T₁ and T₂ working ranges.

Tabela 2. Tempos médios dos elementos parciais do ciclo operacional do harvester avaliado na faixa de trabalho T₁ e T₂.

Treatments	Partial elements			Total (seconds)
	DS (seconds)	C (seconds)	PR (seconds)	
T ₁	7.3	3.8	15.5	26.6
T ₂	7.8	3.8	16.0	27.6
p-value	0.002	0.082	0.055	0.004

In which: Displacement and Search (DS); Cutting (C); and Processing (PR); T₁ = working range with width of 12 m and cutting of four planting lines; and T₂ = working range with width of 18 m and cutting of six planting lines.

Table 3. Average times of partial elements by forwarder operating cycle in the treatments T₁ and T₂.

Tabela 3. Tempos médios dos elementos parciais do ciclo operacional do forwarder nos tratamentos T₁ e T₂.

Treatments	Partial elements				Total (seconds)	Volume (m ³ .cycle ⁻¹)
	ET (seconds)	L (seconds)	LT (seconds)	U (seconds)		
T ₁	202.0	816.7	222.5	480.4	1,721.6	21.15
T ₂	190.5	694.2	243.9	424.5	1,553.1	20.41
p-value	0.579	5.21x10 ⁻⁶	0.612	2.00x10 ⁻⁴	2.00x10 ⁻⁴	0.046

In which: Empty Trip (ET); Loading (L); Loaded Trip (LT); and Unloading (U); T₁ = working range with width of 12 m and cutting of four planting lines; and T₂ = working range with width of 18 m and cutting of six planting lines.

Table 4 shows the machine utilization, productivity, and production costs of machines in wood harvesting in both evaluated working ranges. The results show that the machine utilization was low for both evaluated machines, and could compromise the machines' production.

Table 4. Machine utilization, productivity, and production costs in the T₁ and T₂ treatments.

Tabela 4. Utilização da máquina, produtividade e custos de produção nos tratamentos T₁ e T₂.

<i>Harvester</i>			
Procedure	Util(%)	PPMH ₀₋₁ ⁻¹ (m ³ PMH ₀₋₁ ⁻¹)	PC (US\$ m ⁻³)
T ₁	55.1	61.05 ± 13,51	0.95 ± 0.23
T ₂		59.30 ± 13,72	0.99 ± 0.26
p-value	-	0.004	0.004
<i>Forwarder</i>			
Procedure	Util(%)	PPMH ₀₋₁ ⁻¹ (m ³ PMH ₀₋₁ ⁻¹)	PC (US\$ m ⁻³)
T ₁	64.5	44.66 ± 6.69	1.04 ± 0.21
T ₂		48.32 ± 9.82	0.98 ± 0.25
p-value	-	0.057	0.252

In which: Util% = Machine utilization; PPMH₀₋₁⁻¹ = productivity; PC = production cost; T₁ = working range with width of 12 m and cutting of four planting lines; and T₂ = working range with width of 18 m and cutting of six planting lines.

The harvester presented the highest average productivity (61.05 m³ PMH₀₋₁⁻¹) in the T₁ working range, while the forwarder was higher (48.32 m³ PMH₀₋₁⁻¹) in the T₂ working range. These results were directly associated with production costs, especially the forwarder which presented a statistical difference between the working ranges ($\alpha = 0.05$).

The production costs of the wood harvesting system were US\$ 1.99 m⁻³ and US\$ 1.97 m⁻³, respectively in the T₁ and T₂ working ranges. Therefore, the increase in working range (T₂) contributed to reduce the wood production costs to the order of US\$ 0.02 m⁻³ or 1%. However, it should be noted that the T₂ working range showed a reduction of 33.4% in the machine's traffic in order to mitigate environmental impacts to the ground.

DISCUSSION

The time and motion study showed that the times consumed in the partial displacement and search elements presented a statistically significant difference between the T₁ and T₂ treatments, with a longer time consumed in the T₂ treatment with greater width of the working range due to the necessity of stretching the crane machine to search for the most distant trees.

The partial wood processing element consumed the longest time of the harvester's working cycles due to the need to carry out several activities including: removing branches, tracking, and stacking wood. These results corroborate with several authors such as Martins *et al.* (2009), Simões and Fenner (2010a), and Burla *et al.* (2012), who studied the same machines in different operating situations. Regarding the evaluated treatments, it was observed that there was no significant difference between the times consumed in the partial cutting and processing elements, since the operation only had one assortment for pulpwood production.

In relation to the harvester's working cycle as a function of studied working ranges, the difference in total working cycle times can be explained by the increase in displacement and searching time of trees to be felled in the working range (T₂), since the machine worked with its crane stretched to its maximum reach, a situation which often made it difficult to approach the machine to the tree to be felled by it.

In analyzing the forwarder behavior, loading was the partial working cycle element which consumed the longest time, followed by wood unloading. This result is a behavior expected by the forwarder, since it spends most of its time in passive form, loading and unloading as already mentioned by Rodrigues *et al.* (2018a). However, an increase in the woodpile volume in the excess working range was evident in T₂ when the effect of working ranges on the machine's working cycle was evaluated.

This situation has a significant contribution to reduce the forwarder loading time, as well as eliminating additional times for loading storage. It is important to note that the loading time reduction is relevant in forwarder operations, considering that this machine carries out loading and unloading wood operations for a large part of the operational cycle.

In the present study, it was considered that the width of working range is the main variable which directly depends on the machine characteristics and reach of the harvester crane (11 m) and forwarder (9 m). Such influences have already been reported by Mederski *et al.* (2018) in proposing a consortium of harvester and chainsaw operating in the thinning operation which enabled an increase in the breadth of the working range.

According to the time consumed in working cycle, the harvester's productivity was $60.6 \text{ m}^3 \text{ PMH}_0^{-1}$ in the T_1 working range, being $1.75 \text{ m}^3 \text{ PMH}_0^{-1}$ higher than T_2 and explained by the time consumed for searching trees in the working range of 18 m. In relation to the wood extraction operation, it was observed that despite having a higher load volume in T_1 treatment (21.15 m^3) being 0.74 m^3 more than T_2 , the total time of operational cycle in T_2 treatment was lower, with an average productivity of $48.32 \text{ m}^3 \text{ PMH}_0^{-1}$ being explained by the larger processed woodpile volume.

The productivities obtained for these machines should generally be considered satisfactory and superior to those obtained in other studies. Alves *et al.* (2015) found that productivity for the harvester in *Eucalyptus* stands with individual mean volume of 0.17 m^3 varied from 27.9 to $32.7 \text{ m}^3 \text{ PMH}_0^{-1}$ according to work shift. However, when evaluating the influence of tree volume on the performance of the harvester forest processor in *Eucalyptus* stands in generating the same assortment, Rodrigues *et al.* (2018b) obtained an average yield of $47.5 \text{ m}^3 \text{ PMH}_0^{-1}$, with a mean individual volume of 0.366 m^3 .

When comparing the results obtained in the literature (SIMÕES; FENNER, 2010b), the forwarder was found to have high productivity due to high population volume, average individual tree volume and bucket capacity of 23.7 t. After all, small and adapted machines are expected for roughing operations (PROTO *et al.*, 2018).

Regarding the production costs, the T_2 wood harvesting system procedure provided a reduction of only 1%, since the productivity increase of one machine in one procedure offset the productivity of the other. This result showed the feasibility for adopting the procedure with greater working range, especially when applied to the other modules or wood harvesting machines of the forest company under the studied conditions.

On the other hand, although the production costs were lower and significant, the greatest effects were observed in the traffic levels, in which the T_2 treatment presented a 33.4% reduction in relation to T_1 . For Seixas *et al.* (2003) forwarder traffic is systematic and on the harvester traffic track, and its effects on the ground amount to $\frac{1}{4}$ of area. Such values may be even lower if there are changes in work organization. Therefore, increasing the width of the working range is a trend to help reduce environmental impacts on the ground, as this is one of the justifications for machine manufacturers to increase the reach of the machine's crane.

CONCLUSIONS

- Increase in the working range provided larger wood volumes, reduced forwarder loading time and increased productivity;
- *Eucalyptus* wood harvesting in work areas composed of six lines contributed to reduce the cost and can be replicated in other harvesting modules of forest companies under the studied conditions;
- Greater working range showed a reduction of 33.4% of the machines' traffic in order to mitigate environmental impacts to the ground.

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