INFLUENCE OF LOG LENGTH ON THE PRODUCTIVITY OF WOOD HARVESTING AND TRANSPORTATION

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Received for publication: 28/04/2020 – Accepted for publication: 26/08/2021

Resumo

Influência do comprimento de toras na produtividade da colheita e transporte de madeira. A seleção de máquinas e o desenvolvimento de sistemas operacionais constituem o grande desafio para a redução de custos na colheita e no transporte florestal. Este trabalho teve por objetivo realizar uma análise técnica das atividades de colheita e transporte florestal em dois diferentes comprimentos de toras (6 e 7m). Foram avaliados os ciclos operacionais de um tratamento de *harvester*, um de *forwarder* e três de veículos conjugados road trainem áreas de colheita mecanizada. A análise técnica foi realizada por meio de estudos de tempos e movimentos, determinando a eficiência operacional e a produtividade das máquinas. De acordo com os resultados, o processamento consumiu a maior parte do ciclo operacional do *harvester*, enquanto no *forwarder*, o maior tempo foi por carregamento e descarregamento. As produtividades do *harvester* e do *forwarder* com toras de eucalipto de 6 e 7m foram de 35,2 e 45,2 $m^3 \cdot he^{-1}$ e 42,84 e 75,42 $m^3 \cdot he^{-1}$. O maior tamanho de toras levou a um incremento na produtividade do *harvester* de 28% e do *forwarder* em 48%. Dentre os tratamentos de road trainestudados, o que apresentou melhores resultados tanto na análise feita com comprimento de 6 como de 7m foi o de dimensões com 2,35m de largura e 2,85m de altura. Tais veículos apresentaram Peso Bruto Total Combinado de 63,52 toneladas para toras com comprimento de 6 m e 69,17 toneladas para toras de 7 m, um desempenho 8,17% maior. O aumento do comprimento das toras aumentou a produtividade e o desempenho da colheita e do transporte florestal.

Palavras-chave: Técnicas e operações florestais; produtividade florestal; mecanização florestal

Abstract

The selection of machines and the development of operating systems are the major challenge for reducing costs in harvesting and forest transportation. This work aimed to carry out a technical analysis of harvesting and forest transport activities in two different log lengths (6 and 7m). The operational cycles of the Harvester, Forwarder and combined road train vehicle in mechanized harvest areas were evaluated. The technical analysis was performed through studies of times and movements, determining the operational efficiency and productivity of the machines. According to the results, processing consumed most of the harvester's operational cycle, while in the forwarder, the most time was consumed 35,2 and 45,2 $m^3 \cdot he^{-1}$ and 42,84 and 75,42 $m^3.he^{-1}$. The larger log size led to an increase in the productivity of the harvester by 28% and the forwarder by 48%. Among the studied models of road train vehicles, the one that showed the best results both in the analysis made with a length of 6 m and 7 m, was the dimensions with 2.35 m in width and 2.85 in height. These vehicles had a total gross weight of 63.52 tonnes for logs with a length of 6m and 69.17 tons for logs of 7m, with an 8.17% higher performance compared to 6m logs. With the obtained results it can be concluded that the increase in the length of the logs increased the productivity and the performance of the harvest and the forest transport.

Keywords: Forestry techniques and operations; forest productivity; Forest Mechanization

INTRODUCTION

The Brazilian forestry sector has as its main products pulp and paper, industrialized wood panels, charcoal, pellets, sawn wood, firewood and biomass for energy generation. The total area planted with trees in Brazil reached 9.0 million hectares in 2019, being 6.97 million with *Eucalyptus*, 1.64 million with pine and 0.39 million with other species (IBÁ, 2020).

Harvesting and forest transport are the stages among the activities necessary for wood production with require special attention from an economic point of view, due to their high participation in the final cost of the wood placed in the mill and the risk of losses involved in these activities. Therefore, the search for techniques such as sizing the log length are necessary and urgent in order to obtain better yields and economic gains.

With the growth of the Brazilian economy and the demand for forest products, the timber sector has presented advances which have resulted in the adoption and technological sophistication of machines and implements. In turn, planning harvesting activities in conjunction with logistics of machines and optimizing the execution sequence of cutting the stands are steps of fundamental importance, making it possible to increase yield indicators, reduce costs and provide better working conditions (CARMO *et al*, 2015).

Even though mechanization is a growing and evolving process, the choice of the appropriate system is related to the technical and economic conditions of each region and the final use of the wood, also taking into account social and environmental factors. The harvesting systems may vary according to several factors, such as terrain topography, the volumetric yield of the stand, the type of forest, the final use of the wood and the available resources. Selecting the appropriate machines and equipment to be adopted in a forest harvesting system constitutes one of the great challenges for reducting the final costs of wood placed in the mill (BURLA *et al*., 2012).

The log length dimensioning varies according to the techniques and forest operations adopted in wood industries, depending on the final use of the product. Changes in log length may result in gains or losses in space utilization in the cargo compartment of transport vehicles. Thus, studies related to the ideal size of logs help managers to make assertive decisions regarding the best use of the product and economic gains by virtue of increasing operational efficiency, vehicle productivity, as well as providing the necessary reliability for adequate decision-making (ALVES *et al*, 2013).

With this purpose, this study aimed to evaluate the influence of wood logs length on the productivity of operational cycles in mechanized forest harvesting and transport activities.

MATERIAL AND METHODS

Characterization of the study area

The study was conducted in eucalyptus forest plantations in the south of the state of Bahia, Brazil, between the parallels of latitude 18º13’32.75’’S and longitude 39º42’3.05’’W, with an average altitude of 7 m. The relief is characterized as flat and gently undulating, with the predominant soil in the study areas being clayey with a medium clay texture. The data regarding the dendrometric characteristics of the forest stands in the study area are described in Table 1.

Table 1. Characteristics of eucalyptus stands.
Tabela 1. Características dos povoamentos de eucalipto.

Data	Values
Cutting age (years)	5,27
Spacing (m)	3 × 2
Average DBH (cm)	15
Average height (m)	21,77
Average individual volume (m³)	0,19

Wood Harvesting System

The cut-to-length timber harvesting system was used, with the cutting operations carried out by harvesters, who felled, debarked, delimbed and topped the logs into in 6.0 and 7.0 m long eucalyptus logs. Log extraction was carried out using a forwarder perfomed log forwarding and stacking activities on the edges of forest roads according to the points indicated on the micro-planning map.

Cargo Vehicle Combinations (CVCs) were used in the transport operation, comprising a fleet with three different carriers with a payload capacity ranging from 44.5 to 46.6 tons of wood. The workday in the area was distributed into three 8-hour shifts, totaling a continuous activity of 24 hours a day. Table 2 refers to the harvester and forwarder treatment characteristics.

Table 2. Main characteristics of the *harvester* and *forwarder*.
Tabela 2. Principais características do tratamento de *harvester e forwarder*.

Cutting and Extraction		
Machine	***Harvester***	***Forwarder***
Weight (kg)	21000	16800
Motor	Direct injection cylinders, 2000 rpm .	Direct injection cylinders, 2000 rpm
engine power (hp)	155	150
Wheels	Mats with center frame in "X"	6 tires
Cargo Box (m³)	-	18

Operational Analysis

Next, data on the time spent per activity were collected through a study of times and movements in the continuous time method using a digital stopwatch and a form to record the data in order to obtain the operational cycle of the machines. The operations monitoring was "in loco", according to the normal course of activities, without any interference.

The forest harvesting cycle was divided into activities common to all types of machines and into phases within the operations in order to evaluation of operational and non-operational times. Thus, the operational cycle was subdivided according to Table 3.

Table 3. Characterization of the operational cycle of the evaluated machines.
Tabela 3. Caracterização do ciclo operacional das máquinas avaliadas.

Cycle	Cycle Phase	Description
Cutting by *harvester*	**Cutting preparation** 	Cutting preparation started with the harvest displacement from the final position of the last cycle and ended with positioning the head at the next tree to be cut.
	felling 	Felling took place after positioning the harvester head on the trunk and consisted of felling trees.
	Cutting 	The cutting stage occurred after felling the trees and was characterized by delimbing, debarking, twisting, de-topping, and the stacking the wood in the stand.
Extraction by *forwarder*	**Empty displacement** 	Displacement started at the exact moment when the forwarder starts to move from the roadside to the wood bundle and ends when the machine is positioned close to the bundle to be loaded.
	Loading 	Loading started with placing the wooden logs in the forwarders cargo compartment until filling the cargo box space.
	Loading displacement 	Loading displacement occurred after the complete loading and the forwarder's cargo box and consisted of moving the forwarder from inside the field and ended when was positioned at the log stacking location on the side of the road.
	Unloading 	Unloading occurred after positioning the machine at the wood stacking location, and the forwardere begins to remove the logs from the cargo compartment and stacking them the roadsides until sits cargo box is completely emptied.

Machine Productivity

The productivity of machines was determined in cubic meters per effective hour of work. A report on the number of trees harvested (harvester) or number of trips made (forwarder) was used to determine productivity, which were generated by collecting time and movement data, whose value was multiplied by the respective average individual volume and divided by the number of hours actually worked, determined according to Equations 1 and 2.

$$Prod=\frac{(n\times va)}{he} \quad (01)$$

Note: Prod= harvester productivity ($m^3.h^{-1}$); n = number of trees harvested or number of trips (un); va=average volume per tree (m^3); and he = effective working hours (h).

$$Prod=\frac{Vol.}{he} \quad (02)$$

Note: Prod= Forwarder productivity ($m^3.h^{-1}$); vol.=average volume transported (m^3); and he = effective hours of work (h).

Forest transport performance

Regarding forest transport perfomance, road train vehicles are approved to travel with a total gross weight of 74 tons. Considering the tare weight of road train 1 = 27.4, road train 2 = 23.5 and road train 3 = 29.50 tons, the net load must not exceed the values of 46.6, 50.5 and 44.5 tons, respectively. Next, six treatments were established to assess the influence of log length on the total load volume in each CVC, differentiated according to the length of eucalyptus logs and the type of conveyor used (Table 4):

Table 4. Arrangement of types of treatment carried out in forest transport.
Tabela 4. Disposição dos tipos de tratamento realizados no transporte florestal.

Treatment	Length of logs (m)	CVC	Width	Height	Combined Gross Vehicle Weight
A	6	Road train 1	2,32	2,60	27,4
B	6	Road train 2	2,35	2,85	23,5
C	6	Road train 3	2,32	2,35	29,5
D	7	Road train 1	2,32	2,6	27,4
E	7	Road train 2	2,35	2,85	23,5
F	7	Road train 3	2,32	2,35	29,5

The logs had lengths of 6 and 7 m, being destined for pulp production. The bundles were loaded in the transport vehicle in the longitudinal direction of their load compartments, and both the loads of logs with lengths of 6 and 7 m formed three bundles on the chassis.

All wood volumes reported in the study wer obtained using the Logmeter® 4000 mensuring device, which generated real-time information. It used 3D laser technology along with image recognition software to measure the solid volume of wood loaded onto vehicles (Figure 1).

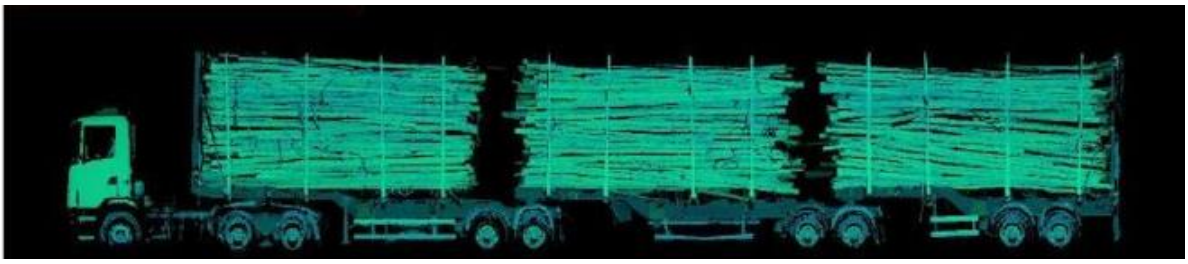

Figure 1. 3D image generated by road train's Logmeter® 4000.
Figura 1. Imagem 3D de um dos tritrens gerada pelo Logmeter® 4000.

Statistical analysis

In transport, the number of trips in the different treatments was compared. In each operation, the minimum number of samples was calculated using the following formula proposed by Conaw (1997):

$$N=\frac{CV^2 \times t^2}{E^2} \qquad (03)$$

Note: n = Sample sufficiency; CV = coefficient of variation; t = value of t for the desired probability level and (n-1) GL; and E = acceptable error.

The normality of errors was evaluated using the Shapiro-Wilk test. Then, the data were subjected to analysis of variance. When the F value was significant, the means of the treatments were subjected to a comparison of means by the Tukey's test at the 95% confidence level to find out if the different lengths of logs would influence the operations evaluated in harvesting and in the forest transport.

Statistical inferences were obtained by menas of analyzes comparing the times of each stage of the operational cycle of the harvester and the forwarder in relation to the length of the eucalyptus logs.

RESULTS

Operational Analysis

Table 5 presents the results of the information obtained from the studies of times and movements of the operational cycle carried out in forest harvesting.

Table 5. Samples collected, average cycle and percentage obtained by continuous methods for the analyzed harvester and forwarder models.

Tabela 5. Amostras coletadas, ciclo médio e percentual obtidos pelos métodos contínuos para os tratamentos analisados de *harvester* e *forwarder*.

Operation Cycle	Mediun Cycle *	(%)
Harvester 6 m (treatment A)		
Cutting preparation (s)	4,00 b	21
Felling (s)	2,25 c	12
Cutting (s)	13,15 a	68
Total (s)	19,40	100
Harvester 7 m (treatment B)		
Cutting preparation (s)	4,1 b	26
Felling (s)	3,15 b	20
Cutting (s)	8,1 a	54
Total (s)	15,35	100
Forwarder 6m (treatment C) for average distance of 125 m		
Empty displacement (min)	1,51 c	6
Loading (min)	15,53 a	62
Loading displacement (min)	1,65 c	7
Unload (min)	6,52 b	26
Total (min)	25,21	100
Forwarder 7m (treatment D) for average distance of 125 m		
Empty displacement (min)	1,32 c	9
Loading (min)	7,45 a	52
Loading displacement (min)	1,02 c	7
Unload (min)	4,56 b	32
Total (min)	14,35	100

Note: a, b and c: for each operation on the same machine analyzed, means of activities followed by the same lowercase letter do not differ significantly from each other, by Tukey's test at 5% significance; s: seconds; min: minutes.

Machine Productivity Measurement

Table 6 highlights the results of the statistical analyzes performed for the elements of the harvester's operational cycle in the different logs lengths studied.

Table 6. Production and productivity of the harvester in wood processing for logs of 6 and 7 meters in length.
Tabela 6. Produção e produtividade do *harvester* no processamento de madeira para toras de 6 e 7 metros de comprimento.

LL	NB (unit)	TV (m^3)	Dur (he)	VMI (m^3 arv^{-1})	Prod. (m^3 he^{-1})
6 m	190.248	36.735,70	0,0054	0,19	35,2 b
7 m			0,0042		45,2 a

Note: LL = Log ;length; NS = Number of Branches; TV = Total volume with bark; Dur = Duration of a cycle; VMI = Average individual volume with bark; Production = Productivity; and he = Effective time. Means followed by the same letter do not differ from each other by Tukey's test at a 95% probability level.

The results found regarding the forwarder productivity in different log sizes are described in Table 7.

Table 7. Productivity (m^3 h^{-1}) of the *forwarder* in the extraction of logs of 6 and 7 meters in length.
Tabela 7. Produtividade (m^3 h^{-1}) do *forwarder* na extração de toras de 6 e 7 metros de comprimento.

Length of Logs (meters)	Load capacity (m^3)	Numbers of trips.h^{-1}	Productivity ($m^3.h^{-1}$)
6	18	2,38	42,84 b
7	18	4,19	75,42 b

*Note: Means followed by the same letter do not differ from each other by Tukey's test at a 95% probability level.

Forest transport performance

In relation to load weight, the road train were approved to travel with a total gross weight of 74 tons. This weight issue was controlled and the vehicles were loaded up to the maximum weight limit allowed for the mode of transport used, with the results obtained in this research described in Table 8.

Table 8. Combined Gross Vehicle Weight with 6 and 7 meters long eucalyptus logs.
Tabela 8. Peso Bruto Total Combinado (PBTC) com toras de eucalipto de 6 e 7 metros de comprimento.

treatment	6m			7m		
	A	B	C	D	E	F
Weight (t)	58,90 B	63,52 A	54,92 C	60,81 b	69,17 a	60,43 b

* Note: t = ton. The means followed by the same capital letter do not differ from each other in the length of 6 m and means followed by the same small letter do not differ from each other in the 7 m treatment by the Tukey test at 5% significance.

There was generally a significant increase in harvester and forwarder productivity from change in log length from 6 m to 7 m due to the decrease in the machines' operating time, which implied a better efficiency of the machine's use, in addition to improving the performance of forest transport vehicles, which makes it possible to travel with greater use of the cargo box, so that the freight cost per cubic meter of wood can be reduced.

DISCUSSION

Operation Analysis

We found that the longest time spent for the harvester at the 95% probability level was tree processing (average of 13.15 seconds for the 6 m assortment and 8.10 seconds for the 7 m assortment). This can be explained by the fact that this activity includes the steps of delimbing, debarking, turning, de-topping and stacking the wood in the field. The difference between the assortments in the processing subdivision is explained by a longer time in the length of 6 m for having one more log than when using the 7 m assortment. Such results were similar to the results found by Lopes et.al. (2015) and Santos et. al. (2018), who also registered this behavior in their results, finding a longer time spent in the operational cycle of the harvester in the processing stage.

When comparing the forwarder treatments, it was found that the step with consumed the highest average was loading (average of 15.53 minutes for the 6 m assortment and 7.45 minutes for the 7 m assortment and the smallest for the loaded and empty machine displacement (average of 1.65 and 1.51 minutes for the 6 m assortment and 1.02 and 1.32 minutes for the 7 m assortment. When we compare the log lengths we visualized a significant difference in the loading and unloading averages which represent 62 % and 26 % for the 6 m length and 52% and 31.89 % for the 7 m assortment, respectively.

Simões and Fenner (2010) also observed that loading and unloading were responsible for most of the forwarder's operational cycle time, evaluating a trans-shipment of eucalyptus logs in the first cut. Seixas (2014) reported that these operations directly interfere in the forwarder's performance, as the machine spent most of the journey performing these activities. Thus, the use of measures to optimize the operation is evident, such as targeted training, standardizated of lengths, wood weights and efficient planning of operations. In this way, it is possible to contribute to the reducing the loading and unloading times and, consequently, the total operational cycle, increasing the operational efficiency of the machine in forestry extraction (OLIVEIRA et al., 2009).

The loading phase statistically differed from the other activities, and unloading differed from loaded and empty displacement, which do not differ from each other. There was no statistical difference when comparing the lengths of the 6 m and 7 m logs, when using the 6 m and 7 m treatment for the empty displacement operation. However, when comparing the other three phases (loading, loaded displacement and unloading) the 7m log assortment presented statistically better and lower results when compared to the 6m assortment.

Thus, the loaded and empty displacement operations had a smaller effective participation in the total operational cycle time of, about 7 and 6% for treatment C and 7 and 9% for treatment D, respectively, and these elements were mainly influenced by the distance from the logging to the roadside.

Productivity Measurement

The forest cutting operation productivity differed between the log lengths. Table 6 shows that the yield in number of processed trees improved with an increase in log length, going from 6 meters to 7 meters. This can be explained by the fact that the 7 m processed wood reduced the number of saber activations for trunk sectioning per harvested tree. As shown in Table 4, the operational cycle of cutting in 6 m logs took an average of 19 seconds to process a tree, while the same procedure took an average of 15 seconds per tree for 7 m logs.

This difference represents 4 seconds in the cutting (head preparation, felling and processing) of each tree. When taking into account the number of trunks 190.248 obtained in this study, there was a reduction of 231 hours, which is equivalent to 11 working days when comparing the standard length of 6 m and 7 m for eucalyptus logs. By adopting the standard measurement of 6 m for the length of eucalyptus logs, it would take 49 days to process the number of trunks mentioned above with an operating cycle time of 0.0054 hours. Furthermore, when taking into account the length of 7 m for the standard length of eucalyptus logs, the same activity would be carried out on average 38 days to process the same number of trunks (190.248 trees).

As can be seen in Table 5, productivity is directly related to the volume cut and inversely proportional to the amount of hours worked. Thus, there was a 28% increase in harvester productivity as the length of the logs was increased from 6 to 7 m (from 35.2 $m^3.\ h^{-1}$ to 45.2 $m^3.\ h^{-1}$, respectively).

The influence of the length of logs on the time spent processing trees with 6 and 7 meter logs is evidenced in Figure 2. It is noted that, as the size of wood increases from 6 meters to 7 meters, the average duration of the processing operation reduces by 14%. However, it appears that the height of the trees must be considered when making the decision to standardize the length of logs in order make better use of the trunks.

In Table 7, it can be seen that there was a significant difference in the forwarder's productivity considering an average extraction distance of 125 m. There was a 43% increase in forwarder yield as it changed the log size from 6 m to 7 m. This variation in results is mainly due to the time spent with the loading and unloading operations.This because the machine operator performs less crane movement to complete the machine's load capacity to carry out these activities with larger log sizing.

Cabral et. al (2020) also found similar results, considering an extraction distance of 200m and a forwarder volumetric capacity of 15 m^3. The authors concluded that there was a 14.6% increase in forwarder production with the variation in log length from 5 to 6 meters. Moreover, the forwarder presented a performance of 22.1 $m^3.\ h^{-1}$ for a lehngt of 5 m and 25.77 $m^3.\ h^{-1}$ for 6m. In studying the forwarder extraction operation, Rodrigues *et al*. (2018) concluded that the loading time was the element which consumed most of the operational cycle time, and its productivity increased as the volume per tree increased and the average distance of extraction decreased.

According to he results presented in Table 6, considering the extraction distance of 125 meters and a machine load capacity of 18 m^3 and a total volume without bark of 32,985.29, the company using the standard length of 7 m will have a reduction 16 days of operation in extraction and consequently a reduction in operating costs.

Forest transport performance

The operations with loads using treatment E presented a performance of 8.17% greater than treatment B, with both using road train 2, but they vary in length of wood from 7m for treatment E and 6m for treatment B. The characteristic responsible for the better performance of road train 2 was because it presents a superior loading box width and height to the other treatments. However, even when presenting these characteristics, the weight in tons of the cargo box of road train 2 is lower when compared to the treatment of road train 1 and road train 3.

Another important factor to be considered is that as the load weight per trip was increased, this resulted in a decrease in trips needed to meet demand, and consequently lower freight costs and better machine forest loading yield indicators in the field and unloading in the industry yard, which can result in lower operating costs.

CONCLUSIONS

- There was a significant increase in harvester and forwarder productivity from alteration the log length from 6 m to 7 m due to the reduction in the machines operating time, which implied better machine use efficiency.
- Standardizing the length of eucalyptus logs to 7 m proved to be effective in increasing the machine productivity, in addition to improving the performance of forest transport vehicles.
- In relation to wood transport, it was found that the use of vehicles with a larger load compartment area enabled trips with greater load utilization, which reduces the number of trips required for transporting wood and, therefore, can reduce the freight cost per cubic meter of wood.

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