Universidade Federal do Paraná
Setor de Ciências Agrárias
Pós-graduação em Engenharia Florestal
Revista Floresta

EFFECT OF WOOD STACKING ON PRODUCTIVITY AND COST OF FOREST EXTRACTION AND LOADING

William Masioli[1], Eduardo da Silva Lopes[2*], Millana Burger Pagnussat[3], Luiz Carlos Garsztka[4]

[1]Universidade Estadual do Centro-Oeste, Programa de Pós-graduação em Ciências Florestais, Irati, Paraná, Brasil - william.masioli@gmail.com
[2*]Universidade Estadual do Centro-Oeste, Departamento de Engenharia Florestal, Irati, Paraná, Brasil - eslopes@unicentro.br
[3]Universidade Estadual do Centro-Oeste, Departamento de Engenharia Florestal, Irati, Paraná, Brasil - millanap@gmail.com
[4]Klabin S.A, Telêmaco Borba, Paraná, Brasil - lgarsztka@klabin.com.br

Received for publication: 24/07/2021 – Accepted for publication: 27/02/2023

Resumo

Efeito do empilhamento de madeira na produtividade e custo de extração e carregamento florestal. Devido à necessidade de implementação de novos procedimentos operacionais que proporcionem ganhos de produtividade e redução de custos na colheita e logística da madeira, objetivou-se neste estudo avaliar o efeito do empilhamento da madeira na produtividade e nos custos nas operações de extração e carregamento florestal. O estudo foi realizado em povoamentos de eucalipto, sendo avaliada a extração da madeira com o *forwarder* e o carregamento de veículos com o carregador florestal. Foram avaliados três modelos de empilhamento das toras na margem do talhão denominados: testemunha, invertida e adjacente, com variações no alinhamento e no distanciamento das toras em relação à margem do talhão. Foi realizado um estudo de tempos e movimentos determinando a produtividade ($m^3.h^{-1}$) e o custo de produção ($R\$.m^{-3}$) das operações. Os dados foram comparados pelo teste de *Tukey* (α=5%) para dados paramétricos e por *Kruskal-Wallis* (α=5%) para dados não-paramétricos, e também verificado por equações o efeito nas diferentes distâncias de extração. O modelo de empilhamento invertido contribuiu para o aumento da produtividade da extração, enquanto o modelo adjacente no carregamento, com redução do custo de produção da ordem de 22,1%. Analisando simultaneamente ambos os modelos de empilhamento da madeira, o modelo padrão adotado pela empresa florestal foi melhor com redução de 6,1% nos custos em relação aos demais. As equações de produtividade mostraram que o modelo de empilhamento invertido contribuiu no maior desempenho do *forwarder* nas distâncias até 140 m. O estudo mostrou que os modelos de empilhamento da madeira afetam as operações florestais, devendo ser consideradas no planejamento operacional.
Palavras-chave: Colheita de madeira; planejamento operacional; pilhas de toras.

Abstract

Due to the need to implement new operational procedures that provide productivity gains and cost reduction in wood harvesting and logistics, the objective of this study was to evaluate the effect of wood stacking on productivity and costs of forest extraction and loading operations. The study was carried out in eucalyptus plantations, where the extraction of wood with the *forwarder* and the loading of vehicles with the forest loader were evaluated. Three log stacking models on the edge of the stand were evaluated: control, inverted and adjacent, with variations in the alignment and distance of the logs concerning the edge of the stand. A study of the times and movements of the operations was carried out, determining the productivity (m³.h-1) and the production cost (R$.m-3) of the forestry operations. The data were compared using the Tukey test (α=5%) for parametric data and the Kruskal-Wallis test (α=5%) for non-parametric data, and the effect of different extraction distances was also verified using equations. The inverted stacking model contributed to the increase in extraction productivity, while the adjacent model in loading, with a reduction in production cost of around 22.1%. Simultaneously analyzing both wood stacking models, the standard model adopted by the forestry company was better with a 6.1% reduction in costs compared to the others. The productivity equations showed that the inverted stacking model contributed to the *forwarder*'s higher performance at distances up to 140 m. The study showed that wood stacking models affect forestry operations and should be considered in operational planning.
Keywords: Wood harvesting; operational planning; piles log.

INTRODUCTION

Harvesting and logistics operations in planted forests are made up of cutting, extraction, loading and final transport, and are highly complex due to the diversity of operating conditions in terms of forest, terrain, machine and vehicle models, which directly affect the production capacity and operating costs, such costs reaching up to 70% of the final value of the wood placed in the industries (Machado, 2014; Gagliardi *et al*., 2020; Nunes *et al*., 2021). Extraction and loading are highly relevant stages for harvesting and forestry logistics, where extraction is responsible for removing the logs from inside the stands to the side of the roads or intermediate yards where they are stacked for a certain period, while loading is responsible for fueling vehicles for final transport. Therefore, these are operations that interconnect different stages within the forest supply chain, where the adoption of a procedure in a specific operation may affect the operation that follows. (Leite *et al*., 2014; Machado, 2014).

As mentioned by several authors, wood extraction is influenced by numerous operational variables that affect the productive capacity and costs of wood harvesting machines, which can highlight the slope of the land, the distance and characteristics of the extraction trails, the length and volume of wood logs, types of log assortments, load capacity of the machine, reach of the hydraulic boom, etc. (Oliveira *et al*., 2009; Seixas, 2014; Lopes, *et al*., 2016; Nunes *et al*., 2021). Loading, in turn, is influenced by the specific weight of the wood, volume and length of the logs, quality of the wood piles, useful grapple area, transport vehicle model, etc. (Alves *et al*., 2008; Simões e Fenner, 2010; Minetti *et al*., 2014; Carmo *et al*., 2015). In addition to these variables, it is important to mention the log stacking model at the edge of the stand that is defined in the micro-planning of the wood harvest, whose procedure may simultaneously affect the productive capacity of the harvesting and logistics operations.

In this aspect, the characteristics of the place destined to the piling of the wood in the margins of the stand; the length, width, height and shape of wood piles; and the distance of the piles concerning the road must be considered in the micro-planning (Malinovski *et al.*, 2006; Machado, 2014). In the literature, many authors report that the loading and unloading stages of wood consume the most time in the operational cycle during extraction with the forwarder, however, this is related to the extraction distance, wood volume, and machine carrying capacity. (Oliveira, *et al*., 2009; Seixas, 2014; Carmo *et al*., 2015; Lopes *et al*., 2016; Gagliardi *et al*., 2020). On the other hand, it should be noted that the format and positioning of the wood piles on the edges of the stand can also affect the operational cycle times of the *forwarder* in the extraction stage and the forest loader in loading the transport vehicle, with a consequent effect on the production capacity and operating costs (Cipriani *et al.* 2015).

Therefore, given the complexity and high operating costs of forest harvesting and logistics, this study aims to investigate the most appropriate wood stacking model that can contribute to the integrated optimization of extraction and loading operations, thereby increasing the production capacity of machines and reducing production costs. Given this, the objective of this study was to verify the effect of stacking wood on the edge of the stand in relation to the production capacity and costs of extraction and loading operations, contributing to the improvement of the planning of forestry operations.

MATERIALS AND METHODS

Study area

The study was conducted in the operational areas of a forest company located in the Parana State, Brazil, where the region was characterized by a Subtropical Humid Mesothermal climate - Cfa, with an average annual temperature ranging from 18 to 22 ºC and an average annual precipitation between 1,200 and 1400 mm. The experiment was carried out in homogeneous stands of clonal propagation of *Eucalyptus saligna* submitted to wood harvesting in the shallow cutting regime. The relief was classified as flat-undulating, while the characteristics of the forest and the machines are presented in Table 1.

Universidade Federal do Paraná
Setor de Ciências Agrárias
Pós-graduação em Engenharia Florestal
Revista Floresta

Table 1. Dendrometric and operational characteristics of the study area.
Tabela 1. Características dendrométricas e operacionais da área de estudo.

Forest Standing Variables	
Species	*Eucalyptus saligna*
Age of settlment (years)	10
Spacing (m)	2,5 x 3,0
Individual average volume (m³)	0,39
Average volume per hectare (m³. ha^{-1})	494,0
Length of logs with bark (m)	7,2
Final use	Celulose

Wood Harvest Operational Variables			
		Machine	**Specifications and technical characteristics**
Activity	**Felling and Processing**	*Harvester* 	Ponsse brand base machine, Ergo 8w model, operating weight of 21,500 kg, engine with nominal power of 275 hp (205 kW), traction force of 195 kN, 10 m long boom, wheelsets with 8x8 traction equipped with processor head with three-roller feeding system and maximum opening of 650 mm.
	Extraction	*Forwarder* 	Ponsse brand base machine, model Elephant King K100, operating weight of 23,700 kg, engine with rated power of 275 hp (205 kW), traction force of 240 kN, boom length of 10 m, grapple of 0.36 m² , wheelset with 8x8 traction tires and 20,000 kg cargo box.
	Loading	*Forest Loader* 	Doosan brand base machine, model DX 225LCA, operating weight of 25,200 kg, 169 engine (110kW) with traction force of 188 kN, track wheelsets and 10 m long boom and 0.80 m^2 grapple.

Description of treatments

In this work, to verify the effect of the wood stacking model on the edge of the plot concerning the extraction and loading operations, the plot was subdivided into three parallel subplots with a unit area of 1.4 hectares and a dimension of 70 x 200 m, aiming at the allocation of treatments. In each experimental plot, stratification was performed in four classes of extraction distances (DE) from the access road: DE ≤ 50 m; 50 < DE ≤ 100; 100 < DE ≤ 150 and 150 < DE ≤ 200 m. Three treatments related to the wood stacking models were proposed, with variations in the alignment and spacing of the logs in relation to the edge of the road plot and the working angle of the forest loader, as described below and illustrated in Figure 1.

1. **Control Stack (T):** standard stacking procedure adopted by the company, where the piles of logs were positioned 5m equidistantly from the boundary of the plot/road and with the logs aligned facing the access road. In this model, the *forwarder* positioned itself between the pile and the road to unload the wood, while the forestry loader

positioned itself between the pile and the road, performing a turn of up to 180º to carry out the loading of the wood in the transport vehicles.

2. **Inverted Stack (I)**: The proposed stacking procedure involves placing the wood piles equidistantly at 5 meters from the edge of the stand/road, with the logs aligned facing the interior of the stand. In this model, the forwarder positioned itself in front of the pile on the stand side for unloading the wood, while the forest loader positioned itself between the pile and the road, performing a working turn of up to 180º for loading.
3. **Adjacent stack (A):** The proposed stacking procedure involves placing the log piles along the edge of the road, with the logs aligned facing the interior of the road. In this model, the *forwarder* positioned itself in front of the pile on the stand side for unloading the wood, and the forest loader positioned itself on the side of the pile, performing a working turn of up to 90º for loading the transport vehicles.

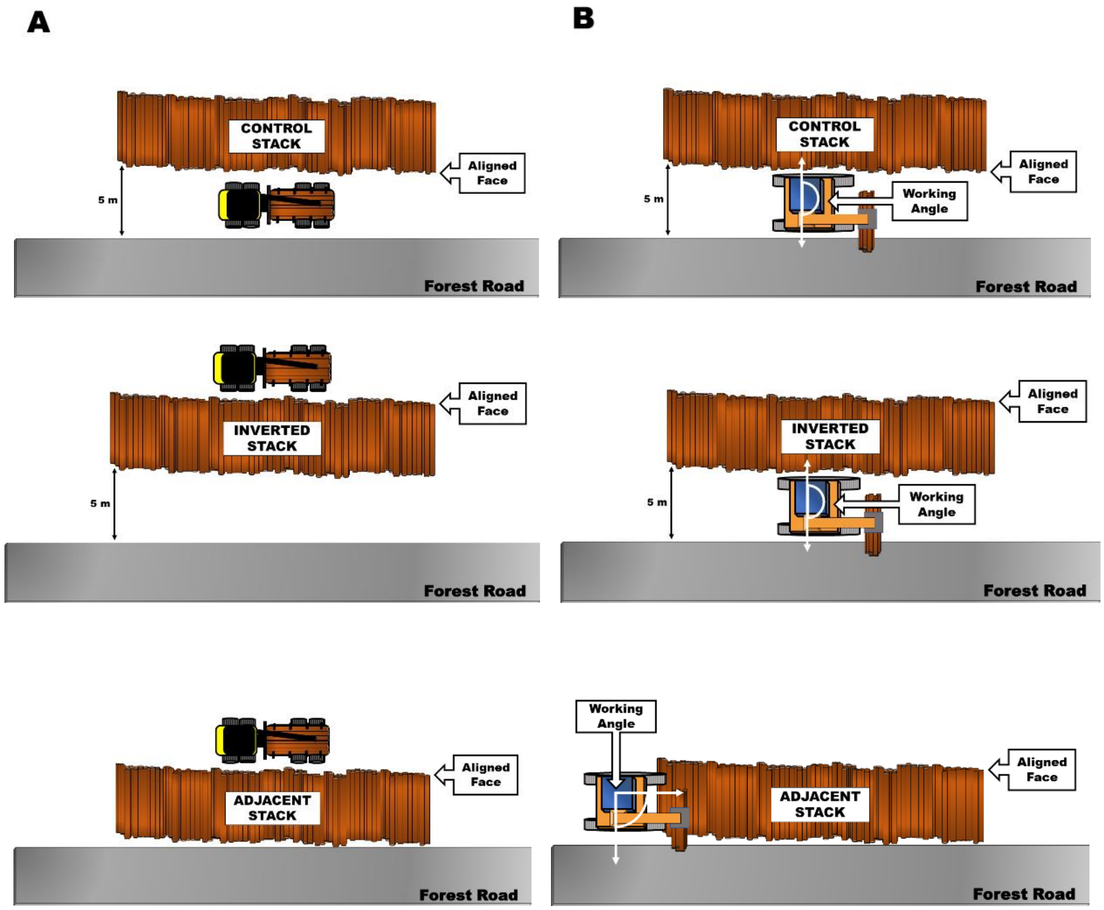


Figure 1. Logs stacking models in the proposed treatments.
Figura 1. Modelos de empilhamento da madeira nos tratamentos propostos.

Data collection

The collection of data in the operations of extracting the wood and loading the transport vehicle in the different treatments was carried out through a study of times and movements using the continuous-time timing method. The operational cycles of the machines in both operations were subdivided into partial activities as described in Table 2. Initially, a pilot study was carried out to determine the minimum number of machine operating cycles, which was later used as a criterion for delimiting the experimental plots, adopting a maximum sampling error of 5% and following the equation proposed by Murphy (2005).

Table 2. Operational cycle partial activities of wood extraction and loading.
Tabela 2. Atividades parciais do ciclo operacional da extração e carregamento de madeira.

Forwarder	
Partial activities of the extraction operating cycle	**Description**
Empty Trip (VV)	Time spent moving the *forwarder* from the roadside to the log pile inside the field.
Loading (CR)	Time consumed by the *forwarder* in carrying out the loading of bundles of logs until completing the machine's loading compartment.
Loaded Trip (VC)	Time consumed by the *forwarder* in moving from the interior of the stand to the wood piles at the edge of the stand.
Unloading (DC)	Time consumed by the *forwarder* in unloading the wood in the wood piles at the edge of the field.
Interruptions (INT)	Time consumed with operational and non-operational breaks.
Forest Loader	
Partial activities of the loading operational cycle	**Description**
Empty crane displacement (DV)	Time consumed in moving the forestry loader crane empty in search of the bundle of logs in the piles of wood at the edge of the plot.
Loaded crane displacement (DC)	Time consumed in moving the loaded crane from the forestry loader with the bundle of logs to the loading compartment of the transport vehicle.
Loading and organization of logs (CR)	Time consumed in unloading, adjusting and organizing the bundle of logs inside the cargo compartment of the transport vehicle.
Interruptions (INT)	Time consumed with operational and non-operational breaks.

Forwarder and forest loader performance and cost indicators were determined through operational efficiency, productivity and production costs. The operational efficiency (EO) of the machines represented the percentage of time effectively worked regarding the scheduled time, while productivity represented the volume of wood extracted and loaded per effective hour of work. To determine the volume of the logs used in the productivity equations, cubage was performed, and subsequent conversion of the volume into mass to evaluate the loading, adopting the conversion factor of 0.9, whose equations are presented in Table 3.

The operating and production costs of extraction and loading operations were carried out using the accounting method, according to the *American Society of Agricultural and Biological Engineers* (ASAE, 2001), with operational information and administrative data provided by the company. Operating costs were obtained by the sum of fixed, variable and personnel costs, expressed per hour of work (R$ h^{-1}), while production costs were obtained by the ratio between operating costs and machine productivity, in cubic meters (R$ m^{-3}). Linear equations were also adjusted to evaluate the effect of logging distance (DE) on *forwarder* productivity as a function of wood stacking models, considering a level of 5% for *Student*'s t test. The models were evaluated using the adjusted coefficient of determination (R^2_{ajust}).

Table 3. Equations used to determine the minimum number of operational cycles, operational efficiency and extraction productivity and forest loading operations in the studied treatments.
Tabela 3. Equações utilizadas para determinação do número mínimo de ciclos operacionais, eficiência operacional e produtividade das operações de extração e carregamento florestal nos tratamentos estudados.

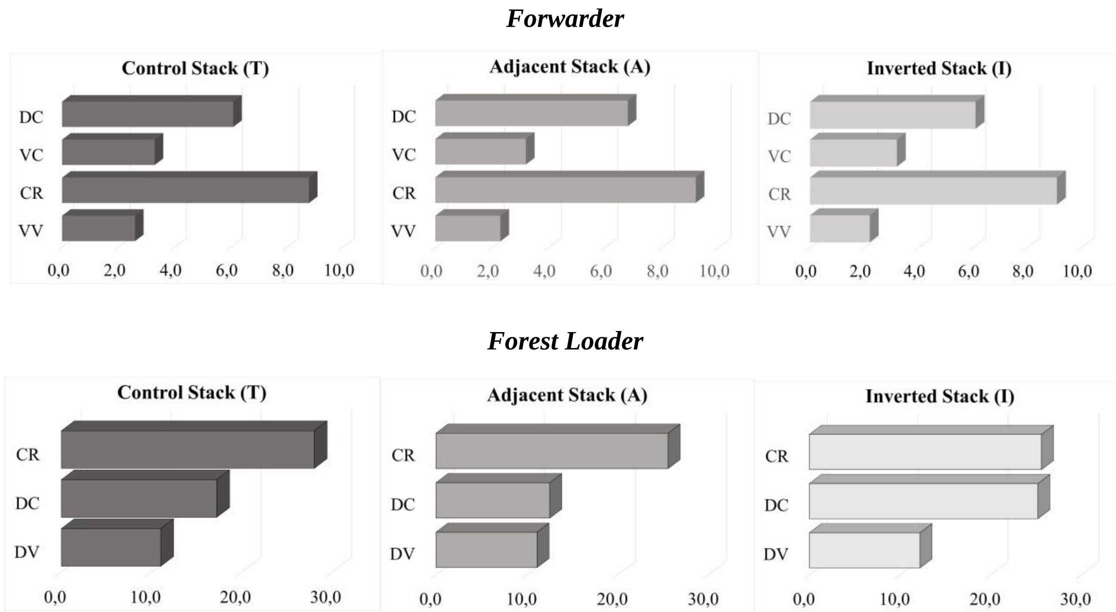
Equation	Description
$n \geq \frac{t^2 \times CV^2}{LE^2}$	n = number of operating cycles; t = *t*-value for the desired probability level in (n-1) degrees of freedom; CV = coefficient of variation (%); and LE = permissible error limit (%).
$EO = \frac{T_e}{(T_e + T_i)} \times 100$	EO = operational efficiency (%); Te = Effective working time (hour); and Ti = Time of operational and non-operational interruptions (hour).
$Pr_{fw};\ Pr_{cf} = \frac{n_t \times v_t \times i_g}{T_e}$	Pr_{fw} = *forwarder* productivit ($m^3.h^{-1}$); Pr_{cf} = forest loader productivity ($t.h^{-1}$); n_t = number of logs collected per grapple attack (dimensionless); v_t = individual log volume (m^3); and i_g = number of thrusts with the *forwarder* claw (dimensionless); and T_e = Effective working time (hour).

Statistical analysis

The treatments were carried out in a completely randomized design (DIC) for the variables productivity and production cost in the extraction and loading operations, totaling 30 repetitions per treatment for the *forwarder* and 90 repetitions per treatment for the forest loader. The data were submitted to the *Kolmorov-Smirnov* normality test (α=5%), and later, the homogeneities of the variances were analyzed by the *Bartlett* test (α=5%). Subsequently, the data were submitted to ANOVA, with the averages between the treatments compared by the Tukey test for independent samples (α=5%). For non-parametric data, the Kruskal-Wallis multiple comparison test was applied at a 5% error probability level.

RESULTS

The percentage distribution of the operational cycle times of the *forwarder* and loader in the wood extraction and loading operations, respectively, in the different treatments, are presented in Figure 2. The total effective operating cycle time of the forwarder consumed 20.8; 21.5 and 20.6 minutes in the control, adjacent and inverted stacking models, respectively. As mentioned by several authors (Oliveira, *et al*., 2009; Seixas and Castro, 2014; Lopes *et al*., 2016; Gagliardi *et al*., 2020), the forwarder loading and unloading stages consumed the longest operating cycle times, emphasizing the importance of reducing these periods and with the premise that the new log stacking models may contribute to its reduction, with a consequent increase in the production capacity of extraction of wood. Interruptions consumed, on average, 4.4 minutes per work cycle of the machine, resulting in an average operating efficiency of 82.6%. Regarding the loading of wood in the transport vehicle, it should be noted that there was a need, generally, for 16 operational cycles of the loader's crane to complete the vehicle's loading compartment, with an average effective time per cycle of 56.2; 49.1 and 62.7 seconds, thus making a total effective vehicle charging time of 15.0; 13.1; 16.7 minutes in the control, adjacent and inverted stacking models, respectively. When analyzing the partial activities of the operational cycle, it is observed that the loading and organization of the logs in the vehicle load compartment (CR) consumed an effective time of 28 seconds per cycle in the control stacking model, representing 8.6% higher to the inverted model (25.6s) and 8.9% higher than the adjacent stack model (25.5s). Then, the displacement of the empty crane (DV) was the phase with the greatest oscillation in cycle time, where the inverted stacking model demanded 25.2 seconds, with a 31.7% higher average than the control stack (17.2 s) and 50.4% concerning the adjacent stack (12.5s). Operational and non-operational interruptions consumed, on average, 18.7 seconds of the total operational cycle time, resulting in an average operational efficiency of 75.0%, caused by the need to reposition the charger regarding the batteries for a new charge.



Where: VV = empty trip; CR = loading; VC = trip loaded; DC = offloading; DV = empty crane displacement; DC = loaded crane displacement; and CR = loading and organization of logs in the vehicle.

Figure 2. Distribution of the operational cycle of the forwarder and the forest loader in the extraction and loading operations in the different wood stacking models.

Figura 2. Distribuição do ciclo operacional do *forwarder* e do *carregador florestal* nas operações de extração e carregamento nos diferentes modelos de empilhamento da madeira.

The productivity of extraction and loading of transport vehicles in the different stacking models are shown in Table 4. For the *forwarder*, an average productivity of 55.40 m³.h^{-1} was obtained with an average operational efficiency of 82.6%, while for the forest loader, the average effective productivity was 146.8 m³.h^{-1} with an average operating efficiency of 75.0%. In the extraction of wood, statistical differences were found between the stacking models. The inverted pile model (I) and the control model (T) allowed for higher effective *forwarder* productivity, with an average of 46.6 and 45.3 m³.h^{-1}, respectively. The adjacent model resulted in an average productivity of 40.4 m³.h^{-1}, with a productive difference of around 13.3% in relation to the other treatments. And for the loading of wood in the transport vehicle, the adjacent stacking model (A) contributed to the highest productivity of the loader (156.7 m³.h^{-1}), followed by the control with 136.9 m³.h^{-1}.

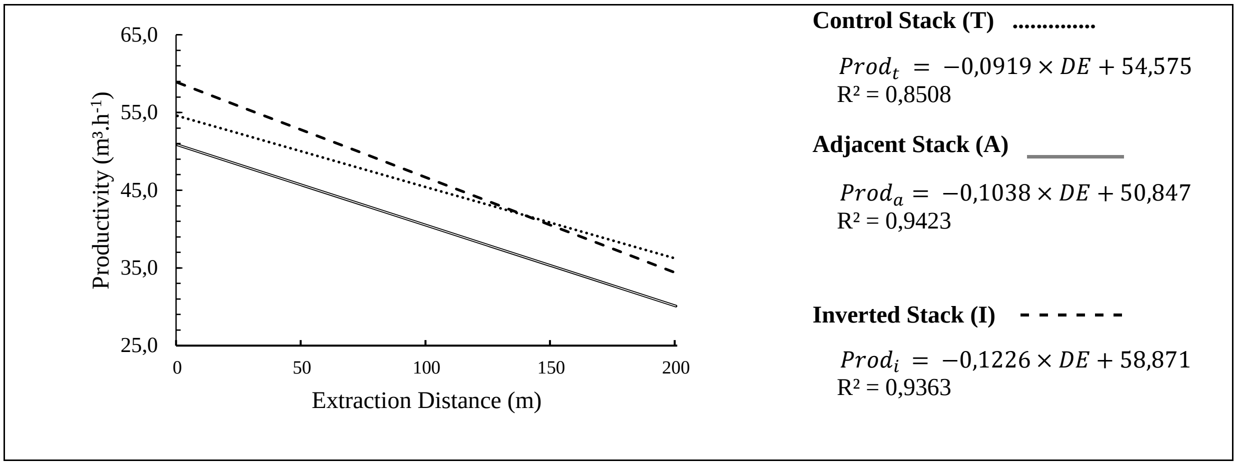
Table 4. Productivity and average operational efficiency of extraction and loading in different logs stacking models.

Tabela 4. Produtividade e eficiência operacional média da extração e carregamento nos diferentes modelos de empilhamento da madeira.

Treatment	**Extraction**		**Loading**	
	Productivity (m³. h^{-1})	Operational Efficiency (%)	Productivity (ton. h^{-1})	Operational Efficiency (%)
Control Stack (T)	45,3 B		136,95 b	
Adjacent Stack (A)	40,4 C	82,6	156,73 a	75,0
Inverted Stack (I)	46,6AB		122,26 c	
Mean	55,4	82,6	146,8	75,0

Where: means followed by capital letters do not differ statistically from each other by the Kruskal-Wallis test at 5% probability of error; means followed by lowercase letters do not differ by Tukey test at 5% probability of error; T = Control pile, A = Adjacent pile; I = Inverted stack.

Forwarder productivity estimates as a function of logging distance (DE) in the different stacking models are shown in Figure 3. The stacking models showed adjusted coefficients of determination (R²adjust) greater than 0.85, thus validating the effect of the extraction distance (DE) variable, which corresponded, on average, to 90% of the *forwarder* productivity oscillation. The best representation of productivity was observed in the adjacent pile model (95.8%), followed by the control pile (85.1%).



Where: T = Control pile, A = Adjacent pile; I = Inverted stack

Figure 3. Linear prediction of forwarder productivity as a function of extraction distance (DE).

Figura 3. Previsão linear da produtividade do *forwarder* em função da distância de extração (DE).

The production costs of wood extraction and loading are presented in Table 5. In the extraction, a forwarder operating cost of R$ 330.08 m^{-3} was obtained, making an average production cost of R$ 7.66 m^{-3}. The inverted stacking model provided a lower production cost (R$ 7.25 m^{-3}) from a higher *forwarder* productivity, being 13% lower than the adjacent stacking model, with a significant difference. Regarding vehicle loading, an operating cost of the charger of R$ 307.85 m^{-3} was obtained, resulting in an average production cost of R$ 2.50 m^{-3}. Note the lower loading production cost in the adjacent stacking model (R$ 2.19 m^{-3}), with such cost being 12.7% and 22.1% lower regarding the control and inverted stack models, respectively. And when analyzing the sum of the costs of operations in the different wood stacking models, the lowest total production cost is observed in the control stack model.

Table 5. Production cost of wood extraction and loading.

Tabela 5. Custo de produção da extração e carregamento de madeira.

Treatment	Extraction Cost (R$. m^{-3})	Loading Cost (R$. m^{-3})	Total Cost (R$. m^{-3})
Control Stack (T)	7,38 B	2,51 b	9,89*
Adjacent Stack (A)	8,34 C	2,19 a	10,53
Inverted Stack (I)	7,25 AB	2,81 c	10,06
Média	7,66	2,50	10,16

Where: means followed by capital letters do not differ statistically from each other by the Kruskal-Wallis test at 5% probability of error; means followed by lowercase letters do not differ by Tukey test at 5% probability of error; T = Control pile, A = Adjacent pile; I = Inverted stack; and (*) minimum production cost.

DISCUSSION

When analyzing the operating cycle times of the extraction with the *forwarder* in the wood stacking models, it is observed that the control treatment demanded a longer time in the productive displacement of the machine, being 6.8% less efficient compared to the adjacent model and 8.5% smaller compared to the inverted model. As for the unloading activity, it was possible to identify that the control pile model allowed greater agility of the machine compared to the other treatments. Regarding the total time of the operational cycle, it is noticeable that the shorter time required by the machine, in the inverted and control stacking models of the logs and control, occurred due to the smaller number of maneuvers required by the machine to perform unloading near the piles and by the non-mandatory alignment of the logs in the pile at the boundary of the plot and the road, a situation that requires greater skill from the operator and, consequently, greater demand for execution time. In addition, the loading and unloading steps depend on other operational variables, which may highlight the grapple reach capacity and extraction model (single or double direction). And in this aspect, Mazão *et al*. (2016) comparing two grippers with a 14% difference in load capacity, observed a 6% and 1% reduction in loading and unloading times, respectively. It is also important to highlight the longer working time consumed by the partial activities of loading and unloading wood, a result also pointed out by several other authors (Oliveira *et al*., 2009; Simões e Fenner, 2010; Leite *et al*., 2014; Seixas e Castro, 2014; Gagliardi *et al*., 2020).

Loading and organizing the logs in the vehicle's cargo compartment took up to half of the effective time, and this result was attributed to the need to position the wood in the vehicle to reduce empty spaces and make better use of capacity. The lower performance of the machine in this partial activity in the inverted stacking model can be associated with the inverse alignment of the logs during stack formation, increasing the number of movements to organize the bundles, and consequently, in greater time expenditure. It is important to mention that some variables interfere with the standardization and quality of the stacks, such as length, height and width; log volume and stacking method (Malinovski *et al*., 2006). Regarding the loaded crane displacement (DC), a lower performance of the machine was observed in the control and inverted stacking models compared to the adjacent model, explained by the working angle of the loader crane during the operation displacement, while in the adjacent stack, the angle did not exceed 90º, while in the other treatments, the crane displacement angle reached up to 180º, favoring the machine's approach to the stacks and the transport vehicle.

The stacking model adjacent to the road allowed for a greater production capacity, reaching up to 13.3% compared to the other treatments. The higher productivity observed in the inverted stacking model can be explained by the lower displacement of the *forwarder* during the operation, and for the execution of a productive displacement, the other treatments resulted in a greater number of machine maneuvers, mainly in the greater extraction distances. Thus, the productive displacement to perform the inverted stacking model tended to be more effective, reflected in the production gain over the other treatments in wood extraction with the *forwarder*.

In forest loading, the angle of machine movement for crane displacement was favored in the adjacent stacking model, resulting in a superior average productivity of up to 22% compared to the inverted stack model. The control model allowed for intermediate machine productivity, with a 10.7% higher average than the inverted stack model. Therefore, in addition to the working angle of the loader crane, it should be considered that the alignment of the logs in regarding the road favors the productivity of forest loading, and consequently, the placement and organization of the logs inside the transport vehicle cargo compartment. Thus, it should be considered that a smaller working angle, combined with alignment towards the access road, will favor the productivity of the loading stage, with consequent gains for logistics.

Upon analyzing the performance of the forwarder in the studied treatments, it can be seen that the higher productivity in the inverted stacking model was due to the need for a smaller amount of maneuvers and machine displacement distance. As reported by Leite *et al.* (2014), the greater extraction distances tended to increase the displacements of the machine, compromising the effective working time and productivity. Therefore, to reduce this time, several authors propose the optimization of extraction distances through efficient planning of the forest road network and the compartmentalization of work units (Malinovski *et al*., 2008; Duka *et al*., 2017; Proto *et al*., 2018). In terms of wood loading, it was observed that the adjacent stacking model contributed to the higher productivity of the forest loader, favored by the angle for moving the machine's crane, as well as the greater proximity of the piles to the road and the transport vehicle.

The production cost of the operations showed significant differences between the studied treatments. For extraction, inverted stacking had a lower cost associated with the higher productivity observed in the *forwarder*. For forest loading, adjacent stacking allowed for lower costs compared to other treatments, also associated with better performance of the loader in aligned stacks at the limit between the stand and the road. However, it is important to evaluate operations together in terms of overall costs. In this study, it was found that the current stacking model adopted by the company is still the most viable in terms of costs. In wood extraction, the inverted stacking model provided greater productivity for the *forwarder*, which is the most costly operation, being favored by the shorter distance traveled by the machine and the ease of positioning behind the stack to proceed with the unloading of the wood. Such behavior was favored in the extraction distance of up to 140 m, while above this, the control stacking model became the recommended model. The lower productivity of the machine in adjacent stacking, even with the machine traveling a shorter distance, can be explained by the lesser practice of the operator in this new stacking procedure.

CONCLUSIONS

- Stacking the logs in the inverted model contributed to greater productivity and reduced extraction costs, favored by greater ease in positioning the machine to perform the unloading of wood on the ground, being recommended for scenarios with an extraction distance of less than 140 m, while above this, it is recommended to use the current stacking model adopted by the company. For distances above this one, the use of the current stacking model adopted by the company is recommended.
- Analyzing the extraction and loading of wood simultaneously, the stacking of wood in the standard model adopted by the company was of greater operational efficiency, bringing a total cost reduction of 6.1% regarding the other models studied, being, therefore, the recommended model in the studied situation.
- The format and positioning of the wood stacks on the edge of the plot is an important aspect to be considered in operational planning, influencing the extraction and loading operations of vehicles, however, the model with the lowest overall cost should be chosen.

ACKNOWLEDGMENTS

We would like to thank the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) for financial support and forestry company for the financial and logistical support.

REFERENCES

ALVES, R. T., FIEDLER, N. C.; SILVA, E. N.; LOPES, E. S.; CARMO, F. C. A. Análise operacional do descarregamento de madeira com diferentes comprimentos em fábrica de celulose. **Re.C.E.F**., v.21, n.1, p. 1-11. 2013.

AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS (ASAE). **ASAE standards 2001: machinery, equipment and buildings: operating costs**. Iowa, Ames, 226p., 2001.

CARMO, F. C. A.; FIEDLER, N. C.; MINETTE, L. J.; SOUZA, A. P. Otimização do uso do trator florestal *forwarder* em função da produtividade, custos e capacidade de carga. **Revista Árvore**, v.39, n.3, p.561-566, 2015.

CIPRIANI, N. H.; VIEIRA, A. B.; ROCHA, R. B.; COSTA, J. N. M.; MENDES, A. M.; ARAÚJO, L. V.; JÚNIOR, J. R. V. Sistemas de produção: Cultivo de eucalipto para madeira em Rondônia. Porto Velho: **Embrapa**, 2015. 85 p.

DUKA, A.; GRIGOLATO, S.; PAPA, I.; PENTEK, T.; PORŠINSKY, T. Assessment of timber extraction distance and skid road network in steep karst terrain. **I Forest,** v.10, n.1, p.886-894, 2017.

GAGLIARDI, K.; ACKERMAN, S.; ACKERMAN, P. Multi-product forwarder-based timber extraction: time consumption and productivity analysis of two forwarder models over multiple products and extraction distances. **CROJFE**. v.41, n.2, p. 231-242. 2020.

FENNER, P. T; SIMÕES, D. Avaliação técnica e econômica do forwarder na extração de madeira em povoamento de eucalipto de primeiro corte Simões, Danilo. **Floresta**, v.40, n.4, p. 711-720, 2010.

LEITE, E. S.; FERNANDES, H. C.; MINETTE, L. J.; SOZA, A. P.; LEITE, H. G.; GUEDES, I. L. Modelagem do desempenho da extração de madeira pelo forwarder. **Revista Árvore**, v.38, n.5, p. 839-887, 2014.

LOPES, E. S.; DINIZ, C. C. C.; SERPE, E. L.; CABRAL, O. M. J. Wood assortment effect on productivity and *forwarder* cost in commercial thinning of *Pinus taeda*. **Scientia Forestalis**, v.44, n.109, p. 57-66, 2016.

MACHADO, C. C. **Colheita Florestal**. 3 ed. Viçosa: Editora UFV, 2014, 543 p.

MALINOVSKI, R. A.; MALINOVSKI, R. A.; MALINOVSKI, J. R.; YAMAJI, F. M. Análise das variáveis de influência na produtividade das máquinas de colheita de madeira em função das características físicas do terreno, do povoamento e do planejamento operacional florestal. **Floresta**, v.36, n.2, p. 169-182, 2006.

MALINOVSKI, R., A.; FENNER, P. T.; SCHACK-KIRCHNER, H.; MALINOVSKI, J. R.; MALINOVSKI, R. A. Otimização da distância de extração de madeira com o forwarder. **Scientia Forestalis**, v.36, n.79, p. 171-179, 2008.

MAZÃO, C.; BROWN, R. O.; ROBERT, R. C. Análise de produtividade de um *forwarder* com aumento da área da garra de carregamento. **Espacios**, v.38, n.1, p.20-27, 2016.

MINETTI, L. J.; SOUZA, A. P.; FIEDLER, N. C.; SILVA, E. N. **Carregamento e descarregamento**. In: Colheita Florestal / Carlos Cardoso Machado (Org.). 3ª ed. Viçosa: UFV, p. 162-172, 2014. 543p.

NUNES, I. B; LOPES, E. S.; PAGNUSSAT, M. B.; ARCE, J. A.; Productivity curve models in eucalypt timber forwarding. **Southern Forests**, v.83, n.3, p. 01-09. 2021.

OLIVEIRA, D.; LOPES, E. S.; FIEDLER, N. C. Technical and economical evaluation of the *forwarder* in the extraction of the pine logs. **Scientia Forestalis**, v.37, n.84, p. 525-533, 2009.

PROTO, A. R.; MACRÌ, G.; VISSER, R.; RUSSO, D. Comparison of Timber Extraction Productivity between Winch and Grapple Skidding: A case Study in Southern Italian Forests. **Forests**, v.9, n.61, p.1-12, 2018.

SEIXAS, F; CASTRO, X. **Extração**. In: Colheita Florestal / Carlos Cardoso Machado (Org.). 3ª ed. Viçosa: UFV, p. 106-157, 2014. 543p.

SIMÕES, D.; FENNER, P. T. Avaliação técnica e econômica do forwarder na extração de madeira em povoamento d eucalipto de primeiro corte. **Floresta**, v.40, n.4, p. 711-720, 2010.