MODELING TECHNICAL, ECONOMIC AND ENVIRONMENTAL PARAMETERS OF FOREST MACHINES ACCORDING TO THE VOLUME OF THE TREES

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Resumo

Modelagem de parâmetros técnicos, econômicos e ambientais de máquinas florestais em função do volume das árvores. Aumentar a produtividade de harvester e forwarder e manter o consumo de combustível é a chave para uma colheita florestal mais eficiente, com menor impacto ambiental e maiores retornos econômicos. Mediante isso, objetivou-se com a presente pesquisa avaliar a influência do volume das árvores em relação aos parâmetros técnicos, econômicos e ambientais do harvester e forwarder em florestas de eucalipto. A pesquisa foi executada no município de Teixeira de Freitas, Bahia, Brasil. Foram avaliadas as operações do harvester e forwarder em povoamentos florestais com volume médio individual de 0,08; 0,12; 0,16 e 0,20 m³ árvore^{-1}. Foi determinado produtividade, demanda energética, custo de produção e quantidade de dióxido de carbono emitido. Os dados foram submetidos à análise de regressão, sendo os modelos ajustados por meio do coeficiente de determinação, comportamento do fenômeno e significância dos coeficientes de regressão. De forma a se obter uma colheita florestal com menor impacto ambiental e mais viável economicamente as árvores devem ser abatidas com volume médio individual entre 0,16 e 0,20 m³ árvore^{-1}.

Palavras-chave: Harvester, forwarder, mecanização florestal**.**

Abstract

Increasing harvester and forwarder productivity and maintaining fuel consumption is the key to more efficient forest harvesting, with less environmental impact and greater economic returns. Therefore, the objective of this research was to evaluate the influence of the volume of trees on technical, economic, and environmental parameters of harvester and forwarder in eucalyptus forests. The research was carried out in the municipality of Teixeira de Freitas, Bahia, Brazil. Were evaluated the harvester and forwarder operations in forest stands with an average individual tree volume of 0.08; 0.12; 0.16 and 0.20 m³ tree^{-1}. Productivity, energy demand, production cost and amount of carbon dioxide emitted were determined. The data were submitted to regression analysis, and the models were adjusted utilizing the determination coefficient, phenomenon behavior, and significance of the regression coefficients. To obtain a forest harvest with less environmental impact and more economically viable, trees should be felled with an individual average volume between 0.16 and 0.20 m³ tree^{-1}.

Keywords: Harvester, forwarder, forest mechanization.

INTRODUCTION

Among the forestry activities, forest harvesting is the one that generates the highest cost for the wood placed in the factory, comprising the operations of cutting, extracting, and loading the wood in transport vehicles (SANTOS *et al*., 2016). In Brazil, wood harvesting operations are usually carried out by mechanized methods, using machines of high productive capacity (RODRIGUES *et al*., 2018), aiming to increase yield and thus reduce production costs (SANTOS *et al*., 2016).

The harvester and the forwarder are the main forestry machines used to harvest wood using the cut-to-length system. The Harvester is used to cut, delimb, peel, and section logs, providing high-quality log dimensions, a characteristic required mainly in companies that operate in the generation of multi-products (MURPHY, 2013). The forwarder is used to transport the wood from the interior of the stand to the edges of the roads or intermediate yard. Both machines are designed to increase productivity, reduce costs, safety and comfort during operations. However, these machines are expensive and emit polluting gases into the atmosphere.

The average production cost of the harvester and forwarder in forest harvesting operations carried out in Germany was 43 US\$ m^{-3}, in Spain 17 US\$ m^{-3} and in Brazil 4.17 US\$ m^{-3} (LAINA *et al*., 2013; GHAFFARIYAN *et al*., 2017; SANTOS *et a*l., 2018a). The cost of fuel consumption is one of the most representative expenditures in the operational cost of forest machines. Therefore, increasing machine productivity and maintaining fuel consumption is the key to more efficient forest harvesting, with less environmental impact and greater economic returns (SPINELLI *et al*., 2018).

Reducing fuel consumption by forest machines can contribute to reducing operating and production costs, as well as contributing to reducing pollutant gas emission rates since there is an equivalence between the amount of fuel burned and the number of gases emitted to the atmosphere (SANTOS *et al*., 2018b).

Mechanized operations performed during forest harvesting emit greenhouse gases (ZHANG *et al*., 2016). Such a situation occurs due to the burning of fossil fuels at high temperatures, which generates polluting gases such as carbon dioxide. Technological advancement has provided improvements in the energy efficiency of machines, however, there is still room for improvement (LANG *et al*., 2018). Harvester and forwarder emit 9.9 to 14.7 kg CO_{2eq} per ton of harvested wood (HANDLER *et al*., 2014). Emitting lower amounts of polluting gases per cubic meter of wood makes forestry operations more environmentally sustainable.

Harvesting trees with a high volume of wood can mitigate environmental impacts and reduce production costs. Higher forest productivity, in terms of volume, results in greater productivity of forest machines, with a consequent reduction in production costs (SIMÕES *et al*., 2014; CARMO *et al*., 2015). The productivity and energy demand of the machines is the most influential factors in the emission of pollutants and in the cost of production (ZHANG *et al*., 2016).

Based on the above, the objective was to evaluate the influence of wood volume on technical, economic, and environmental parameters of the harvester and forwarder in eucalyptus forests.

MATERIAL AND METHODS

Study area

The research was carried out in areas of forest harvesting operations located in the municipality of Teixeira de Freitas - BA. The region has an average annual temperature of 24.4 °C and an average annual rainfall of 1,350 mm. The area was populated with hybrid clones of *Eucalyptus grandis* x *Eucalyptus urophylla*, planted in a spacing of four meters between rows and three meters between plants. The survey was carried out between January and March 2019.

Harvest system

The research was carried out in a forest harvesting system cut to length composed of harvester and forwarder machines. The harvester was responsible for cutting, stripping, delimbing, debarking, sectioning, and stacking the 6.20 meter long logs. The forwarder carried out the extraction of wood from the interior of the stands to the sides of the roads.

The harvester used consisted of a Komatsu hydraulic excavator, model PC200F-8M0; equipped with mats; diesel engine, brand Komatsu, model SAA6D107E-1, with six cylinders and 110 kW of nominal power and cylinder head, brand Komatsu, model 370E (Figure 1A).

The forwarder used was a Komatsu model 895 with a six-wheel drive. The machine was equipped with the AGCO power engine, model 74CW3, with six cylinders and rated power of 193 kW at 1,950 rpm. The cargo compartment had a capacity of 23 cubic meters of wood (Figure 1B).

Figure 1. (A) Harvester PC200F-8M0 and (B) forwarder 895.
Figura 1. (A) Harvester PC200F-8M0 e (B) forwarder 895.

Experimental units

The research was carried out with a mean individual volume of trees of 0.08; 0.12; 0.16 and 0.20 m³ $tree^{-1}$, totaling four treatments. In each volume, 20 experimental plots were demarcated for each machine. Simple random sampling was used to demarcate the experimental plots. In each plot, the number of planting failures, dead trees, broken trees and bifurcated trees was quantified, the last being counted as a single tree.

The experimental plots of the harvester had a rectangular shape, arranged in four rows with twenty trees each, totaling eighty trees per plot. The harvester's operational cycle was subdivided into displacement and search, felling, cutting, and processing operations. About the forwarder, each experimental plot was represented by an operating cycle of the machine, that is, the time spent for the machine to perform empty displacement, loading, loaded displacement, and unloading. In each plot, information was collected to determine productivity, energy demand, production cost, and carbon dioxide emission.

Determining the individual volume of trees

The volume per tree (m^3 $tree^{-1}$) without bark was determined by rigorous cubing following the Newton method (HUSCH *et al*., 2003). The volume of twenty trees in each treatment was measured, chosen through simple random sampling.

Machine instrumentation

To measure the amount of fuel consumed in each experimental plot, a volumetric flow meter (flowmeter) was installed in the harvester and forwarder. The flowmeter was installed in the fuel supply system, right after the primary filter. A flow meter, brand flowmate M-III®, model LSF41C was used. Consumption was determined by the equipment based on the rotation frequency of the rotors that constitute it, with one rotor turn corresponding to 1 milliliter of fuel consumed. Along with the flowmeter, a graphic display (indicator) was installed, brand TechMeter, model LCT. The amount of fuel consumed by the machines was instantly visualized on the graphic display in liters per hour.

Technical parameters

The yields (m^3 h^{-1}) of the harvester and forwarder were calculated through the ratio between the volume of wood in the plot (m^3) by the time spent in that plot (h). The volume in each harvester plot was calculated as the product between the number of trees in each plot and the respective individual volume of the trees. The volume per parcel of the forwarder was equal to the amount of wood present in the load compartment of the machine, that is, 23 m^3 per load. The energy demand, in L m^{-3}, was determined through the quotient between productivity (m^3 h^{-1}) and hourly fuel consumption (L h^{-1}).

Economic parameters

The production cost, in US$ m^{-3}, was determined through the quotient between the operational cost and the productivity of the machine. The operating cost was determined by the sum of fixed and variable costs. Regarding fixed costs, the cost of depreciation, interest, insurance, security, administrative staff, operator's salary, and maintenance personnel costs were calculated. The variable cost was composed of the cost of fuel, hydraulic oil, lubricating oil, grease, chain oil, spare parts, and the organization of the module area. An exchange rate of 1 US$ = R$ 5.36, quoted on 06/25/2020, was used.

Environmental parameters

As an environmental parameter, the amount of carbon dioxide (CO_{2eq}) emitted by the harvester and forwarder during wood harvesting was measured. The values were calculated using the equation below. A specific emission factor for carbon dioxide was established, as determined by the Intergovernmental Panel on Climate Change (IPCC, 2006).

$$ACD = \frac{EF\ \ HFC\ \ CV}{P}$$

where: ACD = amount of carbon dioxide (kg m^{-3}); EF = emission factor (Kg TJ^{-1}); HFC= Hourly fuel consumption (Kg h^{-1}); CV = Calorific value (TJ kg^{-1}); and P = productivity (m^3 h^{-1}).

Data analysis

Data were analyzed using simple regression, the independent variable being the volumes of wood (0.08; 0.12; 0.16; 0.20 m^3 $tree^{-1}$) and the dependent variables productivity, energy demand, production cost, and carbon dioxide. The models were selected based on the coefficient of determination, behavior of the phenomenon under study, and the significance of the regression coefficients, using the “t” test and adopting the 5% probability level.

RESULTS

Technical analysis

The volume of wood significantly and quadratically influenced the production values of the harvester and forwarder (Figure 2A). The volume of wood had a significant and linear effect on the energy demand values of the harvester and a significant and quadratic effect on the energy demand values of the forwarder (Figure 2B). The productivity and energy demand values of the harvester and forwarder are shown in Table 1.

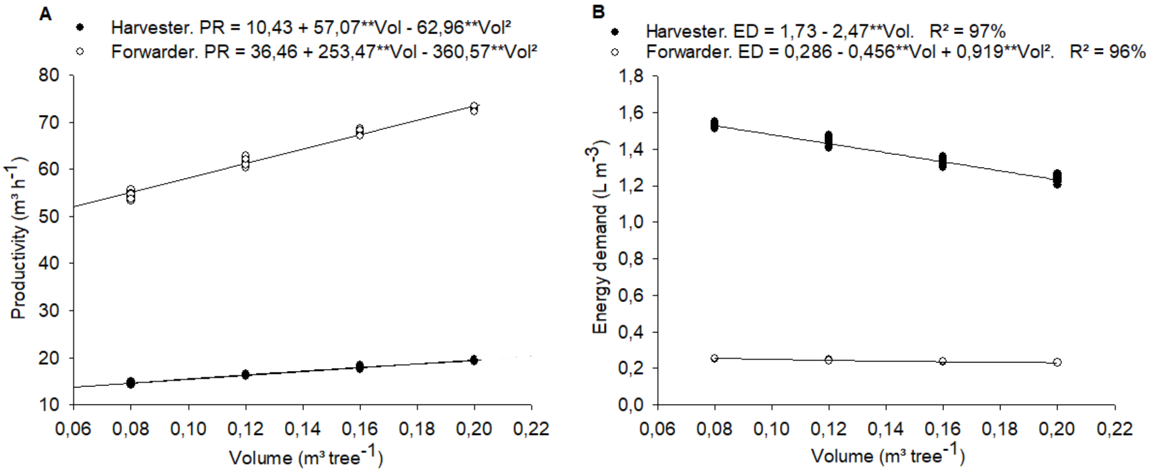

Figure 2. Behavior of productivity (PR) and energy demand (ED) as a function of wood volume. Where: Vol = volume (m³ $tree^{-1}$); ** = significant at the 1% probability level; aHand R^2 = coefficient of determination.
Figura 2. Comportamento da produtividade (PR) e demanda energética (ED) em função do volume da madeira. Em que: Vol = volume (m³ $árvore^{-1}$); ** = significativo ao nível de 1% de probabilidade; e R^2 = coeficiente de determinação.

Table 1. Values of productivity and energy demand for harvester and forwarder in the four volumes surveyed.
Tabela 1. Valores de produtividade e demanda energética de harvester e forwarder nos quatros volumes pesquisados.

Volume (m³ $tree^{-1}$)	Harvester		Forwarder	
	Productivity (m³ h^{-1})	Energy demand (L m^{-3})	Productivity (m³ h^{-1})	Energy demand (L m^{-3})
0,08	14,59	1,53	54,43	0,255
0,12	16,37	1,43	61,68	0,244
0,16	17,95	1,33	67,79	0,236
0,20	19,33	1,23	72,73	0,231

Production cust

The volume of wood had a significant and quadratic effect on the production cost of harvester and forwarder (Figure 3). The production cost values of both machines can be seen in Table 2. The total production cost of the short log system was 5.03; 4.45; 4.02; and US$ 3.75 m^{-3} in volumes of 0.08; 0.12; 0.16 and 0.20 m³ $tree^{-1}$, respectively, with the harvester responsible for 75% of the total.

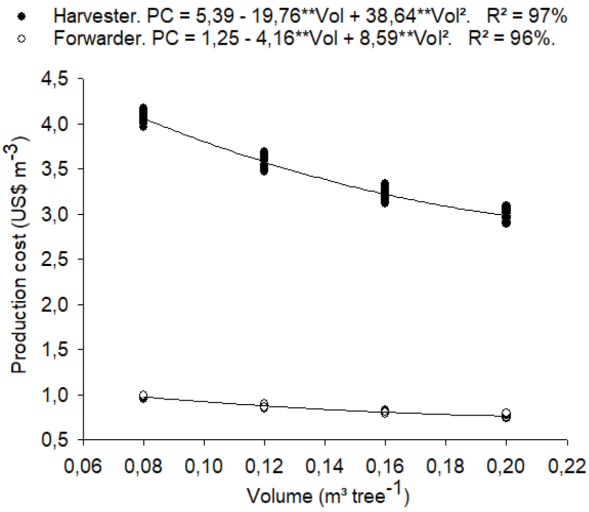

Figure 3. Behavior of production cost (PC) as a function of wood volume. Where: Vol = volume (m³ $tree^{-1}$); ** = significant at the 1% probability level; and R^2 = coefficient of determination.

Figura 3. Comportamento do custo de produção (CP) em função do volume da madeira. Em que: Vol = volume (m³ $árvore^{-1}$); ** = significativo ao nível de 1% de probabilidade; e R^2 = coeficiente de determinação.

Table 2. Production cost values for harvester and forwarder in the four volumes surveyed.

Tabela 2. Valores de custo de produção de harvester e forwarder nos quatros volumes pesquisados.

Volume (m³ $tree^{-1}$)	Production cost (US$ m^{-3})	
	Harvester	Forwarder
0,08	4,06	0,97
0,12	3,58	0,88
0,16	3,22	0,81
0,20	2,98	0,76

Carbon dioxide

There was a significant and linear effect of wood volume on the amount of carbon dioxide emitted by harvester and forwarder (Figure 4). The CO_{2eq} values are shown in Table 3. Harvester and forwarder together emitted 5.42; 5.33; 5.23 and 5.11 kg CO_{2eq} m^{-3} of harvested wood, in volumes of 0.08; 0.12; 0.16 and 0.20 m³ $tree^{-1}$, respectively.

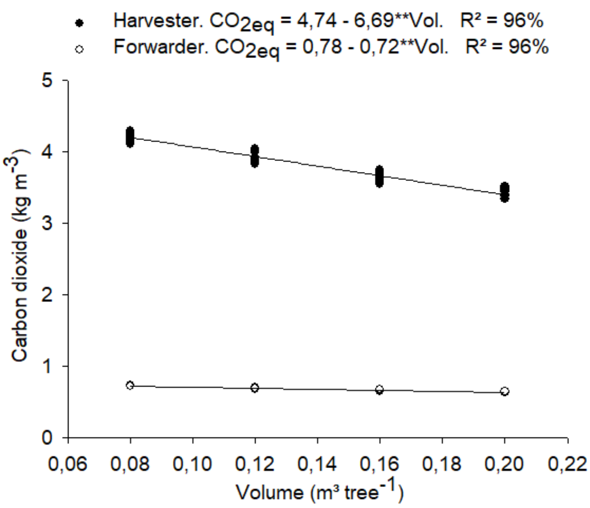

Figure 4. Behavior of the amount of carbon dioxide (CO_{2eq}) emitted as a function of the volume of the wood. Where: Vol = volume (m³ $tree^{-1}$); ** = significant at the 1% probability level; and R^2 = coefficient of determination.

Figura 4. Comportamento da quantidade de dióxido de carbono (CO_{2eq}) emitida em função do volume da madeira. Em que: Vol = volume (m³ árvore^{-1}); ** = significativo ao nível de 1% de probabilidade; e R^2 = coeficiente de determinação.

Table 3. Carbon dioxide values of harvester and forwarder in the four volumes surveyed.
Tabela 3. Valores de dióxido de carbono de harvester e forwarder nos quatros volumes pesquisados.

Volume (m³ tree^{-1})	Carbon dioxide (kg m^{-3})	
	Harvester	Forwarder
0,08	4,69	0,72
0,12	4,64	0,69
0,16	4,57	0,66
0,20	4,47	0,64

DISCUSSION

The increase in the volume of wood provided an increase in the productivity of the harvester since while the individual volume of trees increased by 150% (0.08 to 0.20 m³ tree^{-1}), the number of trees felled and processed per hour decreased only 88%. In the volumes of 0.08 and 0.20 m³ tree^{-1}, 182 and 97 trees were felled and processed per hour, respectively. This fact can be explained by the need for a shorter individual harvesting time for trees with volumes of 0.08m³ because they are smaller and thinner, which increases the number of operations (moving and searching, cutting, felling and processing) in a plot, and thus the harvest time of the same, resulting in a decrease in machine productivity. According to Rodrigues *et al*. (2018), the characteristics of the trees affect the performance of the machine in the execution of the forestry operation.

With regard to the forwarder, the increase in productivity with the increase in the volume of wood was because greater volumes are required for a smaller number of wood bundles to complete the machine's cargo box, thus resulting in less loading and unloading time. Similar results were observed by Lopes *et al*. (2017) and Visser & Spinelli (2012), in which they found a direct relationship between productivity and tree volume. Such results emphasize the need for planting in regions with more productive soils and the adoption of more efficient forest management, which maximizes the volume of trees in the short term and, in some situations, carries out forest harvesting later. According to Rodrigues *et al*. (2018), the productivity and production costs of forest machines are directly influenced by the individual volume of the trees.

The reduction in energy demand, production cost, and carbon dioxide with the increase in the volume of trees occurred due to a significant increase in productivity and a non-accentuated increase in the hourly fuel consumption of the machines. When analyzing the values in the volumes of 0.08 and 0.20 m³ tree^{-1}, it was found that the productivity of the harvester increased by 32% as the hourly consumption grew by 8%. About the forwarder, productivity increased by 34% while hourly fuel consumption rose by 17%. Productivity and hourly fuel consumption are the main items forming the production cost of machines and are indicative of the efficiency of the process of converting the chemical energy of the system into useful work.

In all volumes surveyed, the harvester emitted an average of 85% more CO_{2eq}, when compared to the forwarder. Possibly due to its high fuel consumption, 50% more, and low productivity, 276% less. The factors that most influence the emission of polluting gases during forest harvesting are productivity and fuel consumption, the first being a positive factor and the second a negative factor (ZHANG *et al*., 2016). Forest harvesting operations are responsible for most pollutant gas emissions throughout the wood production process, due to the large consumption of fossil fuel (DIAS & ARROJA, 2012; MORALES *et al*., 2015).

CONCLUSIONS

- The volume of wood significantly influences the values of productivity, energy demand, production cost and carbon dioxide of harvester and forwarder. In order to obtain a forest harvest with less environmental impact and more economically viable, the trees must be felled with an average individual volume between 0.16 and 0.20 m³ tree^{-1}.

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