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Articles

Modeling the optimal density of forest roads for different scenarios based on average individual forest volume and vehicular load combinations

Modelagem da densidade ótima de estradas florestais para diferentes cenários com base no volume médio individual de árvores e nas combinações veiculares de carga

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ABSTRACT

Forest logistics processes account for over 50% of production costs, emphasizing the need to optimize these stages. Road network planning should follow optimization principles, particularly through the use of Optimal Road Density models. However, these models rarely consider vehicle load capacity and Average Tree Volume. This study aimed to determine the optimal forest road density under different scenarios combining average Individual Tree Volume and Vehicle Load Configurations. The study was conducted in Ribas do Rio Pardo, Mato Grosso do Sul, Brazil. The optimal road density was determined by minimizing the sum of operational costs, forest harvesting costs, road construction and maintenance costs, and the loss of productive area. The analysis considered various scenarios of average tree volume (0.15, 0.20, and 0.25 $m^3.tree^{-1}$) associated with different vehicle configurations (bitrem, tritrem, and hexatrem). Operational costs were estimated based on mechanized forest harvesting, while road costs were calculated as the sum of pavement construction and maintenance expenses. The costs related to the loss of productive area were derived from the value of the land occupied by roads and the estimated revenue from the effective use of the area. The variation in optimal road density across the evaluated scenarios ranged from 19.57 to 27.61 $m \cdot ha^{-1}$, corresponding to the lowest average volume of 0.15 $m^3.tree^{-1}$ (hexatrem) and the highest of 0.25 $m^3.tree^{-1}$ (bitrem). For the 0.15 $m^3.tree^{-1}$ volume scenario, the optimal densities were 25.57 and 23.68 $m \cdot ha^{-1}$ for bitrem and tritrem, respectively. For the 0.20 $m^3.tree^{-1}$ scenario, the values were 26.16, 24.46, and 20.45 $m \cdot ha^{-1}$ for bitrem, tritrem, and hexatrem, respectively. Finally, for the 0.25 $m^3.tree^{-1}$ scenario, the optimal densities were 26.91 and 22.06 $m \cdot ha^{-1}$ for tritrem and hexatrem, respectively. We concluded that the Optimal Road Density varies according to the Individual Average Volume of trees and the Vehicle Load Capacity. Lower Individual Average Volumes combined with higher-capacity vehicles resulted in lower Optimal Road Density values.

Keywords: Forestry logistics; Vehicular load combinations; Forestry operations; Forest road network; Operating costs

RESUMO

Os processos logísticos florestais representam mais de 50% dos custos de produção, o que reforça a necessidade de otimizar essas etapas. O planejamento da rede viária deve seguir princípios de otimização, especialmente por meio da utilização de modelos de Densidade Ótima de Estradas. No entanto, esses modelos raramente consideram a capacidade de carga dos veículos e o Volume Médio Individual das Árvores. Este estudo teve como objetivo determinar a densidade ótima de estradas florestais em diferentes cenários que combinam o volume médio individual das árvores e as configurações veiculares de carga. A pesquisa foi conduzida no município de Ribas do Rio Pardo, Mato Grosso do Sul, Brasil. A Densidade Ótima de Estradas foi determinada por meio da minimização da soma dos custos operacionais, custos de colheita florestal, custos de construção e manutenção de estradas, e da perda de área produtiva. A análise considerou cenários com volumes médios individuais de 0,15; 0,20 e 0,25 m^3.árvore^{-1}, associados às configurações veiculares bitrem, tritrem e hexatrem. Os custos operacionais foram estimados com base na colheita florestal mecanizada, enquanto os custos das estradas foram calculados somando-se os valores de implantação e manutenção do pavimento. Já os custos relacionados à perda de área produtiva foram derivados do valor da terra ocupada pelas estradas e da receita estimada com o uso efetivo da área. A variação da Densidade Ótima de Estradas entre os cenários avaliados foi de 19,57 a 27,61 m·ha^{-1}, correspondendo ao menor volume médio (0,15 m^3.árvore^{-1}, com hexatrem) e ao maior volume médio (0,25 m^3.árvore^{-1}, com bitrem). No cenário de 0,15 m^3.árvore^{-1}, as densidades ótimas foram de 25,57 e 23,68 m·ha^{-1} para bitrem e tritrem, respectivamente. Para o cenário de 0,20 m^3.árvore^{-1}, os valores foram de 26,16; 24,46 e 20,45 m·ha^{-1} para bitrem, tritrem e hexatrem, respectivamente. Por fim, no cenário de 0,25 m^3.árvore^{-1}, as densidades ótimas foram de 26,91 e 22,06 m·ha^{-1} para tritrem e hexatrem, respectivamente. Concluímos que a densidade ótima de estradas varia conforme o volume médio individual das árvores e a capacidade de carga dos veículos, sendo que menores volume médio individual das árvores combinados com veículos de maior capacidade resultaram em menores valores de densidade ótima de estradas.

Palavras-chave: Logística florestal; Combinação veicular de carga; Operações florestais; Malha viária florestal; Custos operacionais

1 INTRODUCTION

Wood supply management is established based on forestry macro-planning, which includes all topographic characteristics and the allocation of forest roads, which can be characterized as roads with low traffic volume, due to the number of vehicular load combinations (VLC). These combinations have technical characteristics associated with the integration of the forestry base and the transformation industry, demanding cost minimization due to the representativeness in the composition of the logistics costs in the final product.

One of the alternatives for reducing these costs is the use of load vehicle combinations with greater wood transport capacity, associated with the sizing of the forest road network. Given this, Simões *et al*. (2022) point out that forest managers need to dedicate efforts to the logistical planning of the entire production process, from implementation to delivery of the final product.

Currently, Brazilian forest plantations occupy 9.55 million hectares (ha), of which 78% are composed of species of the genus *Eucalyptus spp.* (Ramalho *et al*. 2022). This is due to a series of characteristics, such as edaphoclimatic conditions, territorial extension and investment in technological development, research and innovation in the forestry sector (Lacerda *et al*. 2022).

Despite the significant area covered by forest stands with commercial destinations all over the world, population growth, changes in consumption patterns and the increase in demand for raw materials of forest origin, have meant that logistical and operational planning activities of companies in the field are increasingly intensified to ensure the continuous and quality production of these products with a high yield rate (Fiedler *et al*. 2020, Keramati *et al*. 2020, Pitz *et al*. 2021).

Therefore, during forest logistic planning, the allocation and optimized construction of roads must be taken as a basis for carrying out subsequent extraction and transport activities (Vargas *et al*. 2022). However, for road network planning to be efficient, managers need to consider factors associated with quality, uniformity and road maintenance costs (Beaudoin *et al*. 2008). The factor that is closely intertwined with these variables is the Optimal Road Density (ORD).

The ORD allows estimating the ideal amount of forest roads per effective, that is, the optimal amount of roads, in linear meters, concerning the planting area, moreover, it is one of the most important indicators for cost reduction and future gains with productive areas. For this reason, the extraction must be planned considering this parameter. In turn, the dimensioning of the forest road network directly influences the wood harvesting system, forest management and terrain conditions (Zagonel *et al*. 2008. Simões *et al*. 2022).

Thus, it is significant to ORD in the reduction of operating costs and in the efficiency of the extraction and transportation of wood. Despite technical and economic advances, a lack of integration between the sizing of the road network and the capacities of the vehicular load combinations can be seen (VLC), which highlights a gap in forest planning.

In this study, we consider the problem of how to improve the ORD in different scenarios of IAV and VLC, analyzing variables such as the cost of construction, maintenance, extraction and storage capacity. The main hypothesis of this study is that the Optimal Road Density (ORD) varies according to the Vehicular Load System (VLS) and the Individual Average Volume (IAV), such that higher-capacity Vehicular Load Combinations (VLCs), when associated with different levels of forest productivity, result in a lower ORD and reduced total wood production costs.

Given this context, the objective was to determine the ORD based on vehicular load combinations with different load capacities used in the transport of short logs from *Eucalyptus*-planted forests.

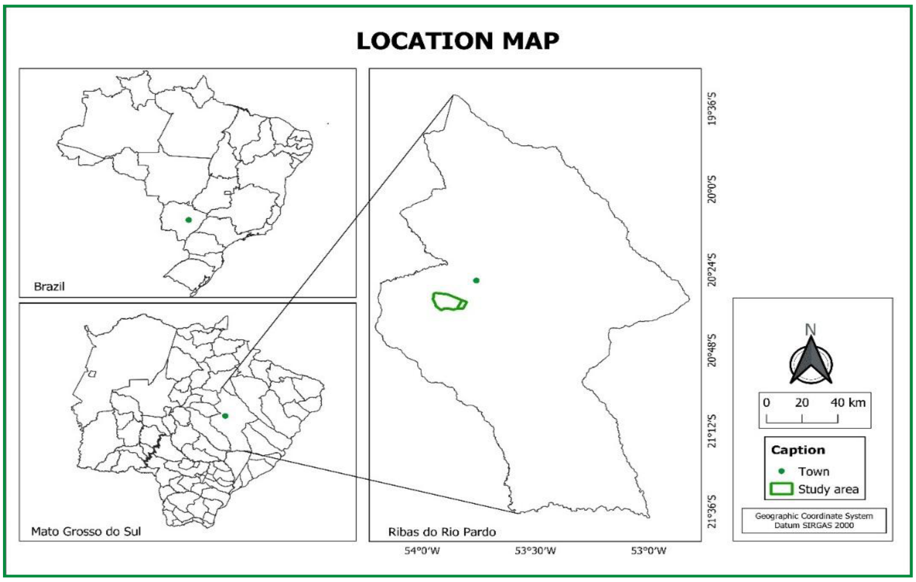
2 MATERIAL AND METHODS

2.1 Characterization of the study area

The study area was located in the Cerrado Biome, in the municipality of Ribas do Rio Pardo, central-eastern region of Mato Grosso do Sul, between the geographic coordinates 20°26’ 36” South latitude and 53°45’36” longitude West (Figure 1). In that área, there were 6,050.3 ha with planted forests of *Eucalyptus spp.* and 3,758.4 with a legal reserve and permanent preservation areas.

The predominant climate in the region is of the “Aw” type (tropical climate with dry season, with summer rains and dry winter), according to the Köppen classification. Álvares *et al*. 2013). It had an average annual temperature ranging between 19 and 23°C, precipitation around 1,300 mm per year and the average altitude of the region is 380 meters at sea level (Souza *et al*. 2017).

Figure 1 – Study area located in the municipality of Ribas do Rio Pardo, Mato Grosso do Sul, Brazil



Source: Authors (2025)

2.2 Wood harvesting system

The wood harvesting system analyzed in the road density study, under the different conditions of IAV and VLC, was the short logs one (cut to length – CTL). The CTL system is composed of the harvester that performs the cutting and processing and the forwarder that performs the extraction of the logs.

The forwarder adopted by the company for forest extraction was the Komatsu brand, model 895, with a load capacity of 20 tons (t) (Figure 2).

Figure 2 – Extraction machine adopted in the forest company (Forwarder)

Source: Authors (2025)

2.3 Characterization of VLC in forest transportation

Three VLCs were considered, two with authorization for on-road traffic and one used only off-road, namely:

Bitrem: tractor vehicle with 3 axles, a 2-axle semi-trailer with a fifth wheel at the rear of its chassis and a second 2-axle semi-trailer, with a Combined Total Gross Weight (CTGW) of 57 t, net load capacity of approximately 37 t and a maximum length of 19.80 m, on-road (BRAZIL 2006).

Tritrem: made up of 4 vehicles, one tractor vehicle with 3 axles, two 2-axle semi-trailers with a fifth wheel at the rear of each chassis and a third 2-axle semi-trailer. This set has a Combined Total Gross Weight (CTGW) of 74 t, a net load capacity of approximately 48.8 t and 9 axles in total. Maximum length of 30.00 m (BRAZIL 2006).

Hexatrem: can be described as a set formed by 7 vehicles, being a tractor vehicle with 3 axles, 5 semi-trailers with 2 axles, with a fifth wheel at the rear of each chassis and another sixth semi-trailer with 2 axles. This set has a Combined Total Gross Weight (CTGW) of 250 t, a net load capacity of approximately 197.3 t and 15 axles in total. Length close to 60 m.

In the present study, the behavior of the optimal road density was simulated based on three different forest IAV scenarios: 0.15, 0.20 and 0.25 $m^3.tree^{-1}$ (Table 1).

Table 1 – Study scenarios relating vehicle type to forest IAV

IAV ($m^3.tree^{-1}$)	Forest Transport VLC Type		
0.15	Bitrem	Tritrem	Hexatrem
0.20	Bitrem	Tritrem	Hexatrem
0.25	Bitrem	Tritrem	Hexatrem

Source: Authors (2025)

Each IAV scenario was associated with three types of VLC used to transport wood. They are realistic scenarios, which represent the average productivity of the forests and the wood transport strategy in the study region.

2.4 Determination of operating costs

The operating costs of building and maintaining roads, logging and loss of productive area in different scenarios, in addition to the productivity of equipment used in operations, were generated based on data provided by the forestry company, and will be detailed in the items below.

2.5 Forest Roads

Depreciation costs, in relation to road construction, were obtained based on the methodology applied by Souza *et al*. (2018). This method is based on the dilution of the amount invested in the construction of the road, considering six years (harvest cycle), this period, which is the reconstruction of the roads, according to Equation (1):

$$DP = \frac{CRC}{IT} \quad (1)$$

In which: DP is depreciation (US$.m^{-1}); CRC is the cost of road construction operations (US$.m^{-1}); IT is the interval between harvest (years).

Opportunity costs were considered as the costs related to the use of land and the capital employed in the construction of roads. The opportunity cost of capital was calculated according to Equation (2) of the USDA (2001) apud Souza *et al*. (2018):

$$Ccapital = \frac{Vi}{2 * i} \quad (2)$$

In which: Ccapital is the annual opportunity cost of capital (US$.m^{-1}.yr^{-1}); Vi is the initial investment value for road construction (US$.m^{-1}); i is the interest rate (8% p.a.)

After determining the depreciation and opportunity costs of capital in reais per linear meter, they were converted into reais per cubic meter of wood (US$.m^{-3}), according to Equation (3):

$$CC = \frac{(DP + Ccapital) * RD * A}{V} \quad (3)$$

In which: CC is the construction cost (US$.m^{-3}); DP is the depreciation (US$.m^{-1}); Ccapital is the capital opportunity cost (US$.m^{-1}); RD is road density (m.m^{-2}); A is the effective area of the farm, planting and roads (m^2); V is the total volume of wood on the farm (m^3).

Costs related to maintenance activities were not depreciated, as the calculation was considered only for the specific period, being generated according to Equation (4):

$$MC = \frac{COM * RD * A}{V} \quad (4)$$

In which: MC is the cost of road maintenance (US$.m^{-3}); COM is the cost of maintenance operations (US$.m^{-1}); RD is road density (m.m^{-2}); A is the total area with settlement and roads (m^2); V is the total volume of wood on the farm (m^3).

With this, the final calculation of the cost of roads is the following Equation (5):

$$Croad = CC + MC \quad (5)$$

In which: Croad is the total cost with forest roads (US$.m^{-3}); CC is construction cost (US$.m^{-3}); CM is road maintenance cost (US$.m^{-3}).

2.6 Forest extraction

The operating costs of the forwarder in the extraction of wood were obtained through the following fixed costs: depreciation, interest and insurance; and the following variable costs: fuel, maintenance, lubricating oils, grease, hydraulic oil, rolling stock, labor and others.

Wood extraction costs were calculated based on the operating cost of the machine and the estimated productivity in the extraction operation, as described in Equation (6):

$$Cforw = \frac{CO}{Pr} \tag{6}$$

In which: Cforwis cost of forest extraction (US$.m^{-3}); CO is the operating cost of the machine (US$.h^{-1}); Pr is the average effective productivity of the operation (m³.h^{-1}).

The productivity of the forwarder in the extraction was obtained through a model provided by the company, which estimates the productivity of the machine from the variables of the average distance of extraction (AFD) and average individual volume of the forest (IAV). It should be noted that the model was developed by the company based on a historical database, which comprises all the harvesting modules, through notes via the telemetry system and average extraction distances acquired via the elaboration of the operational micro-planning of the wood harvest.

Through the AFD generated in the different scenarios, it was possible to obtain the road density (RD), which was calculated by the equation of the efficiency factor of forest roads described by FAO (1974) and used by Ghaffarian (2009) and Faria *et al*. (2022), as described in Equation (7):

$$RD = \frac{a * 1000}{AFD} \tag{1}$$

In which: AFD is the average distance of extraction (m); RD is the road density (m.ha^{-1}); a is the road efficiency factor.

A factor equal to 4.5 was adopted since plots and roads are not perfectly linear, that is, it is unlikely that there will be plots and roads with a perfect geometric shape as recommended by (FAO 1974).

2.7 Loss of productive area

Subsequently, based on previous analyses, the value associated with the area occupied by land with roads was obtained by the product of the price of land and the area occupied by roads, according to Equation (8):

$$LC = Ar + Pl \tag{8}$$

In which: LC is the cost of land in an area with roads (US$); Ar is the area occupied by roads (ha); Pl is the land price ($US\$.ha^{-1}$).

The calculation of total revenue in areas occupied by roads was obtained through Equation (9):

$$Tr = Ar * v * Wp \tag{9}$$

In which: Tr is the total revenue in the area with roads (US$); Ar is the area occupied by roads (ha); v is the volume of wood ($m^3.ha^{-1}$); Wp is the price of standing wood ($US\$.m^{-3}$).

Finally, through Equation (10), the value associated with the loss of productive area was obtained:

$$Clopa = \frac{(LC * Tr)}{V} \tag{10}$$

In which: Clopa is the cost of loss of productive area ($US\$.m^{-3}$); LC is the cost of land in an area with roads (US$); Tr is total revenue in the area with roads (US$); V is the total volume of wood on the farm (m^3).

2.8 Determination of optimal road density

The current density of roads (RD) in the study area was determined by dividing the total length of roads (meters) by the effective area available for production (hectares), according to the methodology used by Lotfalian (2009), described in the Equation (11):

$$RD = \frac{R}{S} \tag{11}$$

In which: RD is the current density of roads ($m.ha^{-1}$); R is the total length of the roads (m); S is the total effective area (ha).

The determination of the ORD, for each scenario studied, was obtained through the indirect method, based on the work of FAO (1974), Zagonel *et al*. (2008) and Souza *et al*. (2018).

ORD is found at the point at which the sum of road construction and maintenance costs, extraction costs and cost of loss of productive area are minimum. Using Equation (12):

$$TC = Croad + Cforw + Clopa \tag{12}$$

In which: TC is the Total cost (US$.m^{-3}); Croad is the Total road costs (US$.m^{-3}); Cforw is the Extraction costs (US$.m^{-3}); Clop é the Costs of loss of productive area(US$.m^{-3}).

The ORD, then, was determined as the lowest value of the total cost curve, resulting from the relationship of this variable with the road density. The spacing between roads (RS) was also determined for the situation of RD and ORD, this indicator can be calculated according to Equation (13) presented by Rezaei *et al*. (2013):

$$RS = \frac{10{,}000}{(RD\ or\ ORD)} \tag{13}$$

In which: RS is the Spacing between roads (m); RD is the Current density of roads(m.ha^{-1}); ORD is the Optimal road density(m.ha^{-1}).

2.9 Determination of wood storage capacity

To obtain the theoretical storage capacity, adapted from the study by Faria *et al*. (2022), a pile height standard was considered, obtained through a field survey. The piles were on average 3.5 m high and the length of the wood was 6.8 m.

The volume was based on a procedure made available by the company, which contains theoretical factors that, through the height and length of stacked wood, transform the volume of m³ stereo into solid m³, according to Equation (14):

$$Vw = Hs * Lwood * Fc \tag{14}$$

In which: Vw is the volume of wood per linear meter of the road ($m^3.m^{-1}$); Hs is the standard height of the piles in the field (m); Lwood is the target length of cutting the wood (m); Fc is the theoretical conversion factor from m^3 stereo to solid m^3 of wood.

Another point analyzed is whether the ORD will support the volume of wood stored on the roads. To understand this issue, the storage capacity of roads at different densities was evaluated using Equation (15):

$$Cstock = Vw * RD \tag{15}$$

In which: Cstock is storage capacity ($m^3.ha^{-1}$); Vw is the volume of wood per linear meter of road ($m^3.m^{-1}$); RD is the road density ($m.ha^{-1}$).

3 RESULTS

The costs of road operations, extraction, and loss of productive area under current, optimal conditions and depending on the road storage capacity, for the nine interaction scenarios between IAV and VLC, are described in Table 2.

The current production cost, at a road density of 52.72 $m.ha^{-1}$ and an average distance of extraction (AFD) of 85 meters, considering a IAV of 0.15 $m^3.tree^{-1}$, was US$ 2.61, US$ 2.86 and US$ 3.92 per m^3 of wood, respectively, for VLC of the bitrem, tritrem and hexatrem types.

Analyzing the ORD, for the IAV of 0.15 $m^3.tree^{-1}$, different values were found for the VLC of the bitrem, tritrem and hexatrem types, being, respectively, 25.57, 23.68 and 19.57 $m.ha^{-1}$ of roads (Figure 3). The optimal production costs in the aforementioned scenarios were US$ 2.18, US$ 2.30 and US$ 2.72 per m^3, respectively, for VLC of the bitrem, tritrem and hexatrem types.

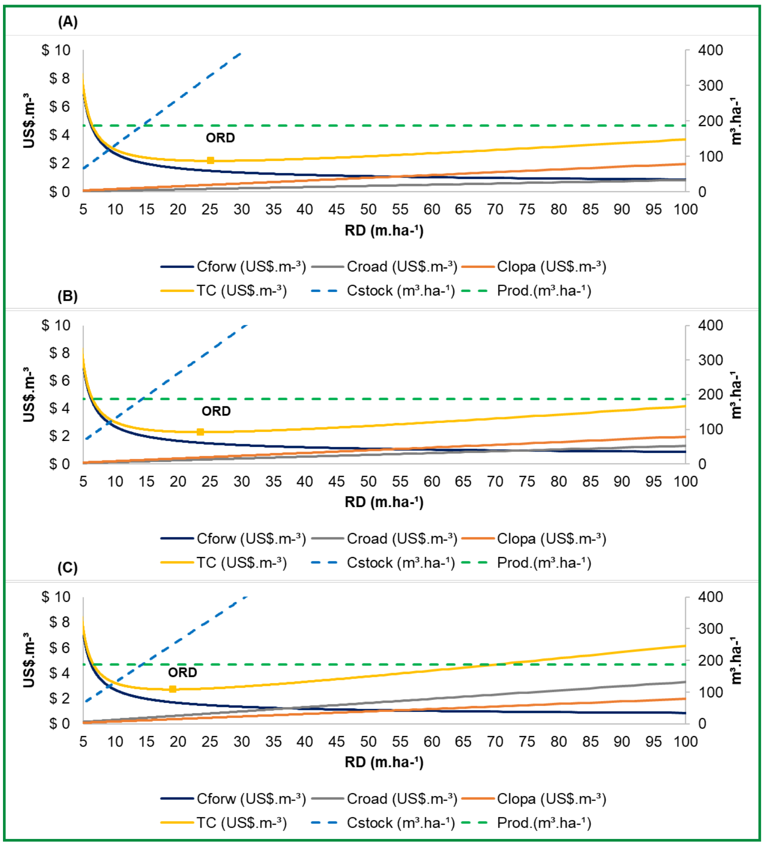
Table 2 – Physical and financial variables of current density, optimal density and road density as a function of storage capacity in different IAV and VLC scenarios for forest transport

Variables	IAV: 0.15 ($m^3.tree^{-1}$)			IAV: 0.20 ($m^3.tree^{-1}$)			IAV: 0.25 ($m^3.tree^{-1}$)		
	Bitrem	**Tritrem**	**Hexatrem**	**Bitrem**	**Tritrem**	**Hexatrem**	**Bitrem**	**Tritrem**	**Hexatrem**
	Cost Scenario of the Current RD (US$.$m^{-3}$)								
Cforw (US$.$m^{-3}$)	$ 1.12	$ 1.12	$ 1.12	$ 1.08	$ 1.08	$ 1.08	$ 0.88	$ 0.88	$ 0.88
Croad (US$.$m^{-3}$)	$ 0.44	$ 0.69	$ 1.75	$ 0.33	$ 0.52	$ 1.31	$ 0.27	$ 0.41	$ 1.05
Clopa (US$.$m^{-3}$)	$ 1.04	$ 1.04	$ 1.04	$ 0.95	$ 0.95	$ 0.95	$ 0.89	$ 0.89	$ 0.89
TC (US$.$m^{-3}$)	**$ 2.61**	**$ 2.86**	**$ 3.92**	**$ 2.36**	**$ 2.54**	**$ 3.34**	**$ 2.04**	**$ 2.19**	**$ 2.82**
RS (m)	190	190	190	190	190	190	190	190	190
AFD (m)	85	85	85	85	85	85	85	85	85
RD (m.ha^{-1})	**52.72**	**52.72**	**52.72**	**52.72**	**52.72**	**52.72**	**52.72**	**52.72**	**52.72**
	Cost Scenario of ORD (US$.$m^{-3}$)								
Cforw (US$.$m^{-3}$)	$ 1.46	$ 1.52	$ 1.72	$ 1.37	$ 1.42	$ 1.58	$ 1.34	$ 1.38	$ 1.52
Croad (US$.$m^{-3}$)	$ 0.21	$ 0.31	$ 0.62	$ 0.16	$ 0.24	$ 0.49	$ 0.14	$ 0.20	$ 0.42
Clopa (US$.$m^{-3}$)	$ 0.51	$ 0.47	$ 0.37	$ 0.47	$ 0.44	$ 0.35	$ 0.47	$ 0.44	$ 0.36
TC (US$.$m^{-3}$)	**$ 2.18**	**$ 2.30**	**$ 2.72**	**$ 2.01**	**$ 2.10**	**$ 2.43**	**$ 1.95**	**$ 2.02**	**$ 2.30**
RS (m)	391	422	531	382	409	507	362	384	471
AFD (m)	176	190	239	172	184	228	163	173	212
ORD (m.ha^{-1})	**25.57**	**23.68**	**18.83**	**26.16**	**24.46**	**19.74**	**27.61**	**26.01**	**21.23**
	Cost Scenario of RD with Cstock Restrictions (US$.$m^{-3}$)								
Cforw (US$.$m^{-3}$)	NA	NA	NA	NA	NA	NA	NA	NA	$ 1.43
Croad (US$.$m^{-3}$)	NA	NA	NA	NA	NA	NA	NA	NA	$ 0.48
Clopa (US$.$m^{-3}$)	NA	NA	NA	NA	NA	NA	NA	NA	$ 0.40
TC (US$.$m^{-3}$)	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**$ 2.31**
RS (m)	NA	NA	NA	NA	NA	NA	NA	NA	418
AFD (m)	NA	NA	NA	NA	NA	NA	NA	NA	188
RD (m.ha^{-1})	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**23.94**

Source: Authors (2025)

In where: IAV: individual average volume; TC: total cost; Croad: cost of roads; Cforw: extraction cost; Clopa: cost of loss of productive area; RD: current density; ORD: optimal density; AFD: average distance of extraction; RS: road spacing; Cstock: road storage capacity; NA: it was not necessary to restrict by Stock.

Figure 3 – Relationship between road density, cost of roads, cost of extraction, cost of loss of production area, productivity of the area and maximum storage capacity for Bitrem (A), Tritrem (B) and Hexatrem (C) in the scenario of IAV of 0 ,15 $m^3.tree^{-1}$

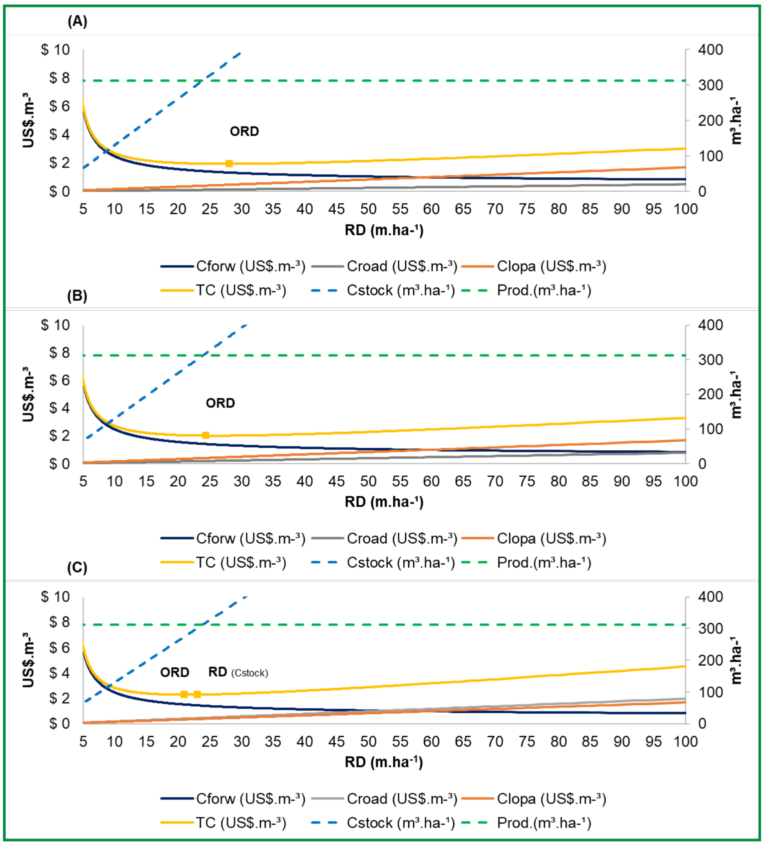


Source: Authors (2025)

In where: CT: total cost; Croad: cost of roads; Cforw: extraction cost; Clopa: cost of loss of productive area; DE: Density roads; ORD: optimal road density; Cstock: road storage capacity.

For the IAV scenario of 0.20 m³.tree^{-1}, different ORD was also verified for the VLC of the bitrem, tritrem and hexatrem types, respectively, 26.16, 24.46 and 20.45 m.ha^{-1} of roads (Figure 4). The optimal total production costs in the aforementioned scenarios were US$ 2.01, US$ 2.10 and US$ 2.43 per m³, respectively, for VLC of the bitrem, tritrem and hexatrem types.

Figure 4 – Relationship between road density, cost of roads, cost of extraction, cost of loss of production area, productivity of the area and maximum storage capacity for Bitrem (A), Tritrem (B) and Hexatrem (C) in the scenario of 0.20 m³.tree^{-1}

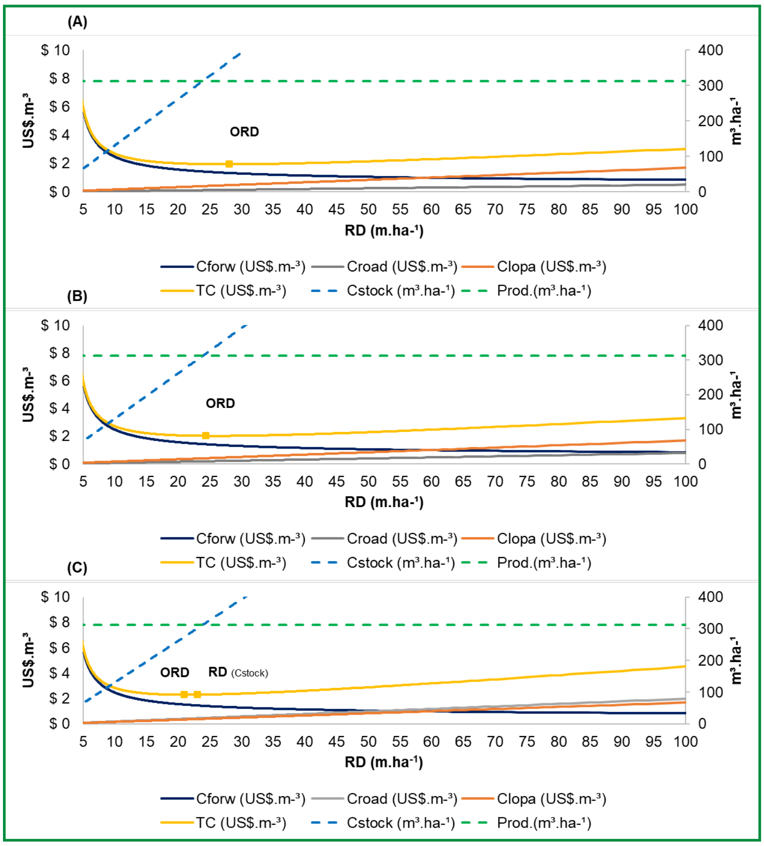


Source: Authors (2025)

In where: CT: total cost; Croad: cost of roads; Cforw: extraction cost; Clopa: cost of loss of productive area; DE: Density of roads; ORD: optimal road density; Cstock: road storage capacity.

Finally, the IAV scenario of 0.25 m³.tree^{-1} also presented different ORD for the VLC of the bitrem, tritrem and hexatrem types, being, respectively, 27.61, 26.01 and 22.06 m.ha^{-1} of roads (Figure 5). The optimal production costs in the above scenarios were US$ 2.04, US$ 2.19 and US$ 2.82 per m³, respectively, for VLC of the bitrem, tritrem and hexatrem types.

Figure 5 – Relationship between road density, cost of roads, cost of extraction, cost of loss of productive area, productivity of the area and maximum storage capacity for Bitrem (A), Tritrem (B) and Hexatrem (C) in the scenario of 0.25 m³.tree^{-1}



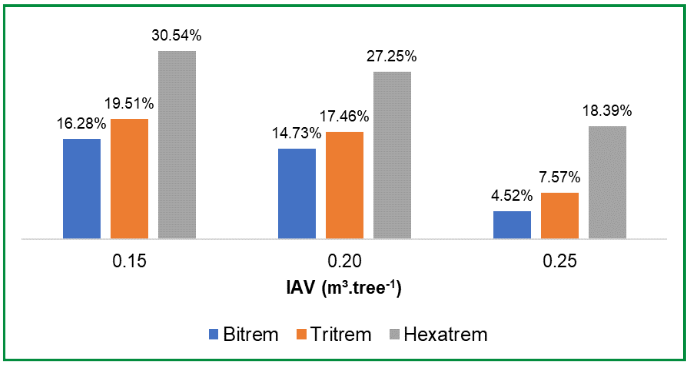
Source: Authors (2025)

In where: CT: total cost; Croad: cost of roads; Cforw: extraction cost; Clopa: cost of loss of productive area; RD: Road density; ORD: optimal road density; Cstock: road storage capacity.

Applying the ORD analysis, there would be a reduction in the total wood cost of up to 30.54%, in the scenario of IAV of 0.15 m³.tree^{-1} with VLC of the hexatrem type, of 19.51% in the same IAV, however, with a tritrem VLC, and 16.28% for a bitrem

VLC. These same trends were also found in the other IAV in the study. The potential cost reduction in the IAV scenario of 0.20 m³.tree^{-1} was 14.73%, 17.46% and 27.25%, respectively representing the VLC of the bitrem, tritrem and hexatrem types. In the IAV scenario of 0.25 m³.tree^{-1}, the potential cost reductions were 4.52%, 7.57% and 18.39%, respectively, bitrem, tritrem and hexatrem (Figure 6).

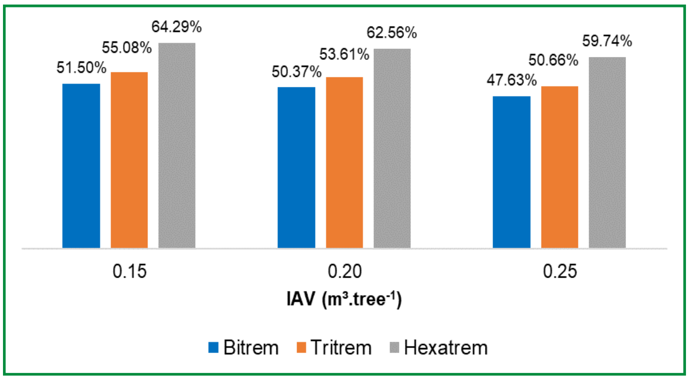
Figure 6 – Total cost of operation reduction in different IAV and VLC scenarios based on ORD



Source: Authors (2025)

The same trend occurred in the reduction of road density in the different IAV and VLC scenarios. The higher the CTGW and the lower the productivity of the area, the greater the proposed reduction in the best road density from an economic point of view (Figure 7).

Figure 7 – Reduction of road density in different IAV and VLC scenarios based on ORD



Source: Authors (2025)

4 DISCUSSIONS

Considering a IAV of 0.20 m³.tree^{-1}, the costs were lower due to the dilution of the fixed cost by the greater volume of wood. The costs found were US$ 2.36 , US$ 2.54 and US$ 3.34 per m³ of wood, for the bitrem, tritrem and hexatrem scenarios, respectively. The costs were more competitive compared to the other IAV. This is due to the greater dilution of costs used in forestry operations (VARGAS *et al*. 2022).

The higher the IAV, the tendency is to find a lower variable operating cost per US$.m^{-3}. Therefore, it would take fewer cycles to complete a load on the forwarder (Zagonel *et al*. 2008). On the roads, however, the fixed cost of construction and maintenance is diluted by the greater volume produced, that is, the investment in the road to transport more wood would be practically the same.

The same effect also influences the cost of loss of productive area, where there is a greater dilution of the fixed cost by the greater volume produced from the forest (Souza *et al*. 2018; Faria *et al*. 2022).

In the ORD scenarios, all extraction costs were higher than the current RD scenario because, with the reduction in density, there was an increase in the average extraction distance due to the reduction in the number of roads. Consequently, there is a reduction in the productivity of the forwarder, as the machine will have to move more, and thus, showing an increase in the variable cost in US$.m^{-3} of wood extraction. Corroborating with the studies by Souza *et al*. (2018) and Faria *et al*. (2022), who also showed an increase in extraction cost in ORD scenarios.

In addition to the IAV, factors such as terrain type (slope and morphology and soil conditions), forest species (composition, silvicultural practices), machine technology (technological advancements, type of machines) should influence extraction costs and the dilution of fixed costs in forestry operations (Guerra *et al*., 2024; Parajuli *et al*., 2019; Simões *et al*., 2022). Thus, although transport configurations with greater load capacities can dilute per-unit costs, they may require larger initial investments in road infrastructure, which may not be feasible in all terrains or for all species to be commercialized.

The ratio of road costs and loss of productive area with ORD showed an inversely proportional relationship to the cost of extraction. It was found that the decrease in ED proportionally affected these costs, as the ORD was lower than the density found. As a result, the areas will have fewer roads to build or carry out maintenance and, consequently, more effective areas will be converted into planting. These facts were also verified in the works of Zagonel *et al*. (2008) and Vargas *et al*. (2022).

The only case in which a restriction on the road storage capacity was found was in the IAV scenario of 0.25 $m^3.tree^{-1}$ with the hexatrem-type VLC. In this scenario, a road density was found that supports the volume of wood theoretically produced, of at least 23.94 $m.ha^{-1}$, being 7.85% greater than the economically optimal density. The total wood costs were US$ 2.31 per m^3. The increase in cost compared to the best economic scenario was only US$ 0.01 per m^3.

The lowest ORD was found for the VLC with the highest combined total gross weight (CTGW), as these vehicles demand greater investments in road construction and maintenance.

The highest costs were found in the VLC scenarios with the highest CTGW. This is due to the fact that the biggest investment in roads, according to the technical list of the forestry company, is the investment in roads for the hexatrem, which is equivalent to more than double the investment related to the VLC of the tritrem type. Due to the length and mass of the vehicle, the truck's hauling capacity is more demanded and, consequently, it presents greater wear on the roads, which reflects in a greater investment in material to cover the roads.

Faria *et al*. (2022) under the same conditions of flat terrain and Eucalyptus plantation in this study, found a reduction in total costs of 24.9%. For Eucalyptus planting in sloping areas, the reduction in total costs was 25.4%.

This trend demonstrates that, for less productive areas, we must redouble our attention when planning the forest road network, since, with lower productivity, there tends to be less volume in the dilution of fixed operating costs, in particular that of roads for vehicles largest CTGW.

Souza *et al*. (2018) in their study found reductions in road density from the current scenario to the optimum ranging from 42% to 65% in Pinus plantations in the state of Santa Catarina. Faria *et al*. (2022) found reductions of 47.1% to 72.8% for flat areas, planted with Eucalyptus and Pine, respectively, and from 57.8% to 63.9% in the same species, respectively, but in sloping terrain. This reinforces that most forest planting areas are subject to optimization in the current road density scenario.

5 CONCLUSIONS

It can be concluded that it is possible to obtain the ORD as a function of the IAV and VLC and that these variables influence the value of the optimal road density. It can be seen that the lowest IAV conditions associated with the VLCs with the highest CTGW, presented lower optimal road densities. With this, it is inferred that knowing the expected productivity of the farm can guarantee a lower ORD and thus reduce costs.

Through the proposed methodology, it was possible to find the optimal density of the area in the evaluated scenarios and to infer that the value obtained in this study is lower than that currently found in the location.

Optimal road density varied as a function of IAV and VLC. It was observed that in the lowest IAV conditions and in the VLC types with the highest CTGW, a lower road density was demanded. The Hexatrem in the scenario of lower IAV demanded the lowest density of roads, due to the minimization of the cost of roads. Because there are fewer roads to carry out maintenance and construction, less effective planting areas, and less volume of wood to dilute fixed costs.

In the condition of the hexatrem with the highest IAV (0.25 m^3/tree), it was necessary to include a new variable, the road stock capacity. This is because the minimization of RD economically does not consider the demand for roads to store the wood after extraction. The use of ORD and RD, including storage capacity, can be a good tool to reduce the total costs of wood production. However, it should be used with reservations, since they are determined only in an economic and theoretical way.

Finally, it is recommended to carry out a new allocation of roads in the study area, aiming to reduce the number of existing roads. Adapting to the type of VLC that will travel and the expected IAV of the forest consequently reduces the total production costs. It is noteworthy that this study did not recommend the type of VLC to be used, but its influence on the ORD and TC analysis.

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