UNIVERSIDADE FEDERAL DO PARANÁ

KAUÊ AUGUSTO OLIVEIRA NASCIMENTO

# INFRASTRUCTURE SOLUTIONS TO SUPPORT DECISION-MAKING IN LOGGING IN THE AMAZON

CURITIBA

2023

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# INFRASTRUCTURE SOLUTIONS TO SUPPORT DECISION-MAKING IN LOGGING IN THE AMAZON

Tese apresentada ao curso de Pós-Graduação em Engenharia Florestal, Setor de Ciências Agrárias, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutor em Engenharia Florestal.

Orientador: Prof. Dr. Julio Eduardo Arce

Coorientadores:
Prof. Dr. Renato Cesar Gonçalves Robert
Prof. Dr. Afonso Figueiredo Filho

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# TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ENGENHARIA FLORESTAL da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **KAUÊ AUGUSTO OLIVEIRA NASCIMENTO** intitulada: **INFRASTRUCTURE SOLUTIONS TO SUPPORT DECISION-MAKING IN LOGGING IN THE AMAZON**, sob orientação do Prof. Dr. JULIO EDUARDO ARCE, que após terem inquirido o aluno e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de doutor está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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A todos os profissionais florestais ou não, que reconhecem, valorizam e trabalham arduamente para garantir o uso responsável da riqueza e o desenvolvimento da Amazônia Brasileira; e para aqueles que ali vivem,

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Gratidão por tudo que a vida tem me proporcionado.

*“Os enganos podem sempre se perdoar; o erro é uma boa coisa, porque conduz à verdade.”*

(FIODOR DOSTOIEVSKI, 1866, Преступленіе и наказаніе p. 142)

*“Não existe bola perdida.”*

(Provérbio do futebol brasileiro)

## RESUMO

A biodiversidade é uma das principais características das florestas tropicais, distribuídas em micro sítios com atributos biofísicos específicos. Estes fatores são muitas vezes pouco considerados no planejamento do manejo florestal na Amazônia, por meio da sistematização espacial da infraestrutura para as operações, geralmente não considerando na tomada de decisão a distribuição do estoque florestal das espécies comerciais e outros fatores bióticos. Este estudo teve como objetivo trazer avanços no planejamento e contribuições para a minimização da infraestrutura necessária nas operações de exploração madeireira, por meio da alocação racional de pátios de estocagem de toras e estradas secundárias, com o uso de restrições ambientais, operacionais e de produção, mantendo a mesma capacidade de produção para o manejo das florestas amazônicas. Foram utilizados dados concedidos pela empresa Mil Madeiras Preciosas que realiza manejo florestal em larga escala, com uso de base de dados de 06 UPAs (unidades de produção anual) consecutivas de exploração madeireira: 2013, 2014, 2015, 2016, 2017 e 2018. Os dados foram analisados em duas etapas: análise e planejamento em sistema digital de informações geográficas (QGIS) e melhorias de utilização da infraestrutura (pacote adicional qneat do QGIS). Ademais, foi feita uma análise complementar dos fatores climáticos e dos custos das operações. A análise geoespacial pretendeu classificar as áreas restritas com base nas condições ambientais e operacionais que foram excluídas da etapa de melhorias. Foram aplicados modelos para melhoria das infraestruturas (estradas, trilhas de arraste e pátios), com o objetivo de minimizar o uso do solo em infraestruturas de suporte à operação, sujeito a restrições operacionais e ambientais. Finalmente, os resultados foram incluídos em mapas de planejamento com ferramentas QGIS, demonstrando as melhorias do processo. A redução da infraestrutura exigida em pátios de madeira variou entre 24,6% e 65,6%, com uma média de 40,6%, o que é relevante, tendo em conta o processo ágil de melhoria do planejamento aplicado ao manejo florestal, neste estudo. A redução da infraestrutura exigida nas estradas secundárias variou entre 17,8% e 39,9%, com uma média de 24,2% menos estradas (em metros), o que é relevante quando se considera a área exigida para a construção de estradas (largura das estradas e remoção da vegetação de bordadura), com grande impacto ambiental e físico nas florestas tropicais. Além disso, as maiores despesas se concentraram entre os meses de Julho a Novembro. Essa é a época em que todas as operações estão ativas. O corte florestal, que é um dos estágios mais cruciais, termina em Novembro, para evitar o início das chuvas na região. As operações mais caras para a empresa foram, respectivamente, operações de pátio (27% do total), transporte (18%) e pré-arraste (18%). Concluímos que o estudo trouxe contribuições sensíveis para o planejamento da exploração madeireira na Amazônia, minimizando a infraestrutura necessária e mantendo a mesma capacidade produtiva. Este trabalho traz subsídios para a melhoria dos processos dessa atividade na Amazônia, bem como estimula a replicação de métodos e contribui para novos empreendimentos de manejo na região. Recomendamos o uso, a replicação e a disseminação desses métodos racionais aqui apresentados, para diferentes contextos de exploração madeireira na Amazônia, testando, se possível, diferentes valores para as variáveis, especialmente aquelas relacionadas ao raio máximo de arraste.



Palavras-chave: Melhorias na exploração florestal. Planejamento espacial. Otimização. Operações florestais. Exploração de madeira tropical.

## ABSTRACT

Biodiversity is one of the main characteristics of tropical forests, distributed in micro sites with specific biophysical attributes. These factors are often poorly considered in forest management planning in the Amazon, through the spatial systematization of infrastructure for operations, generally not considering in decision making the distribution of forest stock of commercial species and other biotic factors. This study aimed to bring planning advances and contributions for the minimization of the infrastructure required in logging operations, through rational allocation of log landings and secondary roads, with use of environmental, operational and production constraints, keeping the same production capacity for the management of the Amazon Rainforests. Data granted by the company Precious Woods Amazon, which carries out large-scale forest management, were used, using a database of 06 consecutive logging UPAs (annual production units): 2013, 2014, 2015, 2016, 2017 and 2018. The data were analyzed in two stages: analysis and planning in digital geographic information system (QGIS) and infrastructure utilization improvements (QGIS qneat add-on package). In addition, a complementary analysis of climatic factors and costs of operations was performed. The geospatial analysis was intended to classify the restricted areas based on environmental and operational conditions that were excluded from the improvement step. Models for infrastructure improvements (roads, skid trails, and yards) were applied to minimize land use in operation support infrastructure subject to operational and environmental constraints. Finally, the results were included in planning maps with QGIS tools, demonstrating the process improvements. The reduction of infrastructure required in log landings ranged from 24.6% to 65.6%, with an average of 40.6%, which is relevant considering the agile planning improvement process applied to forest management in this study. The reduction in infrastructure required for secondary roads varied between 17.8% and 39.9%, with an average of 24.2% fewer roads (in meters), which is relevant when considering the area required for road construction (road width and removal of bordering vegetation), with great environmental and physical impact in tropical forests. Additionally, the highest expenses were concentrated between months July to November. This is the time when all operations are active. Cutting, which is one of the most crucial stages, ends in November, in order to avoid the beginning of the raining season in the region. The most expensive operations for the company were yard operations (27% of the total), transportation (18%) and pre-skidding (18%), respectively. We conclude that the study brought sensible contributions for the planning of logging in the Amazon, minimizing the necessary infrastructure while maintaining the same productive capacity. This work brings subsidies for the improvement of the processes of this activity in Amazon, as well as stimulates the replication of methods and contributes to new management enterprises in the region. We recommend the use, replication and dissemination of these rational methods presented herein for different logging contexts in Amazon, testing, if possible, different values for variables, especially those related to the maximum radius of skidding.



Keywords: Logging improvement. Spatial planning. Optimization. Forest operations. Tropical logging.

**LIST OF FIGURES**

## LIST OF GRAPHICS

## LIST OF FRAMES

## LIST OF TABLES

## SUMMARY

# 1 INTRODUCTION

The Amazon is the largest biome in Brazil, one of the most diverse in plant species in the world and has an area that covers about 50% of the Brazilian territory, where most of it consists of upland forests (IBGE, 2012). The heterogeneity is one of the main characteristics of tropical forests, which consists of the occurrence of numerous species of flora, distributed in multiple sites with diverse and specific biophysical attributes (PUTZ, 1993). These characteristics are still disregarded in many large-scale forest management planning (SILVA et al., 2018). The forest planning is done in a spatially oriented and systematic way using the hydrographic pattern and relief as reference to allocate roads and log landings, do not based on advanced analysis tools, such as computational tools that use statistics or operational research techniques (BRAZ, 2010).

The partial disconnection between Amazonian diversity and the tools used in forest management planning, limit its economic and productive potential (BRAZ, 2010; SILVA et al. 2018). The management of natural forests has attracted very few investors, because they are not offered reliable and accurate management tools, that is, those that guarantee them to minimize costs and have greater productivity, with lower environmental impact (BRAZ, 2010; SILVA et al., 2018; SALES et al., 2019). Modern computational tools that use operational research are good allies in complex problems like this and meet this demand, supporting decision making and optimizing processes and operations (SILVA et al., 2018; SALES et al., 2019). Furthermore, the incorporation of economically viable solutions for planning selective logging would stimulate investments in these forest enterprises (SALES et al., 2019).

Currently, some researches already use optimization or improvement techniques for planning selective logging in Amazon, however, most of them without flexible solutions for several situations and different regions, which return viable planning solutions for different scenarios, however not replicable, presenting too many constraints and applied only for specific cases. On their study, Aguiar et al. (2021) developed a research that aimed to evaluate different computational methods' effectiveness in planning forest roads in Amazon, optimizing resources to reduce damage to the remaining forest, compared to traditional planning methods.

The research concluded that solutions obtained using computational methods more effectively considered the restrictions associated with sustainable forest management, in contrast to those derived from the traditional planning by forest company (AGUIAR et al., 2021). The authors still emphasize that to carry out design of roads based on computational methods, there is no need to change the forest inventory methodology traditionally employed by companies and required by Law. For the data collected during the census, forest inventory and the information obtained by remote sensors, are enough to carry out planning of roads without economic impact (AGUIAR et al., 2021).

Thus, these uses of modern and robust, flexible and effective computational tools are necessary and used throughout the Amazon Rainforests for logging planning, adapting only the default values of the most relevant parameters and constraints for each case. These aforementioned arguments justify the realization of this study. Additionally, this study used the largest database for large forest management areas (6 UPAs) in the Brazilian Amazon. Therefore, that reinforces the statement that results generated bring a great contribution for infrastructure planning in large-scale Amazonian forest logging.

Finally, this study works under the hypothesis that the infrastructure planning of logging in the Amazon, despite being rationally oriented, makes insufficient use of current geospatial and mathematical computational tools, missing out on competitiveness and opportunities to optimize resources and infrastructure needed for forest management enterprises.

## 1.1 OBJECTIVES

### 1.1.1 General objective

This study aimed to bring planning advances and contributions for the minimization of the infrastructure required in logging operations, through rational allocation of log landings and secondary roads, with use of environmental, operational and production constraints, keeping the same production capacity for the management of the Amazon Rainforests.

### 1.1.2 Specific objectives

- Minimize the total infrastructure area (y variables: number of log landings; distance of secondary roads in m; and roads density in m/ha). That through (x predictors: area in $m^2$; and load/unload capacity in $m^3$ of log landings; production capacity of UPA in $m^3$; total permanent primary roads in linear m), maintaining the same production capacity for logging in Amazon rainforests.
- Reallocate the log landings, considering the constraints: technical limit of 250m maximum extraction distance (MED) of logs; and forbidden overlapping of 250m radius extraction limit of log landings.
- Create a defined algorithm for a QGIS software approach in infrastructure planning for logging in Amazon rainforests, through robust and flexible constraints, and spatial planning methods that stimulates the replicability of this approach (PDCA flowchart for database and QGIS geo-processing steps in Appendix).

## 2 LITERATURE REVIEW

The Amazon is the largest biome in Brazil and one of the most diverse in the world (IBGE, 2012). It has an area that covers about 50% of the Brazilian territory, where most of it consists of upland rainforests. According to Amaral et al. (1998), the Amazon has forest resources in huge quantities, sheltering about one third of the world's rainforests. The region produces lots of timber, although exports are still modest (between 10-14% of the global trade in tropical timber), but tends to grow with the exhaustion of Southeast Asian rainforests (BIONTE, 1997). The heterogeneity is one of the main characteristics of tropical forests, which consists of the occurrence of dozens of species of flora, distributed in microsites with specific biophysical attributes (PUTZ, 1993). This important characteristic is currently disregarded in the planning of forest management. There is a complete disconnection between this diversity, the logging planning and the silvicultural activities planned for the forest grown (BRAZ, 2010). In general, the distribution of the road networks and the plots follow contour lines and hydrography patterns, disregarding other important aspects such as soil types and timber stock of commercial species per area unit (BRAZ, 2002). Unsuitable densities of trails and roads are often observed for areas with low timber potential, poorly distributed storage yards, log landings and sizing of annual production units (UPAs), that do not supply the industry with adequate quantity and quality timber. On these cases, in addition to the increased costs of construction and maintenance of non-essential roads, the forest is unnecessarily damaged, accelerating the modifications in its composition and structure, reducing the commercial wood stock for the next cycle (BRAZ, 2010).

During his study, Braz (2010) sought to define techniques for the management of natural forests, based on the determination of the sustained cutting rate and the improvement of timber extraction planning, in order to minimize the costs of production and damages in the forest. The author concluded that it was possible to determine sustainable cutting rates for tropical rainforests, a factor so far disregarded by the management plans. Three ecological groups of species with different cutting intensities were defined: 32.58%; 48.62% and 56.23% of commercial volume, respectively, considered the 25-year cycle. Larger cycles would result in higher intensities. The author recommended the use the cutting rates by ecological groups, because each of them will have a different pace of recovery and growing stock, being another guarantee for the sustainability of the system (BRAZ, 2010). Extraction rates, if not compatible with the diametric structure of the forest, may mean unsustainable management. All activities linked to logging must be related to estimates and simulations that facilitate their planning, so that there are no failures or bottlenecks in critical periods (BRAZ, 2010). Braz (2010) emphasized that the management of natural forests has attracted very few investors because they do not offer adequate management tools, that is, those which in addition to guaranteeing them better environmental gain, also guarantee them lower costs and higher productivity. Braz et al. (2012) highlighted the recent introduction of dendrochronology to obtain growth, bringing valuable information for the determination of cutting rates and specific cycles in the sub-compartments towards a precise forest management in the Amazon.

## 2.1 LOGGING SYSTEMS IN TROPICAL FORESTS

The silvicultural systems used for Sustainable Forest Management (SFM) in tropical forest countries are, in reality, adaptations of the classic models (mainly European) developed for temperate forests. The first silvicultural experiments aimed at SFM were executed in India and Burma in the mid-nineteenth century. According to Lamprecht (1990), the history of MFS in the tropics began to be told after the emergence of the European colonial kingdoms. German botanist Dietrich Brandis wrote the first management plan for the Teak (*Tectona grandis*) of Burma in 1860 in India. He developed the "Taungya" method and founded the Indian Forestry Service. The first manual of tropical forestry was published in India in 1888 (LAMPRECHT, 1990).

In 1883, the first Forest Service was established in Malaysia, which had as its main activities the control of logging, maintenance of forest reserves, legislation and administration, having practically nothing of forest management. In Peninsular Malaysia, between 1910 and 1922, a series of silvicultural treatments, known as Enhancement Cuts, were implemented to favor a single species, *Palaquium guita*. The latex of this species played a significant role in the country's economy, which trees were cut down to make the extraction. Already at that time it was observed that instead of plantations, conducting pre-existing natural regeneration was much more convenient (LAMPRECHT, 1990).

This system was the forerunner of the Malay Uniform System (MUS), which was consolidated in 1948 after the Regeneration Enhancement Cutting System ceased to be used. This was during the reheating period of the world economy, and in particular with the rising demand for timber products from tropical forests. The development of MUS was fortuitous, when abundant regeneration of desirable species was verified after a long period of military occupation by the Japanese and the consequent destruction of natural forests through shallow cuts or large clearings. It was then concluded that desirable species needed large openings for the development of natural regeneration (NR). The first version of the MUS called for cutting all trees with DBH>45 cm and subsequent elimination of all undesirable trees that competed with the natural regeneration (NR) of desirable trees. In *Dipterocarpaceae* forests, MUS was initially successfully executed in Peninsular Malaysia. By 1976, approximately 300,000 hectares had been managed by MUS. In high forests, where species of the family *Dipterocarpaceae* are not abundant, MUS has failed. As a result, various alternatives have been introduced to manage these forests (HIGUCHI, 1994).

In Africa, silvicultural experiments have been recorded since the beginning of the 20th century. The first researches were implanted in Togo and Cameroon, German colonies in 1908. Between 1920 and 1930, in British West Africa, the British set up the first forestry experiments in the region. The French were more active in the Ivory Coast in 1930. The Tropical Shelterwood System (TSS) was consolidated in 1944 in Nigeria, inspired by systems that favored the NR of desirable species, under the matrix trees, by cutting vines and eliminating undesirable species. The first version of TSS was an adaptation of MUS (LAMPRECHT, 1990).

TSS consisted of gradual canopy opening by poisoning of noncommercial species (with sodium arsenite), as well as liana cutting and clearing to control infestation of vines and weeds, with the goal of promoting the survival and growth of NR of desirable species. After managing approximately 200,000 hectares of Nigerian primary forests with TSS, this system was abandoned because this type of utilization did not compete economically with other forms of land use. Where there was some concern for multiple forest use, TSS managed to consolidate (HIGUCHI, 1994).

The selective systems came later and today are the predominant ones in SFM. A rare exception is the Harvesting Band System, used experimentally in the Palcazu River Valley - in Peru - more recently. In the American continent, the example comes from the silvicultural experiments first installed in Trinidad, between 1890 and 1900, by the English foresters.

In the Amazon countries, in the early 1980's, several demonstration areas of forest management were planned, totaling approximately one million hectares, which to this day have not been implemented. In Brazil, the concept of forest management under a sustainable yield regime was initially introduced with the first forest inventories, carried out by FAO experts, at the end of the 1950s. The first registered management plan was made for the Tapajós National Forest, in 1978, for an area of 130,000 hectares. There is probably a sustainable yield management plan being executed in the Amazon, but without supporting records (HIGUCHI, 1994).

In summary, the main silvicultural systems used in sustainable yield forest management were: Uniform Malay (original), Tropical Shelterwood (original), Selective (original), Modified Uniform Malay of the Philippines, Modified Uniform

Malay of Indonesia, Modified Uniform Malay of Sabah, Sarawak Release Thinning, Modified Selective of Peninsular Malaysia, Modified Selective of the Philippines, Modified Selective of Indonesia, Minimum Diameter, Thailand Selective, Ghana Tropical Shelterwood, Ghana Modified Selective, Ivory Coast Natural Population Improvement, Puerto Rico Selective, Trinidad Tropical Shelterwood, Suriname CELOS, French Guiana Natural Population Improvement and Peru Harvesting Bands. After almost half a century of experience, none of these systems has been considered as sustained (HIGUCHI, 1994).

In the Brazilian Amazon, there are records of research on this subject since the late 1950s. Specifically on silvicultural systems, research began in the late 1970s and early 1980s.

The main experiences in Brazil have used two systems, which are of the polycyclic and multiple use type, and have in common the principles of the precursor systems, Malay and Tropical Shelterwood, which use natural regeneration to guarantee subsequent cutting cycles. Neighboring countries, politically included in the Amazon region, have also made large investments in forest research. The systems investigated in Suriname (CELOS) and French Guiana (Natural Population Enhancement), should be considered in any decision making regarding the choice of silvicultural systems for management of the Amazon forest. (HIGUCHI, 1994).

Suriname's CELOS System is divided into two stages: a harvesting system and a silvicultural system. The logging system is polycyclic and consists of harvesting about 20m³/ha of timber, with cutting in periods of 20-25 years. The silvicultural system defines thinning for refinement or selection of commercial species in the 1$^{st}$, 8$^{th}$ and 20$^{th}$ years post-harvesting (HENDRISON, 1990).

## 2.2 USE OF MATHEMATICAL MODELING/OPTIMIZATION TECHNIQUES IN TROPICAL FOREST MANAGEMENT

With use of GPS and satellite images applied to a GIS software, Hamzah (2001) mapped restricted areas for logging in Malaysia, due to environmental factors (water resources, slopes and soils). With the use of buffers and layers of constraints in digital mapping, 33% of the area was restricted for conservation. For a few years, models similar to the ones described by Hamzah (2001) have been applied in Amazon. The most widespread today, requires a sequence of planning that considers the georeferencing of commercial trees marked to felling, inclusion of permanent conservation areas, contour lines and restricted areas, log landings and trails.

This article from Turner et al. (2002) was pioneer in the use of optimization techniques in tropical forest management. This research applied in a native forest management area in Australia, showed that modern optimization algorithms and fast computing can solve integrative forest resource models, at a resolution suitable for operational planning for forest regions where normally at least two levels of planning would be applied. Two packages were evaluated, SPECTRUM, a linear programming (LP) package, and HABPLAN, which uses the Metropolis algorithm to converge on the optimum solution. The SPECTRUM is an LP matrix-generator and report-writer developed by the USDA Forest Service that is specifically designed to schedule the management options of a forested land over time. The multi-objective optimization problem was formulated in a model called HABPLAN. HABPLAN is a landscape management and forest harvest scheduling program written in Java script. HABPLAN uses a simulation approach based on the Metropolis algorithm (MA) with objective function weights based on user defined goals, being adaptively determined at each iteration. The MA is a way of evolving a trajectory so that the configurations in the state space are visited in such a way as to reflect their statistical importance. A configuration defines a unique point in the state space and the trajectory defines a set of configurations/points defining a path in the state space (TURNER et al., 2002).

Preliminary indications were that both packages could handle the problem size, but the HABPLAN package had some additional features which makes it attractive for solving multi-objective problems with spatial components as in modelling sustainable forest management. The authors concluded that the mathematical formulation in the SPECTRUM and HABPLAN models enables the definition of bio-physical and economic constraints within which an objective function can be absolutely or approximately maximized or minimized. It should, however, be noted that thorough interpretation of the production unit model (PU) outputs requires a good understanding of the physical environment and forest management practices of the PU. It has also been demonstrated that sophisticated decision support tools such as SPECTRUM and HABPLAN are capable of handling large forest modelling problems of a size where commonly strategic plans are formulated, while providing the detail commonly found in operational plans (TURNER et al., 2002).

The authors Safiah and Rodziah (2010) started previous researches about the optimization of logging planning in Malaysia, that aimed to optimize the forest road network so that it is aligned based on results of the determination of the Net Production Area (NPA) and the identification of harvestable trees, while being constrained by information on soil loss prediction and hydrological flow direction. Using the Spatial Analyst Tools of a GIS software in optimizing the road routing, there are several matters that were considered, namely that the road should be: as near as possible to clusters of harvestable trees, away from the rivers and their buffers, avoid high erosion risk areas, and avoid relatively steep land. The authors concluded that a number of software problems are experienced in implementing this procedure, but the results obtained in this study show how the final timber harvesting plan might be constructed for the study area, which is ready to be implemented in the forest (SAFIAH and RODZIAH, 2010).

Still in Malaysia, Abdullah et al. (2011) intended to propose an optimization model of timber harvesting planning (THP) that reflects selective cutting in Peninsular Malaysia. The model was tested on seven blocks that consisted a total of 636 trees with different size and species. It was found that optimization approach generates selectively timber harvest plan with higher volume and less damage, in comparison to conventional planning.

This study developed two modelling approaches: a Selective Harvest Planning Model (SHPM), a harvest planning model which is used to form harvest area without optimization approach, and a Selective Harvest Planning Optimization Model (SPOM), with optimization approach by means of mixed integer linear programming. SPOM was used for comparing the impacts of applying optimization techniques in improving harvest volume and reducing damage to the residual trees.

Four decision variables were used as constraints: required tree diameter, a minimum diameter requirement for a tree to be felled; required future stock, a minimum estimated trees to be felled in next planning rotation in each block; economic harvesting, a minimum number of trees to be felled in each block; and maximum harvesting volume, that represents a maximum harvested volume in each block. The objective function aimed to maximize the harvested volume (ABDULLAH et al., 2011).

Overall, Abdullah et al. (2011) concluded that SPOM provides more available blocks to be harvested and selects the most promising blocks to achieve the objective with minimal damage to the residual trees. An optimization approach therefore provides an intelligent alternative of problem solving technique to generate a near optimal plan that provides better monitoring and control of harvesting operations in Peninsular Malaysia.

After a while, the important study of Philippart et al. (2012), developed a binary integer linear programming model (BIPM) similar to the non-capacitated facility location problem, formulated to optimize the locations of the log landings. The software used branch-and-cut algorithms to solve this problem, getting a faster optimal solution. Moreover, GIS software and the geo database were used to support creating and managing data about the skidding network, to apply penalty surface and to visualize results. The model was applied to a selective logging in Central Africa and tested on an annual logging zone in Southeast Cameroon. The authors emphasized that when a BIPM becomes too large, an exact solution method such as branch- and-cut may not be able to solve it. Instead of that, they concluded that the model was successful and it was a first step in the optimization of selective logging applied to the Central African context.

Abdullah et al. (2014) in Peninsular Malaysia, emphasized that most optimization models for timber harvesting planning currently in use are based on clear cutting and restricted to adjacency constraints to prevent the creation of large clear-cut openings in the forest. However, an optimization model based on selective cutting techniques utilized in tropical countries has rarely been described in the literature. The aim of the study was to propose an optimization model for forest planning based on selective logging and subject to a maximum number of trees to be harvested and a minimum number of trees to be damaged during each planning period. The model was solved using three optimization techniques to identify the most suitable technique for use in the process of harvesting area formation: Monte Carlo Programming (MCP), Simulated Annealing (SA) and Threshold Acceptance (TA); all meta-heuristic techniques. The obtained results indicate that the SA method provided better solutions than the MCP and TA methods, regardless of problem size.

The authors highlight that the proposed model was used to form the harvest areas with the objective of maximizing the harvesting volume, subject to the maximum number of trees allowed for harvesting and the minimum number of damaged trees per planning period. In addition, the model implements an approach to exclude one or more potential trees to be felled from the harvest to fulfil the minimum number of future stock required for timber sustainability. The minimum number of trees to be cut was also imposed in each block to ensure economical harvesting; thus, the harvesting areas were formed by combining and selecting a number of blocks in which the harvest volume was at most equal with the maximum number of trees allowed for harvesting in one planning period. Therefore, it was concluded the proposed model provides a tool to generate timber harvest plans with the improved monitoring and control techniques used in harvesting operations in tropical countries (ABDULLAH et al., 2014).

The research of Jamhuri et al. (2021) aimed to give an overview of several algorithm application in optimizing the forest transportation planning problem and give an insightful information regarding the relationships between algorithm and the integration of transportation system characteristics and variables. The authors emphasized that some algorithms that are finding their way to the forest transportation planning problem include Genetic Algorithm (GA), Particle Swarm Optimization (PSO) algorithm, Ant Colony Optimization (ACO) algorithm, Simulated Annealing (SA) algorithm and Tabu Search (TS) algorithm. Although no literature was found regarding forest transportation planning problem optimization with regards to Bees Algorithm (BA), rules set for several transportation problem evidenced from literature search seems to be applicable to forestry. Generally, in this paper, the authors concluded that BA has been given focus for forest transportation planning problem optimization as a potential algorithm to overcome the challenges of environmental degradation and efficiency of timber extraction, as well as its accuracy and less processing time for problem-solving (JAMHURI et al., 2021).

## 2.3 OPTIMIZATION APPLIED TO FOREST MANAGEMENT IN AMAZON

Native tropical forests represent approximately 10% of the existing land surface (Corlett et al. 2016), and about 96% of the tree species (POORTER et al., 2015). Tropical forests destined to wood production correspond to more than 400 million hectares in the world (BLASER et al., 2011, GROENENDIJK et al., 2017). Harvesting these forests is vital for many countries as they generate significant local and export revenues (KÖHL et al., 2015). However, the predatory exploitation of forest resources has resulted in national and international pressure and policies related to their conservation and use (WOLFSLEHNER et al., 2005), leading the countries to implementation of SFM (sustainable forest management) techniques. The main objective of SFM is to facilitate the exploitation of renewable forest resources, in particular wood, based on the reduction of waste and the impact on the remaining forest, as well as to ensure greater safety for workers (AMARAL et al., 1998) and maintenance of the ecosystem (BRAZ et al., 2010).

The use of new technologies and methodologies, which enables better precision in forest management in the planning and execution of the SFM plan, has been regarded as precision forest management (PFM) (FIGUEIREDO et al., 2007; 2016). In planning and implementing the activities of PFM, the use of computational, mathematical, and spatial tools, along with operational research techniques, allows the decision-making process to be optimized in several aspects, especially in terms of the legal, environmental, economic, social, and technical goals. Despite of that, studies aiming to optimize the planning of yard allocation in the Amazon are still incipient (GOMIDE et al., 2011; MARTINHAGO, 2012; ISAAC JUNIOR et al., 2014; Silva, 2014).

Currently, forestry companies in the Amazon have used the logging model called CELOS Harvesting System conceived by Graaf (1986) in Suriname rainforests, which considers ecological and silvicultural needs for the choice of trees in selective logging, the planning of operations and skid trails, the use of pre-skidding machines and mapping of trails and roads (EMMERT, 2014). Proper planning should go beyond the logging of reduced impact, and define optimum points for the activities that compose the forest management (BRAZ, 2010). Roads, skid trails and log landings correspond to the greatest causes of impacts from logging, but when planned properly, reduce damages and operations costs, and increase operational efficiency (SESSIONS, 2007). According to Braz (2010), the use of geographic information systems and mathematical tools aiming to optimize planning, has broad perspectives in the management of natural forests. The author emphasizes that the constant development of researches and training of personal are two crucial factors for the evolution of the technologies applied to forest management. Emmert (2014) emphasizes that different technologies have been applied in forest management, such as geotechnologies and mathematical techniques. These tools can be integrated and combined for a more efficient planning.

There are currently several mapping and geographical software used to support forest planning in Brazil, among them the QGIS software consists of an open source GIS licensed under the General Public License (GNU). QGIS is an official project of the Open Source Geospatial Foundation (OSGeo). It works on Linux, Unix, Mac OSX, Windows and Android and supports numerous vector formats, raster formats, databases and features (MATSUSHITA et al., 2017). The original QGIS tools meet the basic needs for the mapping and classification of land use cover, in addition to having plugins and geo algorithms to manipulate raster images, vectors and tables. It also allows working with aerial images, maps and roads in integration with the Google platform (Earth, Maps and Street View), Bing among others (MATSUSHITA et al., 2017). The combination of this information in GIS digital platform, makes up the MODEFLORA system (Digital Model of Precision Management in Tropical Forests), developed in the State of Acre, Brazil (FIGUEIREDO et al., 2007). The MODEFLORA aims to improve the spatial planning of logging (FIGUEIREDO et al., 2007). According to Figueiredo et al. (2007), the use of MODEFLORA resulted in the increase of yield in operations and the reduction of impacts by deployment of roads and log landings, mainly due to the reduction of the necessary infrastructure. However, Emmert (2014) points out that the skid trails continued systematized, since they are limited to the set of each storage yard and log landings. Additionally, the manual vectorization of the trails in the GIS software becomes a spending time and inaccurate costly work.

This pioneer research in Amazon with use of operational research techniques, was developed by Braz et al. (2004) that presented the purpose to develop a mathematical model to help with the planning and distribution of stands in a small tropical forest farm. The mathematical model resulted in a new concept of stands. Based on the pre-exploratory forest inventory, the compartments were divided into sub compartments with their different values being calculated according to market timber prices. Since the annual logging rate allowed had already been defined based on local and regional studies, the goal was to guarantee that this rate, transformed in monetary value can really be reached annually.

The mathematical model GP (Goal programming) was utilized in the selection of the sub compartments by grouping them into a final compartment with size similar to that of the original annual compartment. The proposed stand model was compared with the type of stand normally used in tropical forests and was proved rather superior to the conventional one, thus guaranteeing small farmers a balanced annual income (BRAZ et al., 2004).

The authors concluded that the proposed model advantageously guarantees to generate a balanced annual income flow for the small owner, which facilitates the annual planning of extraction on the small farmland, which may be adapted for the optimization of wood production in conditions similar to the rainforest. It is concluded that the model enables the best plot initial, making it possible in the annual planning to count with the average potential identified in the forest, according to the appropriate surveys (BRAZ et al., 2004).

Rodriguez et al. (2009) developed a research to maximize the net present value of a sustainable forest management area in Amazon. They described a two phase solution technique to solve the problem: first, select the number of species and maximum volumes per species by means of a linear programming model; and secondly, locate the best trees in the field using a specially developed GIS routine.

The authors suggested that in the first phase, a mixed integer linear programming model was used to maximize gross revenue per hectare constrained by impositions such as maximum allowable harvest volume per hectare and limited by a fixed number of species to be harvested given each species produces a minimum total volume after the forest was cut. As expected in these cases, trees from the most valuable species contribute with most of the final total harvested volume. The model is efficient on evaluating the effect of increasing the number of harvested species. The authors concluded that the mathematical approach produces an efficient replacement mechanism that optimally combines most valuable with less valuable species to produce a strategy that maximizes total revenues and respects the maximum allowable harvested volume per hectare. A second phase, with use of a GIS software must spatially apply the results of the first phase and produce a map with the exact location and wood transportation logistics that minimize costs and reduces environmental impacts (RODRIGUEZ et al., 2009).

Braz (2010) using mathematical models concluded that every species has an ideal point of diametric class for cutting, above which the return in increment will be null. This determination facilitates the definition of the classes that should remain. Applying calculations for optimizing load planning and road networks reduces environmental damage and costs. The constant self-assessment and monitoring improve the company's technologies and facilitate their discussion with environmental institutions. Finally, it concludes that a management that considers the inbound supply chain of the timber is feasible, even with all silvicultural treatments and monitoring required along the years.

According to Lentini et al. (2010), to support public forest planning efforts, the authors intended to combine spatially explicit data on logging profits, biodiversity indexes, and potential for community use for use within a forest planning optimization model. While generating optimal land use configurations, the model enabled an assessment of the market and nonmarket tradeoffs associated with different land use priorities. Thus, the problem was mainly developed as a multiobjective optimization model (LENTINI et al., 2010).

It was brought together two lines of research in forestry and natural resource management to help them to develop the planning model. First, it was drawn upon the mathematical programming literature on the conservation site selection problem, which generally aims to conserve the maximum number of species at a minimum cost or using a minimum number of reserves. Second, the authors drew upon harvest scheduling and tactical planning problems, such as the optimization of infrastructure (e.g. roads), minimization of logging costs, imposition of ecological constraints (e.g. adjacency constraints), and optimization of forest operations (LENTINI et al., 2010). According to the authors, the importance of the study was demonstrated in two ways. First, the model was the first in Amazonia, generating knowledge that solves a timber supply problem within a framework that allocates land across multiple uses. Second, while demonstrated the model on a specific public forest area, the datasets were drawn upon span the entire Brazilian Amazon, implying that the analysis can be repeated for any public forest planning effort within the region (LENTINI et al., 2010).

For the formulation of the scenarios and models, the unconstrained logging scenarios discussed was a linear programming (LP) problem. Non-logging land uses introduced nonlinearities into the objective function, so the other problems were solved using the DICOPT (Discrete and Continuous Optimizer), a solver for mixed integer nonlinear programming (MINLP) problems. DICOPT was chosen because it was robust and efficient compared to other MINLP solution methods. For the largest problem that included all land uses, the model was solved for 13,005 continuous variables and 765 binary variables, with 14,045 constraints, so is a large problem with high computational demanding (LENTINI et al., 2010).

The authors concluded that the model can be used to investigate the impacts of concessions from public forests on the local demand and supply for timber in a given region. Second, it can be used to estimate the revenues that can be generated from concessions and the taxes that can be collected by government through a non-distortionary royalty mechanism. Third, it can be used to investigate the tradeoffs among market and nonmarket uses in terms of reduced timber revenues. Fourth, at the landscape level, this model can help to determine the optimum level of timber production and spatial distribution of alternative land uses from public lands within a given region by taking into account future production trends of the logging industry (LENTINI et al., 2010).

As a way to create new paths of improve forest planning, some researches about the grouping of commercial species in ecological groups, Braz et al. (2012) emphasizes that there is a large gap in tropical forest management plans regarding the adequate intensity of management and logging rates, usually being arbitrarily defined. Their study aimed to define intensities cuttings for groups of commercial tree species, with different growth rates (ecological groups) per unit of production, in the state of Amazonas. The periodic annual percentage increment was used in volume of 26 tree species, obtained from permanent plots. The periodic annual increment, percentage by volume for a differentiating effect, that 1% was considered as the threshold difference. Therefore, as results this study have been identified three cutting intensities for the commercial classes: 24.4% (group I), 35.4% (group II) and 42.4% (group III) for a 25 years cutting cycle.

The main objective of this work was to define different cutting intensities for groups of commercial species, using easy systems execution and assimilation by regulatory agencies and forest companies (BRAZ et al., 2012). The authors concluded that currently low impact forest management are not sustainable because they do not consider the real growth potential of species by forest type. It is strongly suggested calculate the cutting rate, reconciling the potential increment and the cutting cycle, as a reference of the sustainability of the management, differentiated by group of species of same of growth rate (BRAZ et al., 2012).

On their studies Martinhago (2012) and Santos (2019), have applied the capacitated p-median problem to optimize the allocation of log landings, aiming to minimization of the costs of opening log landings and the costs of skidding through two scenarios in order to assist decision taking. The results found proposed the optimal location of the patios with a reduction in opening and skidding costs for scenarios I and II. In this case, both of authors concluded that the used techniques have great potential for solving problems of this type, and their effectiveness in assisting decision-making in Sustainable Forest Management areas (MARTINHAGO, 2012; Santos, 2019).

Martinhago (2012) compared different techniques to optimize the quantity and allocation of log landings in selective logging. It was used the P-Median problem and its variation Capacitated P-Median, with use of spatial constraints applied to a GIS software; using two ways of resolution: linear integer programming and a hybrid metaheuristic. The hybrid metaheuristic is a method that combines elements from different metaheuristics with GRASP (Greedy Randomized Adaptive Search Procedure), tabu search and genetic algorithms. This model was modified to solve the enabled p-median problems and meet the needs of this study. The linear programming model (ILP) basically sought to minimize the tree-yard distances, subject to skidding distance constraint and maximum stock (capacitated model) (MARTINHAGO, 2012). The results showed that metaheuristics presented solutions very close and sometimes equal to exact optimum solutions presented by ILP, in a shorter resolution time (MARTINHAGO, 2012).

In their study with logging operations scheduling, Fernandes et al. (2013) verified the critical paths for of chronological planning of forest operations in Amazon, along the year, for a specific annual production unit. This research aims to present a method that assists planning and distribution of resources by scenarios, formulating in order to optimize the number of teams for each logging activity under time limit to its conclusion. Based on time that a team uses to perform a certain activity and its sequence, it was used operational research techniques, such as linear programming and PERT/CPM (Program Evaluation & Review Technique and Critical Path Method), in order to determine the critical path of supply chain of tropical hardwoods (FERNANDES et al., 2013).

PERT/CPM is a sequence of activities that represent, in a graph, the beginning and the end of an event, as well as other intermediate activities. An event can only be considered started when all the activities that compete with it are completed. Thus, activities that are not executed within the allowed time and end up delaying the total project time are called “bottleneck” or critical activities. These methods, arranging the sequence of activities and determining which ones should receive more attention in planning, optimize the number of teams in order to perform the sequence of activities within a time limit, which is necessary for the region, once the logging operations should be limited to the dry season. As results, the proposed method has demonstrated to be a good alternative for forest planning avoiding greater environmental impacts (operations during rainy season), ensuring the optimal number of teams and performing the entire project in stipulated time (FERNANDES et al., 2013).

The authors emphasized that in selective logging of rainforests, the planners has to deal with specific problems such as the selection of the logging system, the choice of equipment suitable for the system, the elaboration of a secondary roads plan, compatible with the construction costs and the forest's productive potential. Finally, the completion of the tasks on the foreseen dates, which often depend on climatic factors. Along with climatic factors, the forestry company depends on the release by the legal institution of the stand(s) for the year of management. This creates a complication, for example when the released period for logging is ending and for some reason the operations are delayed (FERNANDES et al., 2013).

The objective of this research was the use of operational research techniques to determine the critical path and the “bottleneck” activities of the selective logging operations in Amazon. More specifically, the objective is to determine, through the formulation of scenarios, the ideal number of teams needed to carry out logging in low-impact management, in order to fit into the time limit for the period outside the rainy season, considering here the execution of all activities under these conditions (FERNANDES et al., 2013).

The authors concluded that use of operational research tools allows to plan logging operations during dry season in the region. The sequencing of activities of logging and forest management resulted that all activities are part of the critical path.

Only the activities “Silvicultural treatments”, predecessor of “Felling and log processing”, and “Road maintenance”, predecessor of “Final transport”, are not critical. The study resulted in a total of 25 integer work crews, required for completing the activities within time limit of 168 days (7 months of permitted operations excluding holidays and weekends) (FERNANDES et al., 2013).

Emmert (2014) studied spatial planning in two areas of authorized logging in the Amazon, a private and a public forest, with the goal of developing forest planning models, integrating computational tools of GIS with optimization mathematical models. The author left the proposed model in graph theory, described by Chartrand (1977), and drew up minimum accumulated cost path problems, the so-called minimum spanning trees. A heuristic solution was used for this problem, using the search method of the minimum cost paths to the wood flow based on the hydrological concept applied in a costs surface. The raster vector data were integrated into the models in the GIS software platform (EMMERT, 2014). The aggregation of techniques in GIS and graphics theory has been used to study the rainforest fragmentation on the basis of the roads densities and patterns (ARIMA et al., 2005). Planning models run automatically in GIS eliminating the time spent on manual vectorization. Their application has reduced the amount of roads, trails and storage yards needed, optimizing the necessary infrastructure area and minimizing environmental impacts. The forest planning reduced in 16.5% and 7.0% the infrastructure needed in the private and public forests, respectively (EMMERT, 2014).

Braz et al. (2016) also affirmed a lack of optimization in planning operations schedule, causing conflicts with climatic factors, corroborating with Fernandes et al. (2013). That situation results in difficulties in skidding and transportation, significantly worsened during the rainy season and causing loss of operations’ productivity, higher accident risks and more environmental impacts (soil compaction and erosion). Furthermore, the authors emphasized that information on growth by species and ecological groups of species, soil and slope variables (site classification), are not yet effectively used for long-term forest management. The authors suggested a spatial planning in GIS associated with cluster analysis, in which the model indicates the delimitation of sub-compartments (or sub-plots) separated according to preferential species, volumes, average diameters, slope of the terrain, soil textures, among others (BRAZ et al., 2016).

In its study using geotechnologies to support spatial optimization, Barbosa et al. (2017) developed a study with the aim to use multi-criteria optimization to determine the optimal logging routes based on information derived from an airborne laser scanning data combined into four different cost compositions. Four criteria to be considered in the optimization were derived from the LiDAR cloud: distance sloping (considers horizontal and vertical variation), slope, vegetation height and location of the preservation areas. The results indicated that the more suitable scenarios were: minimization of impact to the APP and balanced minimization (BARBOSA et al., 2017).

The authors concluded that multi-criteria optimization proved to be of great value in allowing to combine different factors in the composition of the cost surface that will be optimized. Different combinations can be adopted aiming to prioritize one or a set of factors, resulting in differences between the results obtained in the optimization. The increasing availability of sensors has considerably increased the quantity and detailing the information available on the management area (BARBOSA et al., 2017).

In their study, Silva et al. (2018a) had the main objective to optimize the location of wood log landings in forest management for the production of wood in the Brazilian Amazon. The research have taken the topography into account, with permanent preservation areas, restricted areas, and remaining trees—and using GIS tools, 7896 sites were identified that could be used as wood log landings. By using mathematical programming techniques, more specifically binary integer linear programming, and based on the classical p-median model, optimal locations for the opening of yards were defined. The scenarios evaluated promoted reductions in infrastructure investment compared with traditional planning. The results showed reductions in the number of forest roads (–6.33%) and trails to extract logs (–15.49%) when compared to traditional planning, concluding that the application of mathematical programming was able to promote significant gains in the logging planning of natural forests in the Amazon (SILVA et al., 2018a).

At their research, Silva et al. (2018b) analyzed ecological and spatial variables to guarantee the best forest structure after logging (CHHENG et al., 2015), although it remains a challenge to achieve a balance between the logging industry and conservation efforts (GATTI et al., 2015). Thus, the aim of this study was to create an integer linear programming (ILP) to fill in the knowledge gaps in the decision support system of reduced impact logging explorations. The minimization of harvested tree distance (Euclidean) to log landings was assessed, using P-median model to optimize the selection of log landings. Forest structure aspects, income and timber production were set in the Branch-and-Bound model, as well as the adjacency constraints. Data are from a dense rainforest in the western Brazilian Amazon. It was applied the phytosociological analysis and BDq method to define the selective logging criteria. Then, ILP models were formulated to allow the application of the constraints. Finally, 32 scenarios (unbalanced forest, UF, and balanced forest, BF) were generated and compared with real executed plans (RE). Robust results were achieved and the expected finding of each scenario was met. The feasibility to integrate ILP models in uneven-aged forest management projects was endorsed. Consequently, the UF and BF scenarios tested were efficient and concise, introducing new advances to forest management plans in the Amazon (SILVA et al., 2018b).

The authors concluded that the mathematical models were able to support forest management planning by estimating a reduction in vegetation damage and guaranteeing timber yield regulation in uneven-aged forests. Furthermore, it was demonstrated that it is possible to integrate an optimum selective logging regime with location log landings (SILVA et al., 2018b).

In their study, Silva et al. (2018c) presented a model of integer linear programming (IP) to optimize the creation of production units, regulated at the level of exploitable trees and to implement a heuristic method to obtain suboptimal feasible solutions. Using a sustainable forest management (SFM) area, it were applied the Euclidean distances to a p-median model with volume and income restrictions; however, the adaptive heuristics development (AHD) was a random, greedy, and adaptive procedure. Four scenarios were formulated with a variation of ±10% to ±20% in volume and income value. The results showed that the AHD was effective in obtaining solutions to the problem presented and could assist forest managers in decision-making to form PUs that handle the presented constraints (SILVA et al., 2018c).

Poudyal et al. (2018) investigated the evolution of researches and applied techniques for selective logging in tropical forests around the globe. The authors concluded that the main constraint factors that limited the improvement of sustainable forest management were related to: reflected limited adoption of these practices on the ground, due to poor implementation of improved forests, harvesting practices and standards. The studies until now are more concerned with biophysical impacts, with poor coverage of immediate timber recovery and amount of wastage in the forest harvesting processes, and their impact on carbon sequestration potential and biodiversity. Moreover, broader forest management outcomes will not be possible until stakeholders and regulatory institutions consider the socio-economic and cultural factors in forest management. Therefore, the interests and needs of the forest manager/owner and the capacity of the stakeholders in the adoption of improved forest management is crucial. Poor collaboration and coordination among stakeholders, hinders application of improved logging practices and affects sustainable forest management outcomes (POUDYAL et al., 2018).

Finally, outcomes and suggestions from the research on impacts of selective logging and the ways to improve implementation, are rarely materialized in policy and practices. Despite increasing efforts to improve forest management practices and the attention of researchers, multiple factors – operational, ecological, economic and cultural – have constrained wider applications. Context specific regulations and incentives are expected to address the constraining factors (PUETTMANN et al., 2015; POUDYAL et al., 2018).

The research developed by Sales et al. (2019) used Dijkstra Algorithm (DA) to define optimal allocation of log landings in order to minimize total skid-trail’s distance in the Amazon Forest. DA minimized trails’ distances and associated transportation costs, leading to an even smaller value when the current planning was disregarded and suggesting the reduction of deleterious environmental externalities. They sought to answer if it is possible to optimize distances and intrinsic costs in the management of Amazonian forests using DA. The objective was to minimize skid trails distances by best allocating yards using DA and to compare four scenarios of forest harvest planning in the Brazilian Amazon. The yards and roads located were compared to three alternative scenarios in terms of total skid distance, trails and road densities, and skidding costs for three successive harvests, seeking to minimize total skid-trails’ distance. Alternative scenarios were to keep the number of yards within work units (WU) and place them in the edge of existing roads (scenario 2); keep the number of yards within each WU (scenario 3); and place 23 yards, disregarding the current planning (scenario 4).

The authors used a GIS software to delimit farm and WUs limits, contours, roads, current yards, and tree points to represent the initial database processed. Sloping areas and close to remaining trees were constrained to yards' allocation due to difficult construction and in order to avoid damaging remaining stock, respectively. Two digital elevation models (DEM) were generated with spatial resolution of 10 m and 20 m. The slope restriction, such as unrestricted site (slope 15%) and restricted (slope > 15%), were generated with the 20 m DEM. Furthermore, yard location and tree-yard allocation of each scenario were carried out with Network Analyst tool available in this GIS software. This tool is based on Dijkstra algorithm (DA), which traces the shortest route between two points. The network was configured by connected arcs among facilities and incident points (trees) considering general and specific restrictions of each scenario (constraints). Tree-yard allocation in first three scenarios considered WUs' limits as constraints. The solution of scenario 4 was generated disregarding the existing planning, locating the same amount of existing yards, 23, in the farm so that total skid-trails' distances were minimized. Each feature contained the tree-yard distances (SALES et al., 2019).

The study found out that total skid-trail's distance, number of trees above optimal extraction distance and densities of skid trails and roads were smaller in scenarios 2, 3, and 4, compared to the current yard allocation (scenario 1). Scenario 4, with fewer restrictions, reduced skid-trails' distances by 23%. Harvest costs decreased from scenario 1 to 4 in all three harvest cycles. The researchers concluded that DA allowed optimized distribution of yards and skid trails and generated efficient results for harvest planning. This reinforces the importance of optimized planning, which establishes satisfactory results in the effort to reduce costs and environmental impact keeping high efficiency (SALES et al., 2019).

The authors concluded that DA algorithm has generated more efficient results for the analyzed scenarios compared to the current planning, reducing skid-trails' distances, trails' and roads' densities, and increasing the number of trees within ideal extraction distance. This has led to reductions in costs and, possibly, environmental impacts of the harvest (SALES et al., 2019).

The road optimization in forestry is crucial for reducing environmental impacts and production costs; that is strongly linked to the optimal location of storage yards, which are essential to forest road planning (SILVA et al., 2020). Considering the present problem and the current solutions available, Silva et al. (2020) conducted a case study that aimed to evaluate the efficiency and eventual gains of optimized forest planning (OFP), as compared to traditional forest planning (TFP). Using the mathematical model of p-median and Euclidean distances, with maximum constraints of connections and capacities, the OFP model resulted in significantly reduction of the distances between tree and yards, with only 0.23 km difference in the quantity of planned forest roads, when compared to TFP. Additionally, OFP demonstrated a higher productivity, a reduction of skid distance (by an average of 17.16%), and reduced the cost of log skidding (by 25.76%) (SILVA et al., 2020).

The authors concluded that considering only the planning phase, the OFP method provided a significant reduction in the tree-yard Euclidean distance, without large variations in the planned amount of forest roads, as compared to the TFP method. Additionally, the execution of OFP provided an increase to the logs skid productivity. This was a result of more efficient allocation of the log storage yards, as compared to the TFP method. The implementation of OFP did not require change in routine of field activities or team training. This fact represented a positive point for the use of this methodology by forest companies (SILVA et al., 2020).

According to Görgens et al. (2020), with use of geo-technologies their study proposed a new multidimensional framework for a precision forestry approach assisted by airborne laser scanning data (ALS). Therefore, successful management operations become a key element in the process of promoting protection through sustainable development. Thirteen relevant variables were derived from ALS data, such as: canopy height, terrain topography, relative vegetation density, forest gaps, slope restrictions, skidder restrictions, load truck restrictions, topographic wetness, flow accumulation, horizontal distance to drainage, vertical elevation from drainage, stream and headspring restrictions. Four different scenarios for the management plan optimization were studied: shortest distance, forest conservation, soil conservation and all combined. Results showed that the detailed forest information from ALS point clouds was useful to indicate regions not suitable for forest operations. Failure to properly consider the different factors involved may result in inadequate infrastructures, lower operational performance and constant re-planning requirements.

The optimization determined the least cost path from the start cell (logging yard) to the end cells (trees). The trees were detected by reclassification of the CHM (canopy height model), using all crowns higher than 35 m and vectorizing polygons with areas larger or equal to 10 m². The polygons' centroids indicated the trees' locations. The optimization procedure first computed the accumulated cost surface to travel from trees to the log yard. The path to connect the start points to the endpoints was determined by the least cost route. A node-link raster cell representation was created where a node was the center of a raster cell and the link connected the node to its neighboring cells. The link could be lateral, connecting the four nearest neighbors, or diagonal, connecting the cell to its corner neighbors. The cost distance was defined as the cost resistance that it takes to travel through those links. Finally, the least accumulative cost between two points (start and end points) was computed based on Dijkstra's algorithm (GORGENS et al., 2020).

The authors concluded that although the motivation of this study is to apply forest precision principles in a context of the Brazilian environmental law, the challenges to consider a multidimensional context is relevant to any other tropical forest management site. The results of this research show that including more criteria into the optimization increases the logging path, likely increasing cost as a consequence. However, it was possible to clearly compute how much the scenario changes after different criteria were included in the problem. The proposed approach improves the traditional method currently used in tropical forest management planning by combining rich and detailed information about the forest structure, terrain model and legal constraints (GORGENS et al., 2020).

In their study, according to Aguiar et al. (2020) the objective of this research was to evaluate the allocation of wood storage yards through exact solution and metaheuristics in a forest management area. The study area was a native forest under sustainable forest management regime located in the Brazilian Amazon. It was used a binary integer linear programming model solved by CPLEX and the metaheuristics: Greedy Randomized Adaptive Search Procedure (GRASP), Tabu Search (TS), Variable Neighborhood Search (VNS) and Simulated Annealing (SA). The results showed that all metaheuristics obtained significant solutions with shorter processing times, only SA obtained feasible solutions in all executions for all three tested instances (AGUIAR et al., 2020).

In general, the metaheuristics were efficient in obtaining feasible solutions faster than CPLEX, which represents the feasibility of the planning of allocating storage yards in large areas, and without significant losses of best-known solution. The SA presented the best performance in the three evaluated instances. The authors concluded that this research contributed to the evaluation of alternative computational methods for planning the allocation of wooden storage yards. Moreover, evidence was obtained of effectiveness and efficiency of assessed metaheuristics and the viable applicability of approximate methods for this problem (AGUIAR et al., 2020).

Silva et al. (2018a) concluded that the optimal distance between roads (ROD) was 516 m. In this case MED (maximum extraction distance) was defined as half of the ROD, so in this case it was equal to 258 m. However, due to obstacles encountered in the field when extracting trees, as well as location errors, which are common in the practice of logging, MED was relaxed from 258m to 342.20m (SILVA et al., 2018a). Aguiar et al. (2020) emphasized that the maximum skidding distance of 250 m, commonly adopted in Amazon forest planning, considers Euclidean distance (Ed) between tree and log landing. However, it is interesting to obtain a 3D distance matrix, which represents the shortest path as a function of horizontal distance corrected by terrain slope. For this, the authors adjusted a linear regression to estimate this value considering a 250 m Ed, with values of 3D distance matrix. The estimated value considered as Dmax in the analyzed instances was 379.45 m (AGUIAR et al., 2020).

On their study, Isaac Junior et al. (2021) aimed to compare alternatives for road sizing and log deck allocation in selective logging of Amazon forest. In a forest management unit, the skidding to log decks was evaluated in two different areas. To determine the skidding/log deck relation, geo-referenced points were generated equally spaced every 50 m. In area 1, the Integer Linear Programming (ILP) model and the Multi-Objective Evolutionary Algorithm (MOEA) were compared. In area 2, only the MOEA was considered. Solutions were then generated to identify the best management alternative.

In order to solve the problem, in the capacitated and non-capacitated forms, two approaches were used, one exact and the other approximate, using the integer linear programming (ILP) and the multiobjective evolutionary algorithms (MOEA). The proposed model for ILP solution was based on a mathematical model formulated to solve the problem of p-medians. In this approach, the proposed objective-function was to reduce the skidding distance to log decks (Euclidean). Furthermore, for bi-objective problem solving, it was used the Improved Nondominated Sorting Genetic Algorithm (Isaac Junior et al. 2021). In both areas, the MOEA showed greater efficiency regarding the processing time, as well as the reduction of log decks number and the road sizing. The multi-objective evolutionary approach assists the decision-making process, due to the presentation of alternatives based on Pareto-optimal solutions (ISAAC JUNIOR et al., 2021).

On their study, Aguiar et al. (2021) developed a research that aimed to evaluate computational methods' effectiveness in planning forest roads, optimizing resources to reduce damage to the remaining forest, compared to traditional planning methods. The study area was a natural forest under a sustainable forest management regime located in Brazilian Amazon. A binary integer linear programming model was used, with application of Dijkstra, Bellman-Ford, Dial, and D'Esopo-Pape shortest path algorithms, implemented in C programming language. During processing of instances, the time taken to obtain the solution increased according to size of instance, however, time difference was not significant. Among the evaluated algorithms, the D'Esopo-Pape algorithm showed the best performance, mainly when considering different spatial scales. The evaluated methods were effective in obtaining an optimal solution for proposed forest road planning. The research concluded that solutions obtained using computational methods more effectively considered the restrictions associated with sustainable forest management, in contrast to those derived from the traditional planning by forest company (AGUIAR et al., 2021).

The authors still emphasize that to carry out design of roads based on computational methods, there is no need to change the forest inventory methodology traditionally employed by companies. For the data collected during the census, forest inventory and the information obtained by remote sensors, are enough to carry out planning of roads without economic impact (AGUIAR et al., 2021).

## 2.4 BRAZILIAN LEGISLATION GOVERNING LOGGING OPERATIONS IN THE AMAZON

Regarding infrastructure planning for selective logging in the Brazilian Amazon, there are several federal and state laws that regulate these activities and operations in the region.

According to the Brazilian Federal Legislation in Forest Resources, compiled in Brasil (2007), regarding the planning and construction of log landings or yards, the number of yards to be built depends on the existing volume in the Work Unit. These yards are built with a track-type tractor, in dry places and preferably in clearings, vines areas or in parts of the forest in early successional stage (with presence of small diameter trees only).

In addition, the Law defines some guidelines:

- ✓ Describe the planning for the construction of log landings;
- ✓ Inform the procedures and specify the machines for the construction of yards;
- ✓ Establish the criteria for the location of yards along secondary roads;
- ✓ Indicate the planned size of the yards (ideally 20m X 25m);
- ✓ Describe the methodology for measuring logs in the yards (BRASIL, 2007).

Regarding the planning and construction of permanent (primary), the assumptions are:

- ✓ Provide for a maximum width of 6m for the roadbed and the opening strip a maximum width of 10m. For roads exceeding the limit, provide technical justification;
- ✓ Indicate the system planned for the road's drainage structures.

For secondary roads, the assumptions are:

- ✓ Provide a maximum width of 4m for the roadbed and the opening strip a maximum width of 6m. For roads exceeding the limit, provide technical justification;
- ✓ Provide that the orientation of secondary roads, whenever possible, be in the east-west direction (BRASIL, 2007).

The concepts and description of the terms are also defined in the Law, the Permanent or primary roads are defined as the main roads feeding raw materials to industries and are used permanently. If year-round use is planned, they should be paved with cobblestone. Unpaved roads with gravel cannot be used in the rainy season. In both cases, the roadbed must be sloped and permanent drainage structures must be built and maintained. The roadbed should be 8-10 meters wide and the open belt should be 15-20 meters wide. The planning of the roads, whenever possible, should consider the use of the watersheds (BRASIL, 2007).

The secondary roads are the roads located in the WUs (Work Units). This type of road is permanent only for that part of the forest. They should be maintained occasionally, for example before logging, to provide access to the harvested UPA for the purpose of applying silvicultural treatments, plantation maintenance, measuring permanent plots, inspection and protection. These roads should not be used year round, unless they are built in parts of the area that will be harvested at the beginning of the dry season or at the end of the rainy season. In this case, they should be paved and well drained. The normal roadbed is 4-5 meters, which is also the width of the opening strip (BRASIL, 2007).

The planning of the main and access roads is based on satellite images and field verification. As for the secondary roads, the planning is based on the maps constructed from the information obtained in the microzoning (BRASIL, 2007).

### 2.4.1 Main States legislation in the Amazon

According to the SDS Resolution No. 17 of 08/20/2013 of the State of Amazonas, in relation to the suppression of native vegetation for forest management activities, Article 13 defines that the suppression of vegetation in the UTs (work units) will be admitted, for the implementation of forest logging infrastructure, respecting the following maximum percentage limits of area:

I - for the construction of roads, the limit of 1.75% of the area of the UTs, respecting the species protected by specific legislation;

II - for the opening of storage yards, a limit of 0.75% of the UTs area;

III - during the implementation of the infrastructure, changes in the plan presented may be allowed, as long as they do not exceed the limits established in items I and II.

The Article 14 describes that the construction of roads, storage yards and other infrastructure on the property outside the management area must be described in the PMFS (Sustainable Forest Management Plan) and must be authorized in the environmental licensing (BRASIL, 2013).

According to the Legislation of the State of Mato Grosso (Decree No. 1313 of 03/11/2022 Article 30), are authorized as of the request protocol, according to the standard term of reference, the minimum infrastructure construction for the forest census in the UPA. These are related to protection, camping and opening of primary roads for access, respecting the limit of 6 meters in width. Paragraph 01 further states that the other planned infrastructures will only be authorized after AUTEX (logging authorization) has been issued. In paragraph 02 it is defined that the sum of the opening areas of planned infrastructures cannot exceed 2% of the UPA area (BRASIL, 2022).

According to the Normative Instruction SEMAS No. 3 of 07/11/2017 of the State of Pará, Article 2 defines the Annual Forest Calendar which comprises 01 (one) embargo period and 01 (one) harvest period for forest logging activities, as defined in the Annex:

I. It is understood by embargo period that in which, during the execution phase of the management activities, the exploration activities (construction of roads, log landings, felling and skidding activities) and wood transport on secondary roads within the approved Annual Production Unit - UPA are prohibited;

II. The execution of management activities refer to all activities developed in the Sustainable Forest Management Plan - SFMP, such as pre-exploratory activities (forest inventory, vine cutting, among others), exploratory activities (construction of main and secondary roads, storage yards, felling trees, hauling and transport of logs, logging, etc.) and post-exploratory activities (measurement of permanent parcels, maintenance of main roads, etc.);

III. The harvest period is the one subsequent to the embargo, during which the logging activities are allowed (construction of roads, log landings, felling and skidding) and the transport of wood in logs and forest residues (BRASIL, 2017).

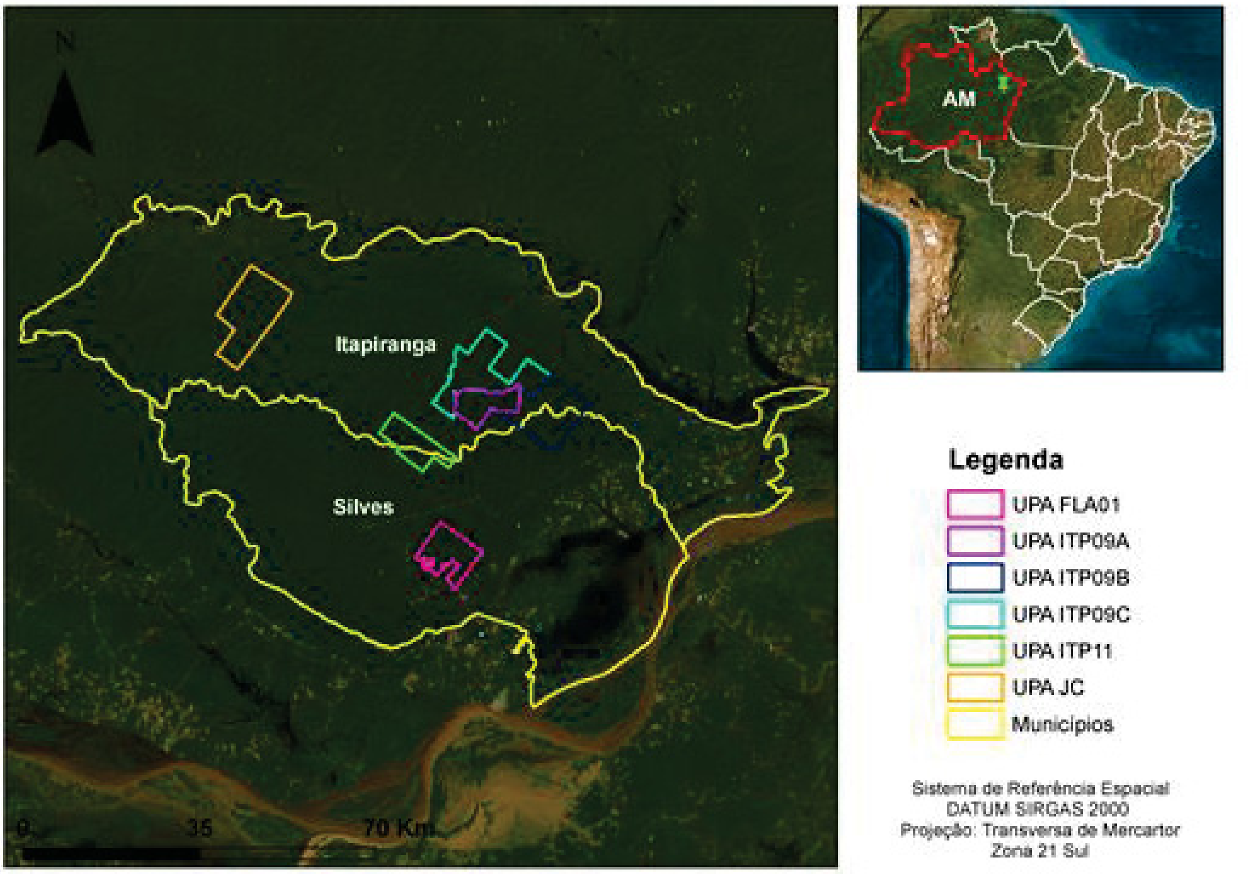
# 3 MATERIAL AND METHODS

## 3.1 STUDY AREA

Founded in 1994, Mil Madeiras Preciosas is a subsidiary of the Swiss group Precious Woods and headquartered in the municipality of Itacoatiara in the state of Amazonas, Brazil. Through operations of Sustainable Forest Management and industrial timber production, Mil stands out as a reference in the field of timber products from native forests in Brazil. The Precious Woods Group (PW) is a publicly traded corporation, with shares traded in Zurich-Switzerland, organized as a holding company. In 1997 it became the first native forest management company in Brazil to obtain the FSC® forest certification seal, adopting its strict principles and criteria. The residues from sawmill provide 40% of the clean energy generated from a thermoelectric plant that supplies the municipality of Itacoatiara (PWA, 2022).

The company works in the tropical timber trade through forest management in private areas that totalize around 248,000 hectares of certified management areas and around 500,000 of total area. The managed areas spread over the municipalities of Silves and Itapiranga FIGURE 1.

FIGURE 1 – SPATIAL LOCATION AND DISTRIBUTION OF THE UPAS (ANNUAL PRODUCTION UNITS) ANALYZED IN THE FOREST MANAGEMENT AREA




SOURCE: The Author (2023).

The climate in the study area is classified as humid tropical (Af), with average annual precipitation of 2200 mm and no defined dry season according to the Koppen-Geiger classification (ALVARES et al., 2013). The average temperature is 28°C and relative humidity 80% (INMET, 2022). According to IBGE (2012), the forest of the region is an Upland Humid Tropical Forest, a dominant phytophysiognomy in the forests of the Amazon.

The company uses a polycyclic logging system, based on the CELOS system, developed by Dutch engineers in Suriname. The company only applies the CELOS Logging System, not considering the Silvicultural System. The forest logging in the region is selective and with use of tree-length system (NASCIMENTO, 2017). The operations are subdivided in 04 stages: chainsaws to cut the trees (felling); tractors with installed winch (pre-skidding the logs from the forest trails to secondary roads); skidder machines (skidding the logs from secondary roads to log landings); and yard operations (load and unload the trucks in log landings and transport to the main yard) (EMMERT, 2014).

### 3.1.1 Logging operations

The dimensioning of the teams varies according to the production goal for the current year and the progress of the operations. From this, there is the determination of the number of teams in each stage and the duration of the workday. In addition, the weather conditions are also essential for the continuity of the forestry operations, as the activities cease during heavy rainfall, for technical and work safety reasons (NASCIMENTO, 2017).

The company carries out operations in the UPA during a maximum period of 08 months per year. In the inactive months vacations are calculated (01 month) and the remainder by the time bank system (03 months). This justifies in parts the extended workday imposed by the company during the months of exploitation. The work schedule in 2015 followed the 11/2 scale, 11 days of work (accommodation) and 02 days off (NASCIMENTO, 2017). The sizing and composition of the teams for the operations are described below in TABLE 1.

TABLE 1 – SIZING, COMPOSITION AND WORKING HOURS OF THE LOGGING AND YARD TEAMS, FOR THE 11/2 SCALE

| Analyzed Stages | Number of teams | Number of employees per team | Occupations involved | Work shift* |
|---|---|---|---|---|
| **Cutting** | 10 | 03 | 01 team leader<br>01 chainsaw operator<br>01 cutting auxiliary | 09 hours<br>(07 – 17h) |
| **Pre-skidding** | 05 | 07 | 01 team leader<br>02 chainsaw operators<br>03 pre-skidding auxiliaries<br>01 tractor winch operator | 10 hours<br>(07 – 18h) |
| **Skidding** | 01 | 06 | 01 team leader<br>01 loader operator<br>03 skidder operators<br>01 chainsaw operator | 12 hours<br>(07 – 20h) |
| **Yard operations – log landings** | 01 | 02 | 01 loading leader<br>01 loader operator | 12 hours<br>(06 – 19h) |

| Analyzed Stages | Number of teams | Number of employees per team | Occupations involved | Work shift* |
|---|---|---|---|---|
| **Yard operations – main yard** | 01 | 09 | 01 yard leader<br>03 measurement assistants<br>01 chainsaw operator<br>03 loader operator<br>01 documentation issuer | 11 hours<br>(06 – 18h) |

* The workday has a 01-hour lunch break (12-13 hours).

SOURCE: Nascimento (2017).

For a better visualization of the activities studied, Table 02 shows the sequence of operations from cutting the tree in the forest to the transport of logs to the main yard, the last stage within the forest management area.

TABLE 2 – SEQUENCE OF ACTIVITIES THAT CONSTITUTE THE LOGGING AND YARD OPERATIONS IN THE COMPANY STUDIED

| Operation | Ilustration | Description |
|---|---|---|
| **Cutting** |  | The teams orient themselves in the forest by means of maps that indicate the location and species of the trees to be cut. After the hollow test, the trees without hollows are felled. |
| **Pre-skidding** |  | The team opens a previously planned track using a track-type tractor to the location of the logs to be extracted. The winch cable, up to 75 m long is taken to the logs, where they are fastened and skidded to the edges of the skid trail, on sites with lower slopes. |

| Operation | Ilustration | Description |
|---|---|---|
| **Skidding** |  | It uses a grapple skidder tractor to skid the logs from the edges of the skid trails to the log landings. |
| **Yard operations – Log landings** |  | First yard operation, in which the logs stacked in the log landings are loaded onto trucks, toward the main or storage yard, outside the forest. |
| **Yard operations – Main yard** |  | Second yard operation, where the logs coming from the forest are unloaded from the trucks, measured, classified, and stacked up by species, constituting a stock for immediate transportation to the industry, according to need. |

SOURCE: Nascimento (2017).

## 3.2 DATA COLLECTION

In this study, a database of: forest inventory, digital maps of infrastructure planning (log landings, skid trails and forest roads), relief/watersheds data, available soils and land use information, as well as updated unit costs of each logging operation were used. It were used granted data from the company database, of 06 consecutive years of logging, presented below TABLE 3.

TABLE 3 – GENERAL DATA FROM ANALYZED UPA'S

| Logging season | UPA's code | Secondary Roads (m) | Area (ha) | Secondary Roads Density (m/ha) | Number of trees (inventory) | Total Production (m³/season) |
|---|---|---|---|---|---|---|
| **2013/14** | ITP09A | 84,832.14 | 6,241.44 | 13.59 | 89,637 | 123,864.18 |
| **2014/15** | ITP09B | 68,089.33 | 13,014.30 | 5.23 | 199,929 | 128,122.91 |
| **2015/16** | ITP09C | 162,677.31 | 13,841.25 | 11.75 | 173,338 | 123,083.45 |
| **2016/17** | ITP11 | 174,257.02 | 7,164.56 | 24.32 | 95,177 | 130,683.92 |
| **2017/18** | FLA01 | 92,335.43 | 7,925.81 | 11.65 | 85,657 | 120,046.31 |
| **2018/19** | JC | 186,528.93 | 15,120.01 | 12.34 | 213,525 | 157,465.17 |

SOURCE: The Author (2023).

To ensure a technical and operational support to redesign the infrastructure, some spatial, operational and environmental variables were considered, in addition to some parameters inherent to the activities already carried out by the company.

Thus, the basic parameters for the initial analysis were: the capacity or stock of exploitable timber volume for each area (m³/UPA), and permanent maintenance of the main roads (permanent infrastructure). A minimum production of 120,000 cubic meters was considered for each UPA, which is the baseline production of the company, per logging season. From this, the potential of the area was estimated, with no maximum limit, to know the potential exploitable volume in each UPA.

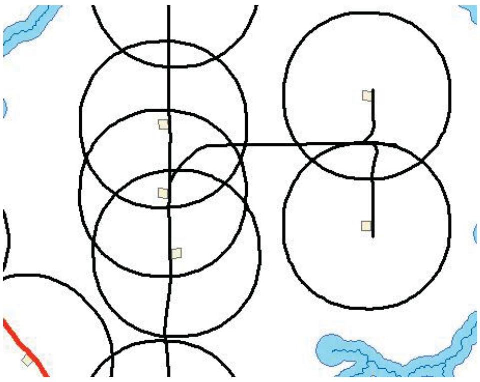
Operationally, the log landings or log yards have a rectangular size of 20x25m, with capacity constraints of up to 350 m³ per load, that were considered with the use of the same structure up to 3 times, totaling a maximum capacity of 1000m³ per planned landing (PERSONAL COMUNICATION PWA, 2022). The maximum skidding distance (tree-log landing) was set at 250m, data cited in several scientific references, considering the economic and operational viability of selective logging of tropical timber using a skidder machine; based on the results found in the study of optimized logging by Silva et al. (2018a) and Aguiar et al. (2020). Based on these assumptions, the process of finding infrastructure solutions to improve forest management processes began.

## 3.3 DATA ANALYSIS

In general, the data presented in this research was analyzed in two stages: a) geoprocessing and b) improvement with use of QGIS extension called qneat (analysis routine in subtopic 3.3.1). Geoprocessing was previously carried out to identify and classify restricted areas (APPs-permanent protected areas, Brazilian environmental laws constraints, operational constraints and prohibited cutting tree species), in restriction layers using the QGIS software. So these areas were excluded from the improvement process.

The analysis sought to minimize the land use for infrastructure, subject to several environmental, production and operational constraints, for each year of logging. After the improvement process, were integrated the spatial data resulting from the iterations into QGIS software development environment, with use of QGIS extension qneat. The results were compared with the current planning for every evaluated year. For the log landing planning, buffers with a radius of 250m were applied around the log landings, and those that overlapped were excluded and/or relocated in order to cover the entire exploitable area (buffers side-by-side), with the process illustrated below FIGURE 2.

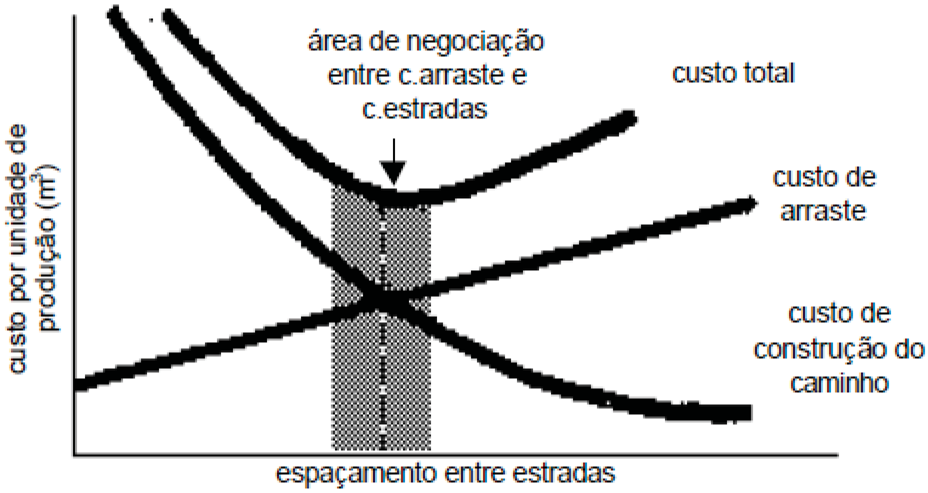
FIGURE 2 – CONVENTIONAL SPATIAL PLANNING OF LOG LANDINGS, WITH MANY OVERLAPS, CONSIDERING THE RANGE DISTANCE (250m) FOR THE IMPROVED PLANNING



SOURCE: The Author (2023).

With improved planning and side-by-side radius of 250m with no overlap, the average extraction distance (AED) consists of half the tree-path distance, i.e. AED of 125m.The FIGURE 3 presents the optimal minimum costs for AED and optimal roads density (ORD).

FIGURE 3 – OPTIMAL BREAK-EVEN POINT BETWEEN AVERAGE SKIDDING DISTANCE COSTS AND OPTIMAL ROADS DENSITY




SOURCE: Braz (1997).

### 3.3.1 Spatial Analysis Routine in QGIS Software platform

**1.** Organization of the cartographic base (downloading, generation or unpacking of the files received).

**2.** Homogenization of the cartographic reference system (CRS). That is, transform all files to the same coordinate system "Datum", and the CRS of the project must also be the same.

For this project we used the QGIS software and the following data:

**Shapefiles**

- Tree points
- Hydrography
- APP areas
- Farm boundary
- Log landings
- Main roads
- Secondary roads
- Trails

**Raster files (image)**

- Digital Elevation Model (DEM) - SRTM image, 30m spatial resolution.

**Step by step**

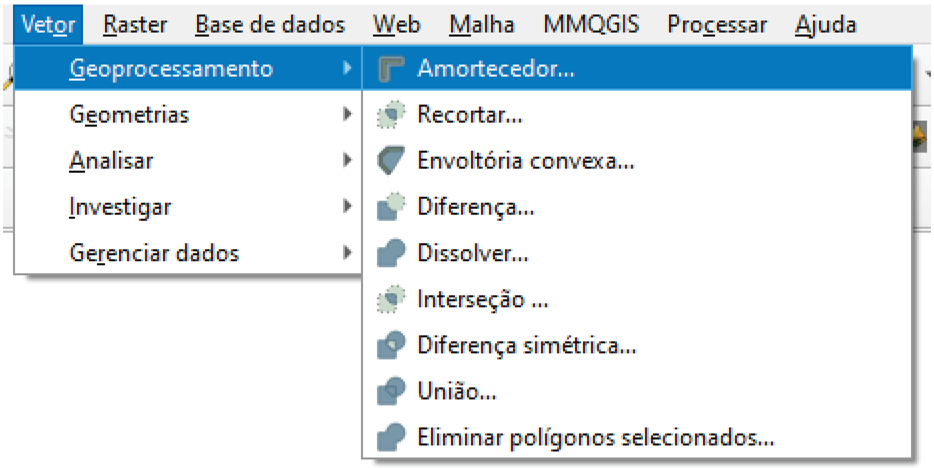
Analysis of the volume of log landings, considering a 250m radius from the central point and the volume of wood available in that area.

**1.** Open QGIS Software

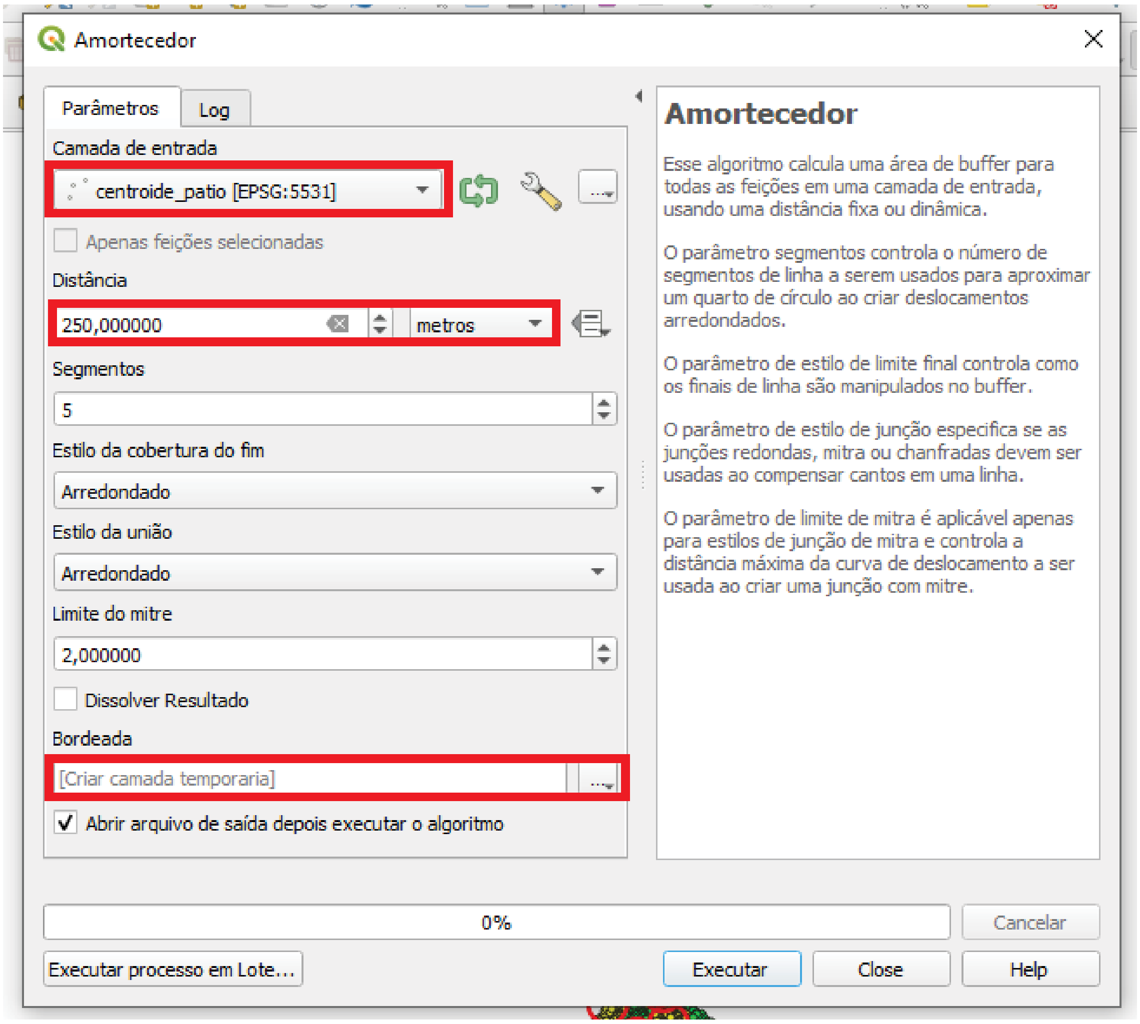
**2.** Open the data

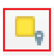
**3.** Leave all data in the same coordinate system as the project.

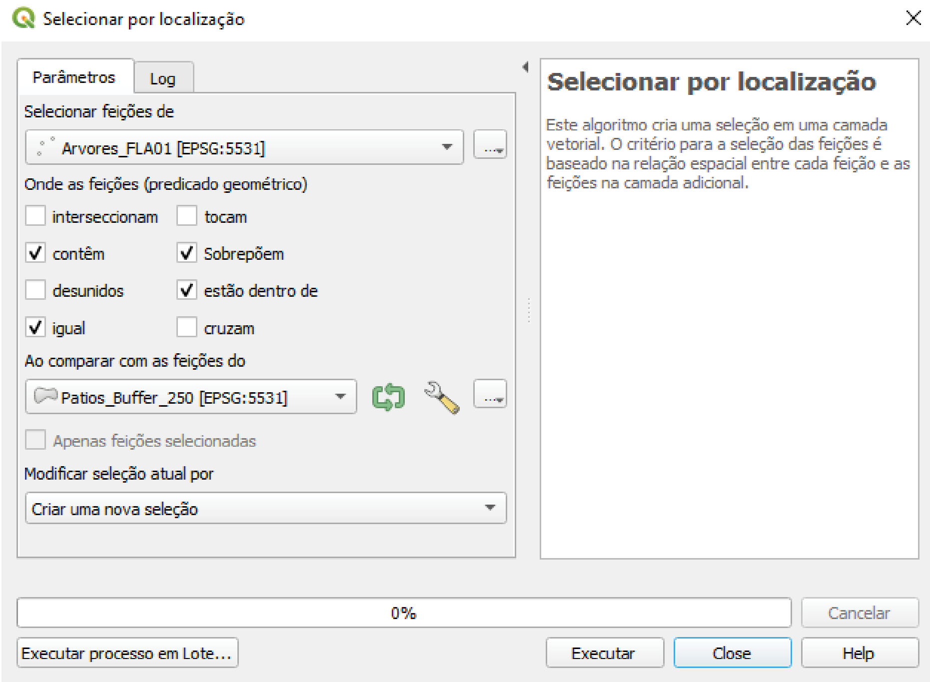
**4.** Find the Vector tab, Geoprocessing item, and buffer option.



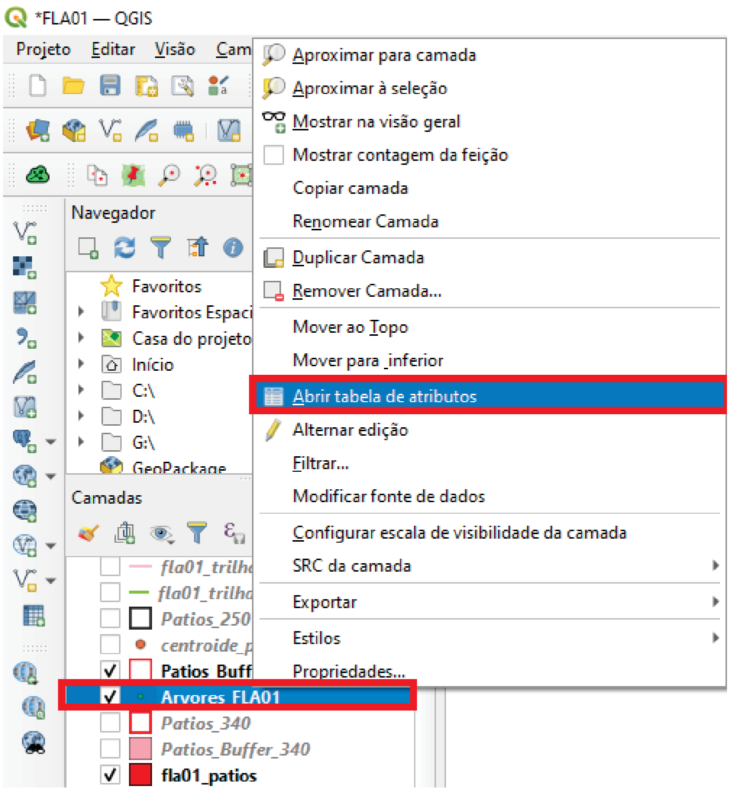

**5.** Choose the file for the centroid of the log landings, determine the desired radius, in this case 250m, and choose a folder to save-in.




**6.** Search for the icon  Select by location, and select the trees, from the 250m radius of the log landings.

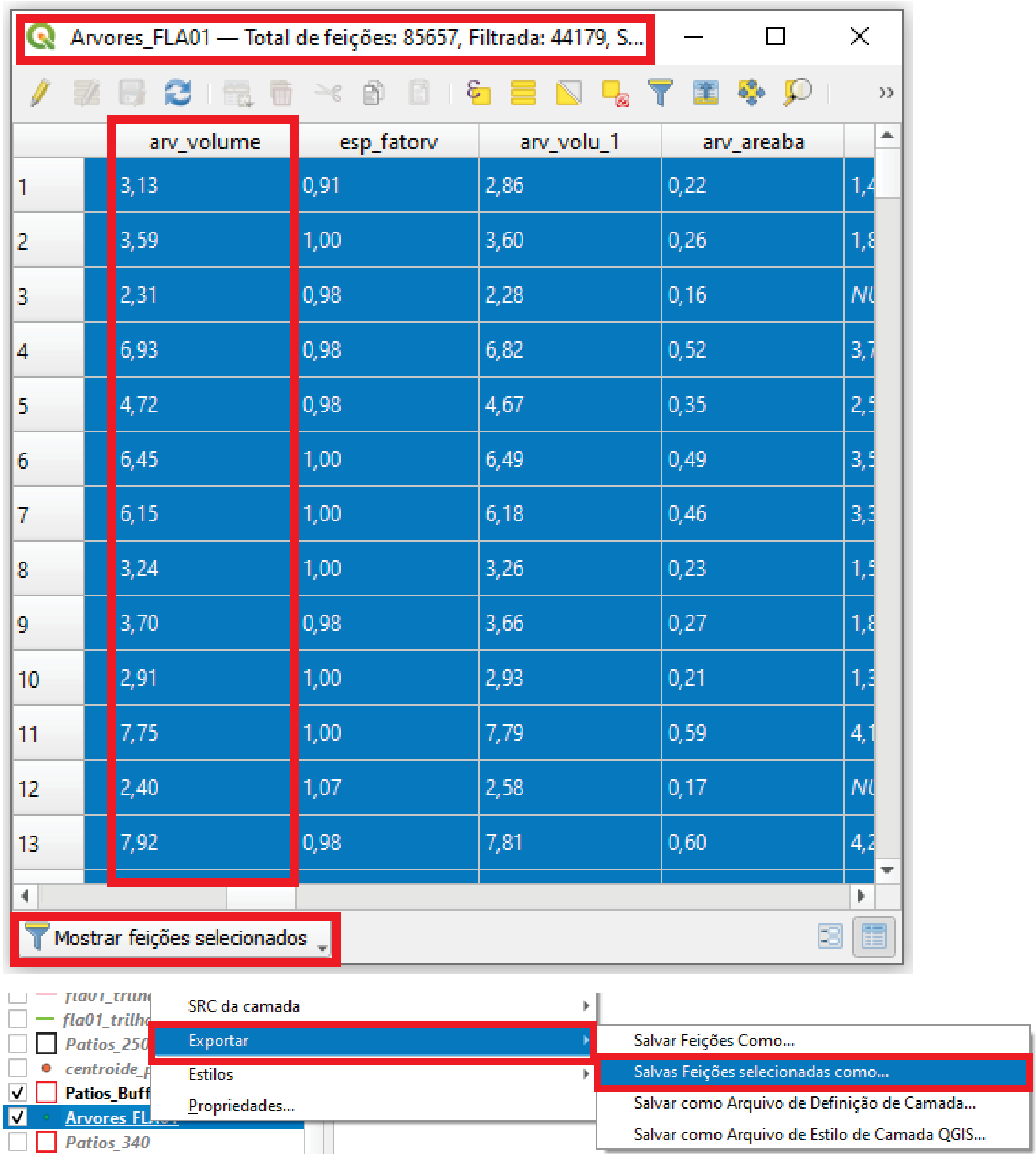


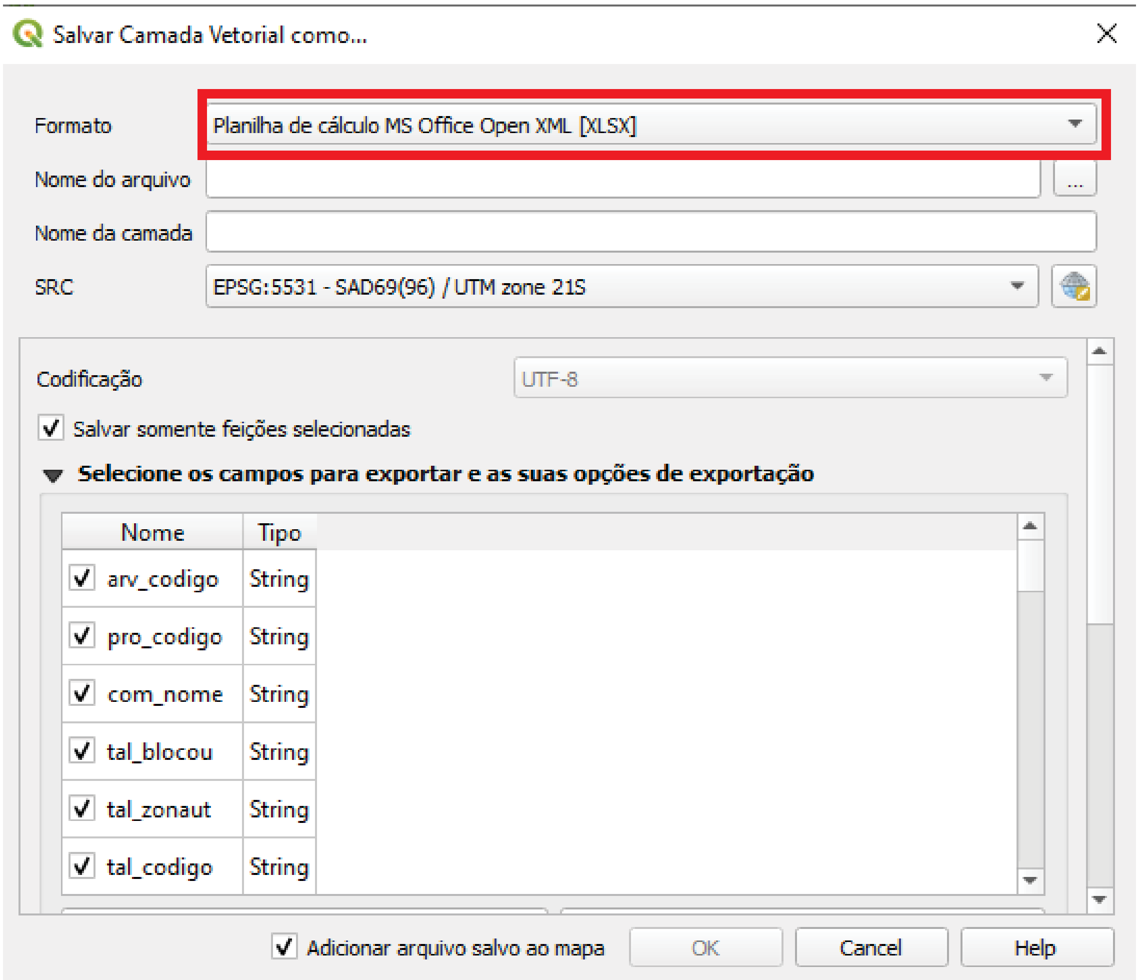

**7.** Open the attributes table of the tree file.




**8.** Look for the option "Show selected features" and then look for the column "arv_volume" - now we have the volume of all the selected trees within the 250m radius of the log landings, and the total number of selected trees.

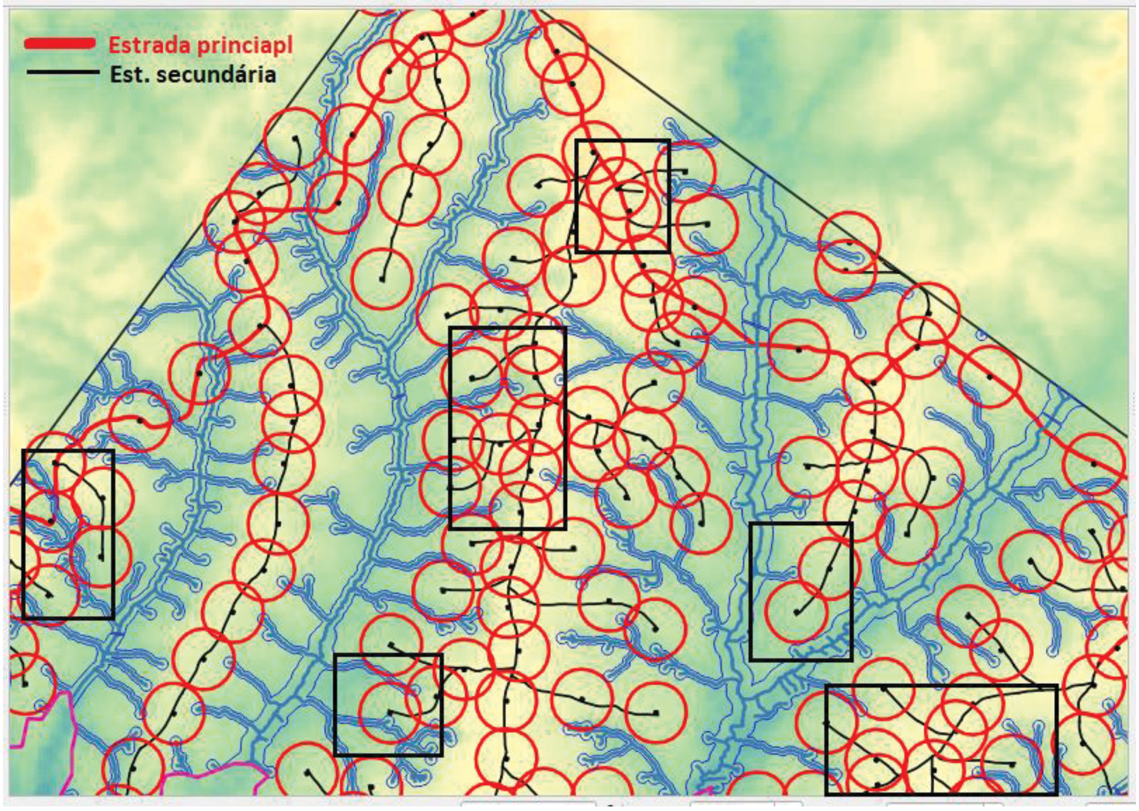
By exporting the selected features in XLSX extension, you can open the Excel spreadsheet with only the trees that were within the 250m radius and calculate the potential volume within the log landings.



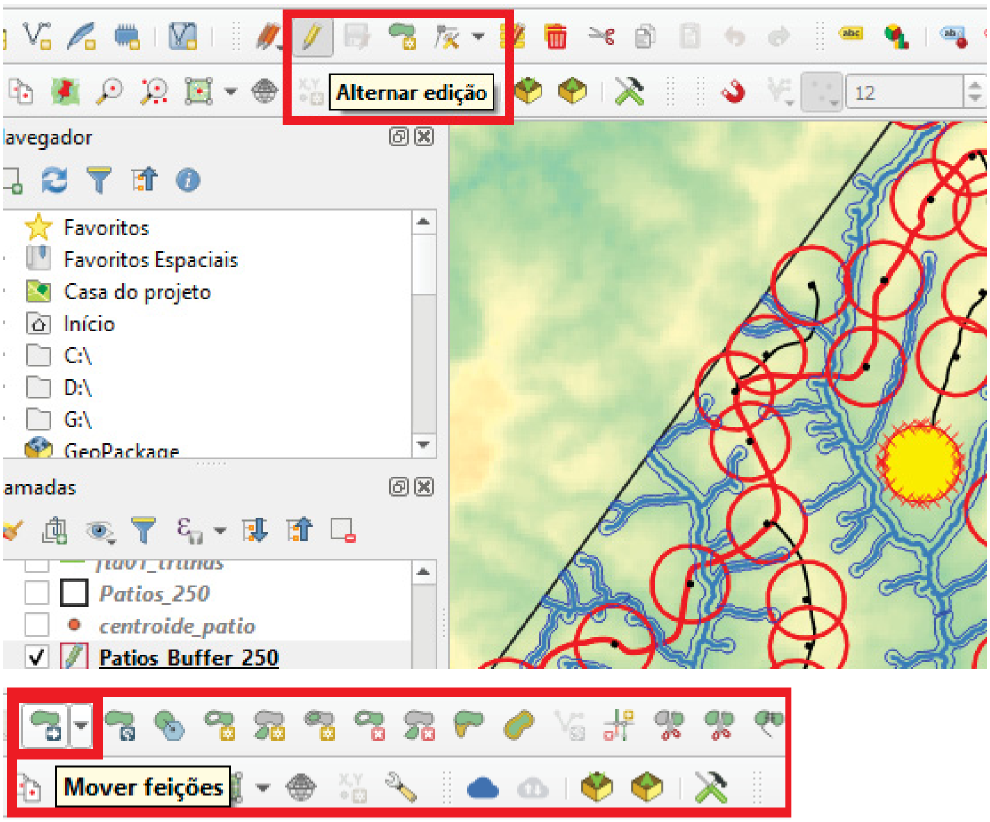



**9.** By evaluating the potential volume of wood computed within the radius and the volume stipulated by the standard, we can evaluate the possibility of relocating and reducing the number of log landings, taking into consideration the physical characteristics of the environment and environmental/legislative characteristics (altitude, proximity to APPs areas and streams).

- In the image below we can be observe through the radius distribution of the patios, that they could be better distributed. Because they present area overlapping, areas over APPs, areas over springs, areas over second order rivers, in valley bottoms where lower altitudes prevail, which means a more expensive climb to the transport truck, and besides being far from the main road.



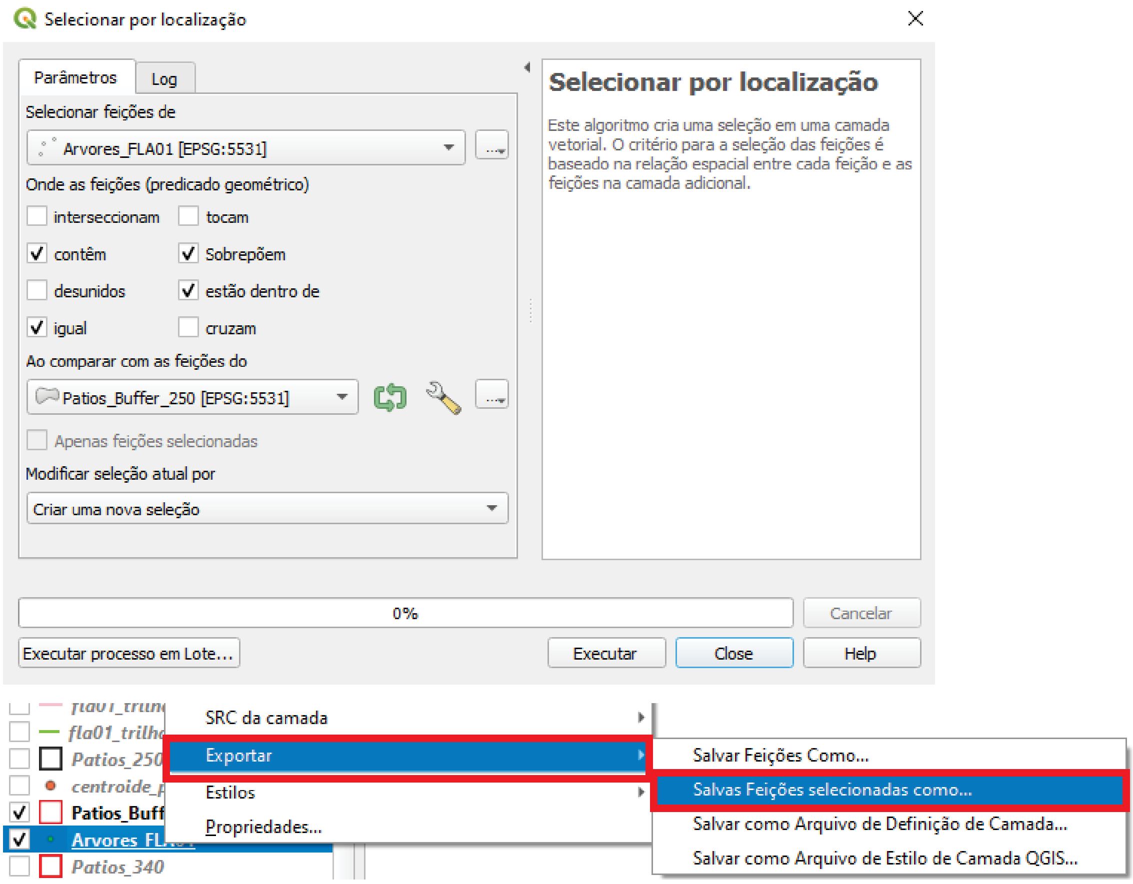

**10.** Using the Alternate Edit tool, we can delete, edit, move and change the location of the log landings. In this case of the radius, which we will use as a guide, and later we can generate new centroid points where the patio itself will be located. Use the "Move Feature" tool to move the positioning of the polygons.



**11.** In this step an analysis of the grid in the qneat extension is performed, in order to reduce the number of log landings according to what the standard says and aiming for an optimization and cost reduction, which is mainly done by reducing the patios that contain overlapping areas, i.e., that are less than 500m away from each other.

**12.** After determining the number of log landings and the stipulated wood volume per area and per log landing, approximately 900m³ per log landing, the same procedure is carried out as step 6 and 8.

From the new number of patios, select the trees within the new relocated radius and then export the selected features, thus separating the trees of interest within the area of interest.



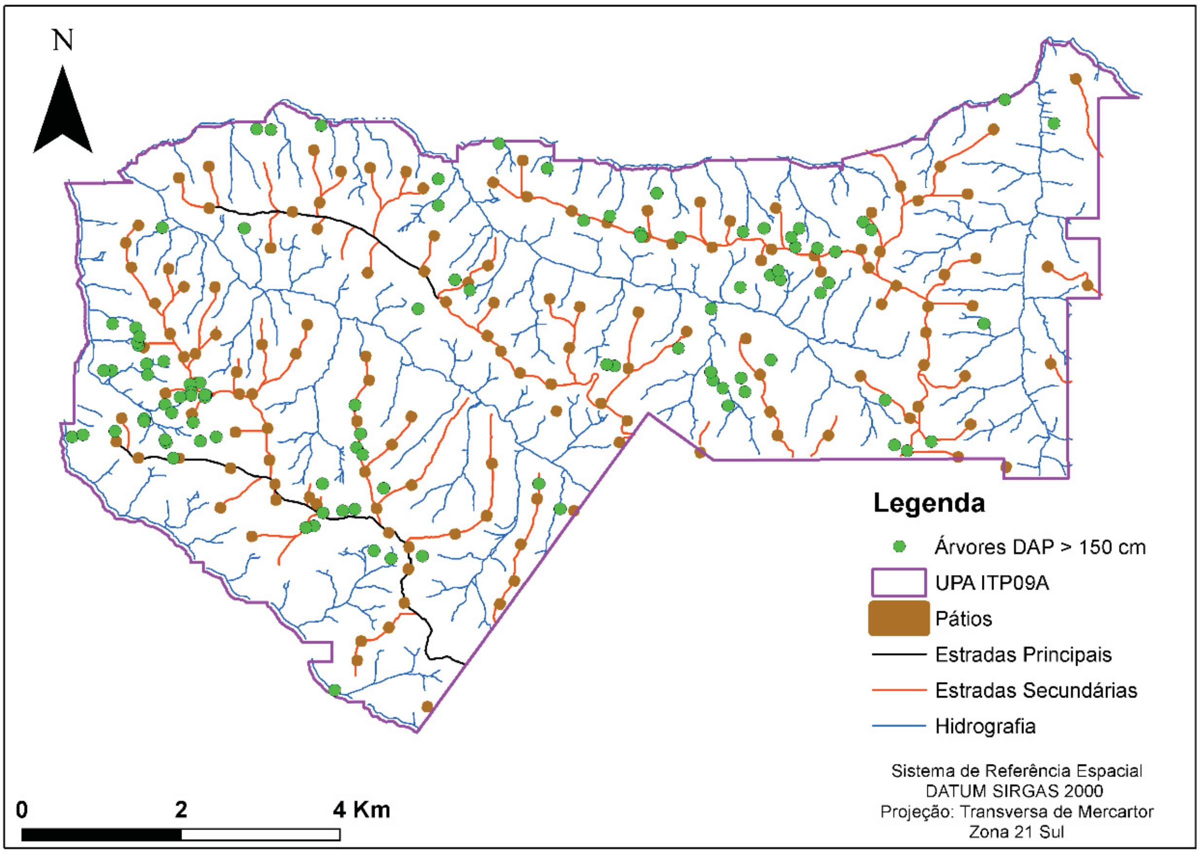

**13.** END

# 4 RESULTS

## 4.1 PREVIOUS ANALYSIS – CONVENTIONAL PLANNING

We initially sought to verify the determinant factors for the conventional spatial infrastructure performed by the company, as well as previous indicators that subsidized planning improvement (watersheds pattern, concentration of thicker commercial trees and current allocation of log landings and roads).

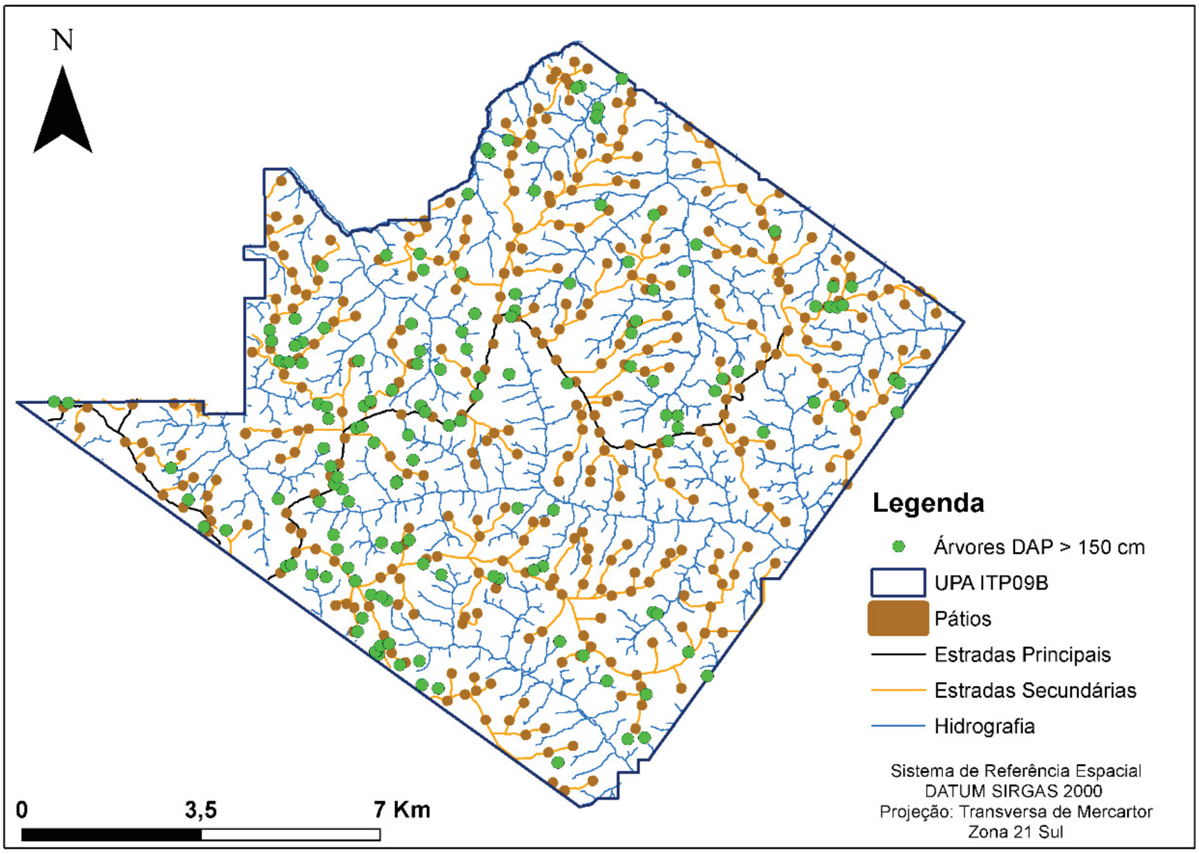
FIGURE 4 – CURRENT SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2013/2014 LOGGING SEASON, HIGHLIGHTING THE LOCATION OF EXPLOITABLE TREES WITH DBH> 150 CM AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 5 – CURRENT SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2014/2015 LOGGING SEASON, HIGHLIGHTING THE LOCATION OF EXPLOITABLE TREES WITH DBH> 150

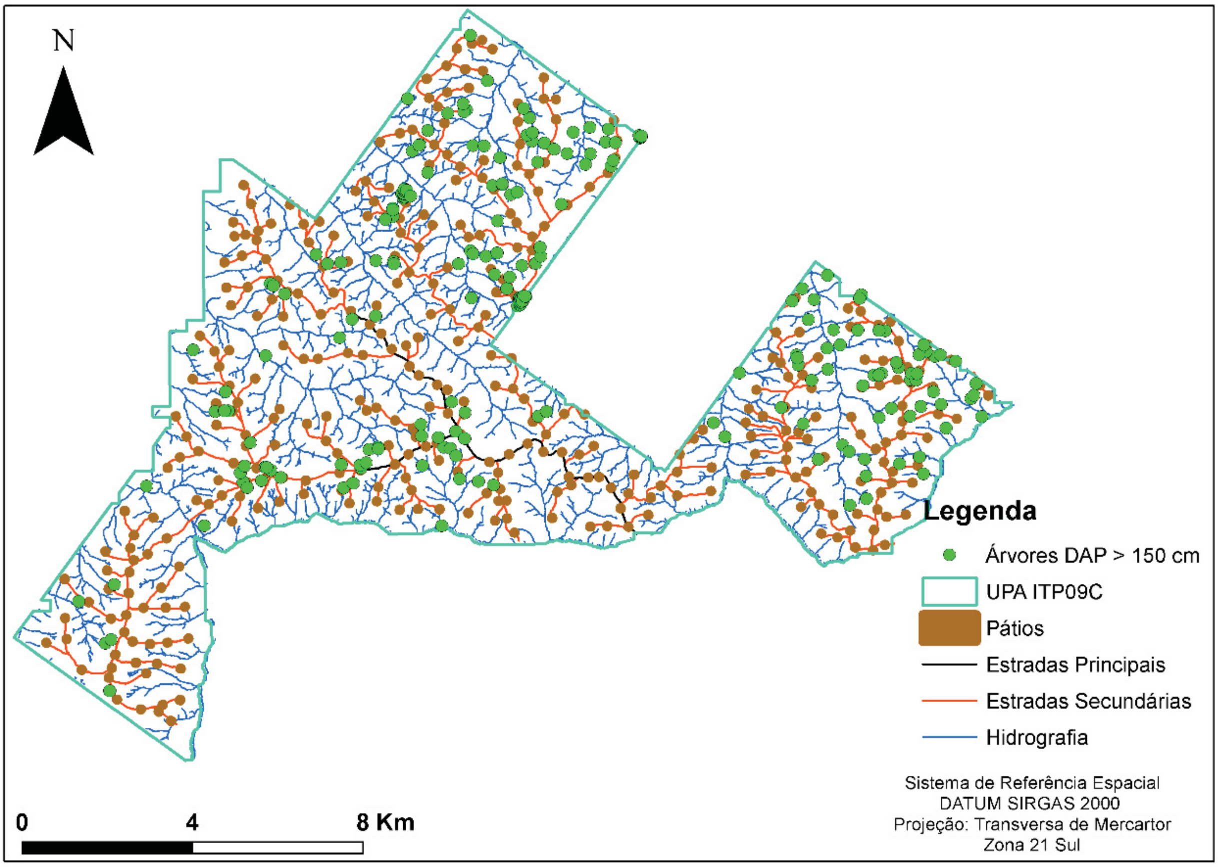
CM AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 6 – CURRENT SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2015/2016 LOGGING SEASON, HIGHLIGHTING THE LOCATION OF EXPLOITABLE TREES WITH DBH> 150

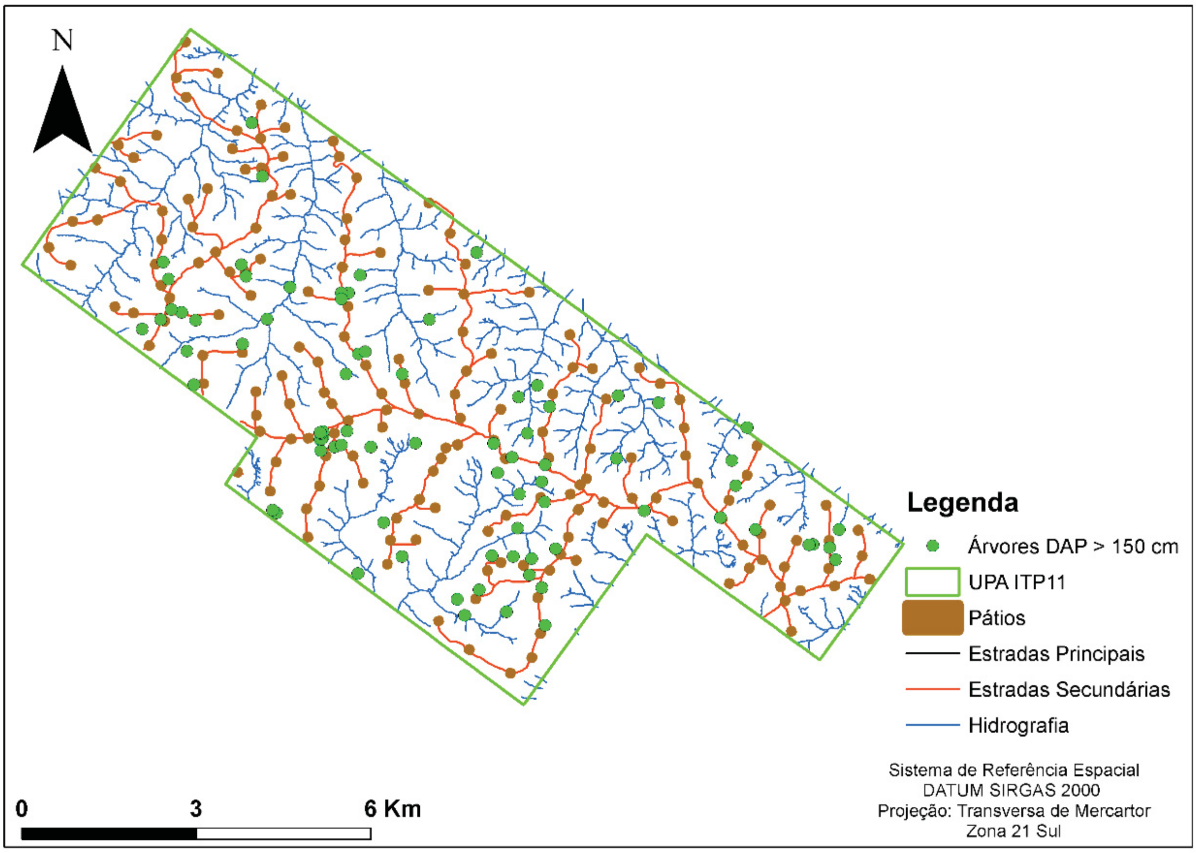
CM AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 7 – CURRENT SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2016/2017 LOGGING SEASON, HIGHLIGHTING THE LOCATION OF EXPLOITABLE TREES WITH DBH> 150

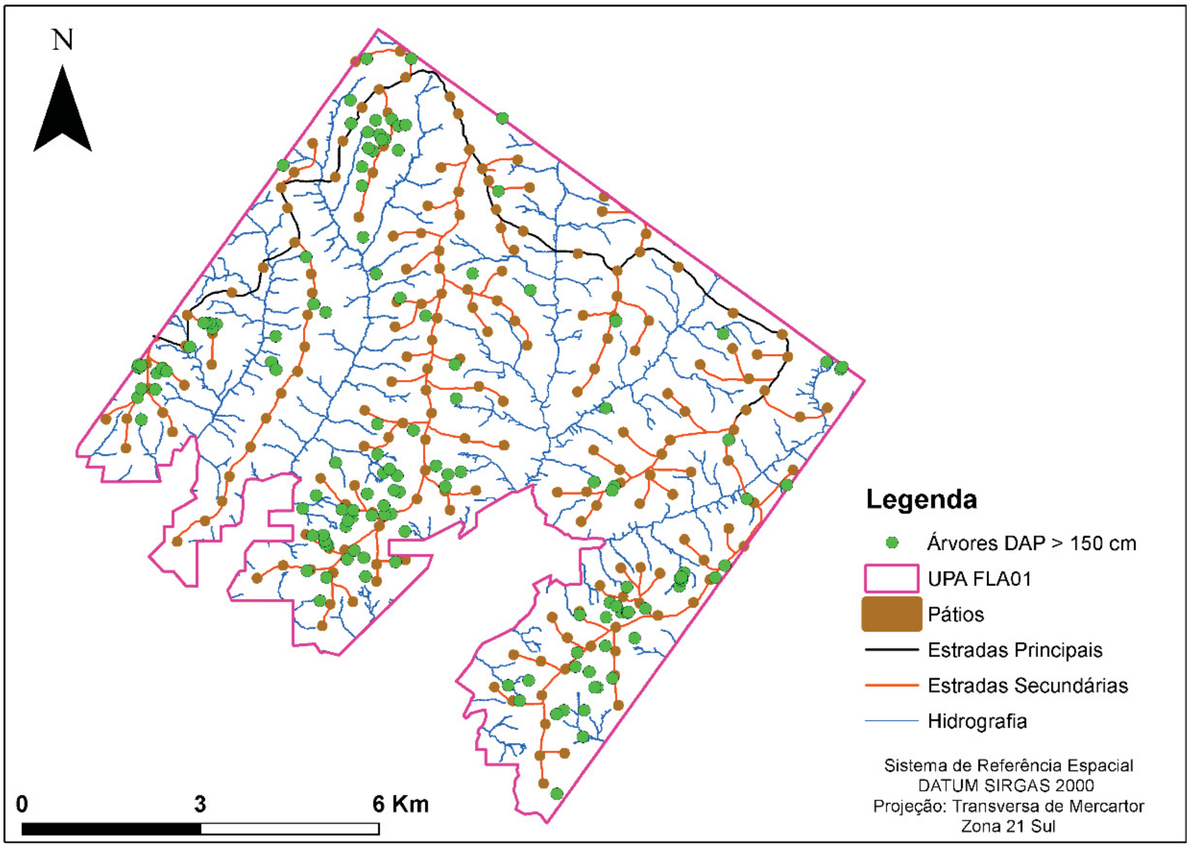
CM AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 8 – CURRENT SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2017/2018 LOGGING SEASON, HIGHLIGHTING THE LOCATION OF EXPLOITABLE TREES WITH DBH> 150

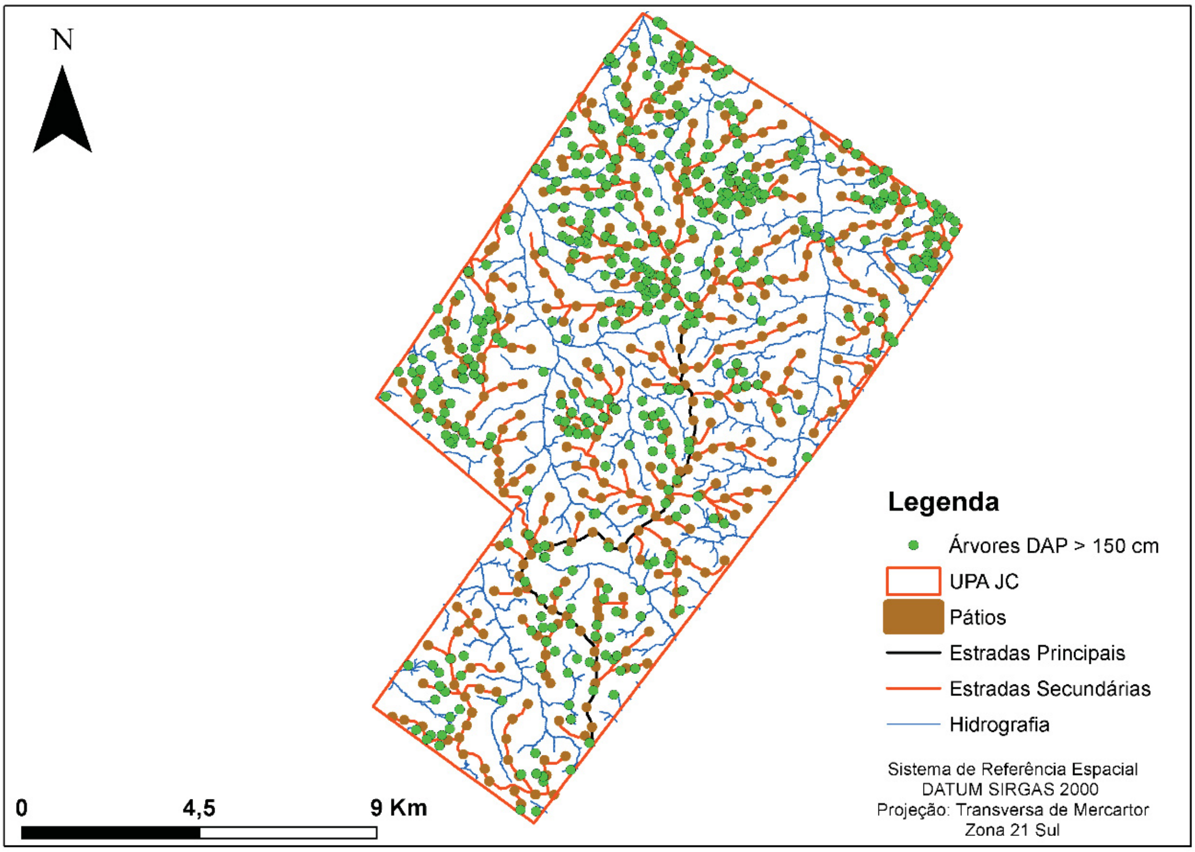
CM AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 9 – CURRENT SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2018/2019 LOGGING SEASON, HIGHLIGHTING THE LOCATION OF EXPLOITABLE TREES WITH DBH>150

CM AND HYDROGRAPHY




SOURCE: The Author (2023).

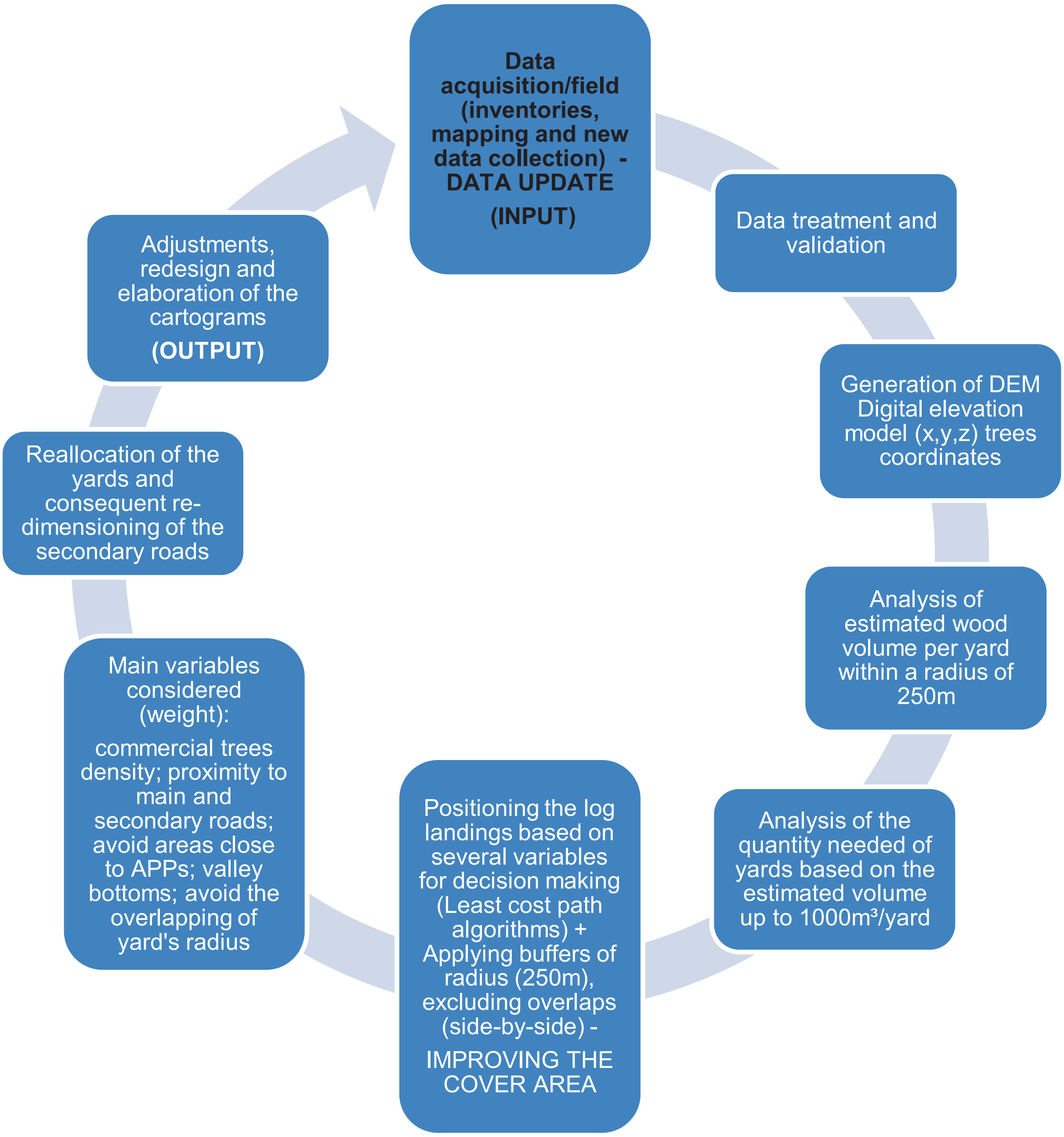
In this preliminary analysis, it sought to better understand how the company defined the necessary infrastructure for logging. It can be seen by the conventional planning that the relief and hydrography were the only determining factors for the allocation of roads and log landings within the UPA. In addition, it can be seen that the log landings have been systematically allocated along the forest roads, sometimes not considering the different patterns of concentration of commercial trees inside the UPAs.

In this previous analysis, the aim is to gather important information taken directly from the forest inventory, such as the spatialization of timber volume within the area, in order to better plan the allocation of secondary roads, as well as the number of log landings. In this case, with the spatialization of density of exploitable trees for the cutting minimum diameter (>50cm) according to Brazilian Law; new decisions can be made in the planning of logging operations, besides guaranteeing greater efficiency of the process. In addition, other factors arising from the inventory are very relevant for reaching better solutions for planning operations, such as the spatialization of commercial species (in order of economic value) and tree shape quality. The use of information collected in the forest census carried out in the UPAs generates important subsidies for the strategic planning of forest management operations. However, this important information is often little considered.

## 4.2 MAIN ANALYSIS - IMPROVED INFRASTRUCTURE PLANNING

Initially, it was elaborated a flowchart of the developed work process to improve the infrastructure planning process that is presented. The process was powered by data from continuous forest inventories (census) and pre-cutting inventories, following the logic of the PDCA (Plan-Do-Check-Act) tool, that is, it is a process of continuous improvement, flexible and applied to any area, illustrated in CHART 1.

CHART 1 – FLOWCHART OF INFRASTRUCTURE IMPROVEMENT ANALYSIS, BASED ON PDCA PROCESS IMPROVEMENT TOOL.




SOURCE: The Author (2023).

After processing and improving the infrastructure planning process, the company's conventional planning was compared with the improved planning based on infrastructure minimization, while maintaining the same production levels and operational characteristics, presented below in FRAME 1.

FRAME 1 – COMPARISON BETWEEN RESULTS OF THE CONVENTIONAL (ORIGINAL) PLANNING AND THE IMPROVED PLANNING

| UPA | Original - Sum of Log Landings | Improved - Sum of Log Landings | ΔL (%) | Original - Secondary Roads (m) | Improved – Secondary Roads (m) | ΔR (%) | Volume-Infrastructure Logging Capacity (m³) |
|---|---|---|---|---|---|---|---|
| **FLA01** | 191 | 121 | -36.6 | 84,832.14 | 69,745.50 | -17.8 | 124,961.02 |
| **ITP09A** | 142 | 107 | -24.6 | 68,089.33 | 56,058.32 | -17.7 | 133,687.89 |
| **ITP09B** | 352 | 121 | -65.6 | 162,677.31 | 99,763.72 | -38.7 | 181,219.46 |
| **ITP09C** | 365 | 150 | -58.9 | 174,257.02 | 104,648.40 | -39.9 | 177,849.90 |
| **ITP11** | 173 | 119 | -31.2 | 92,335.43 | 75,903.18 | -17.8 | 159,666.50 |
| **JC** | 375 | 275 | -26.7 | 186,528.93 | 161,146.79 | -13.6 | 381,913.04 |

SOURCE: The Author (2023).

According to the results presented above, there was a remarkable reduction in the need for physical structure for all areas (log landings and secondary roads), maintaining the same production capacity. Thus, the operational costs of maintaining the areas and environmental impacts were consequently reduced, by not remove much of the vegetation for conversion into infrastructure. The reduction was noticeable for both cases, which is natural, because the relocation and reduction of the number of overlapping log landings, consequently reduced the demand for secondary roads connecting to them.

The reduction of infrastructure demanded in log landings varied between 24.6% and 65.6%, with an average of 40.6%, which is remarkable, considering the agile planning improvement process applied to forest management.

The reduction in infrastructure demanded in secondary roads varied between 17.8% and 39.9%, showing an average of 24.2% fewer roads (in meters), which is noticeable when considering the area demanded for road construction (road width and bordering vegetation removal), with great environmental and physical impacts on tropical forests.

In some areas the log landings were so close, that within a single radius it had 3 log landings; they were allocated at around 200m from each other, and not the 500m that it should be, that is why there was UPA with more than 350 log landings

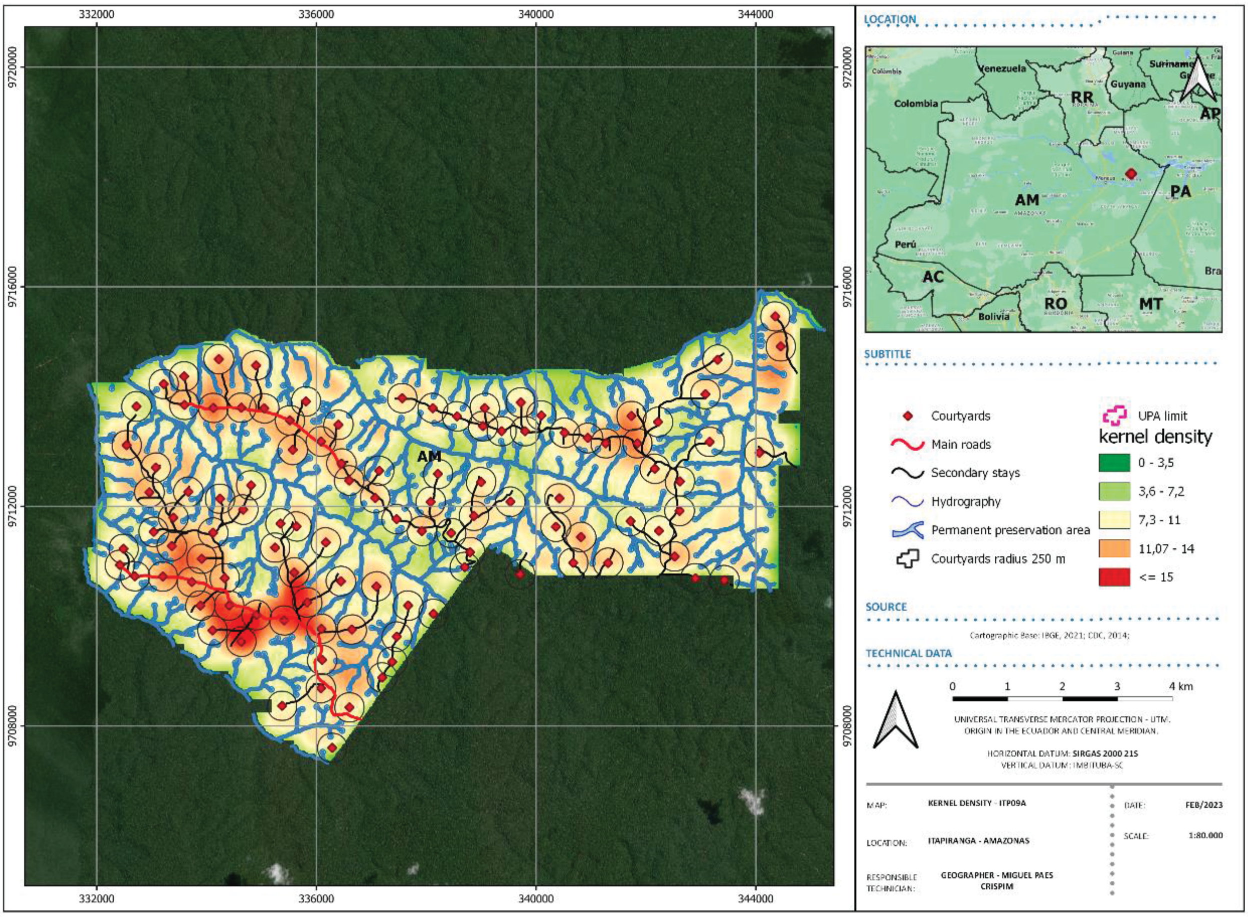
(JC-UPA, for example). Furthermore, this UPA presented discrepant results because it was very large (more than 15,000 ha) with a lower hydrographic network, i.e. many exploitable trees and fewer APPs, increasing the potential areas to allocate log landings.

### 4.2.1 Spatialized improved planning

In this section, initially is it illustrated the concentration of exploitable trees, with use of Kernel's density model for the physical infrastructure of the UPAs, aiming to minimize the use of the area and improving the productivity of the operations.

Additionally, it is presented the result of the improved spatial planning (data presented in the FRAME 1) of the infrastructure for the UPAs, demonstrating a total coverage of the exploitable area by the radius of the allocated log landings (250m), avoiding overlapping of area, thus optimizing the allocation of log landings and secondary roads in the UPAs.

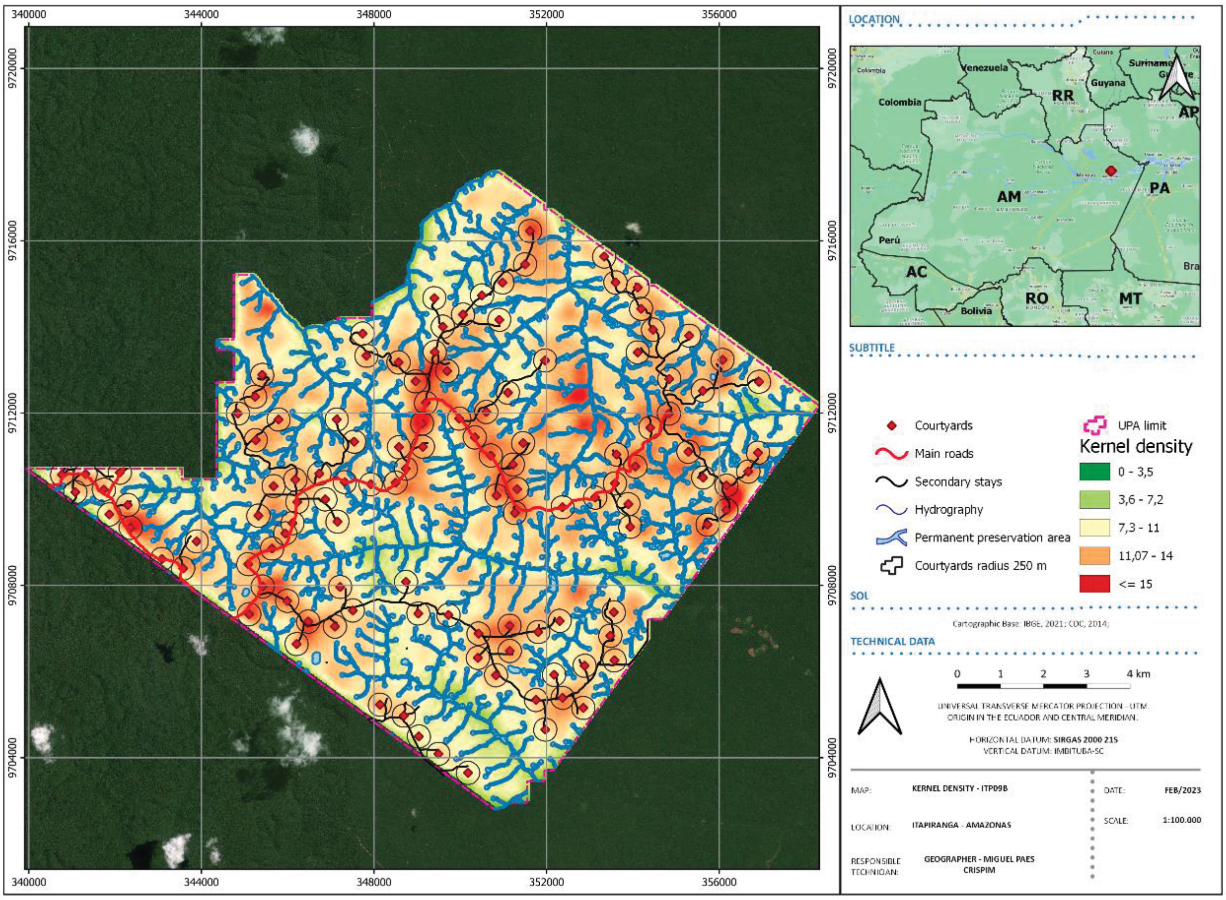
FIGURE 10– IMPROVED SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2013/2014 LOGGING SEASON, HIGHLIGHTING THE DENSITY OF EXPLOITABLE TREES WITH DBH> 50 cm AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 11– IMPROVED SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2014/2015 LOGGING SEASON, HIGHLIGHTING THE DENSITY OF EXPLOITABLE TREES WITH

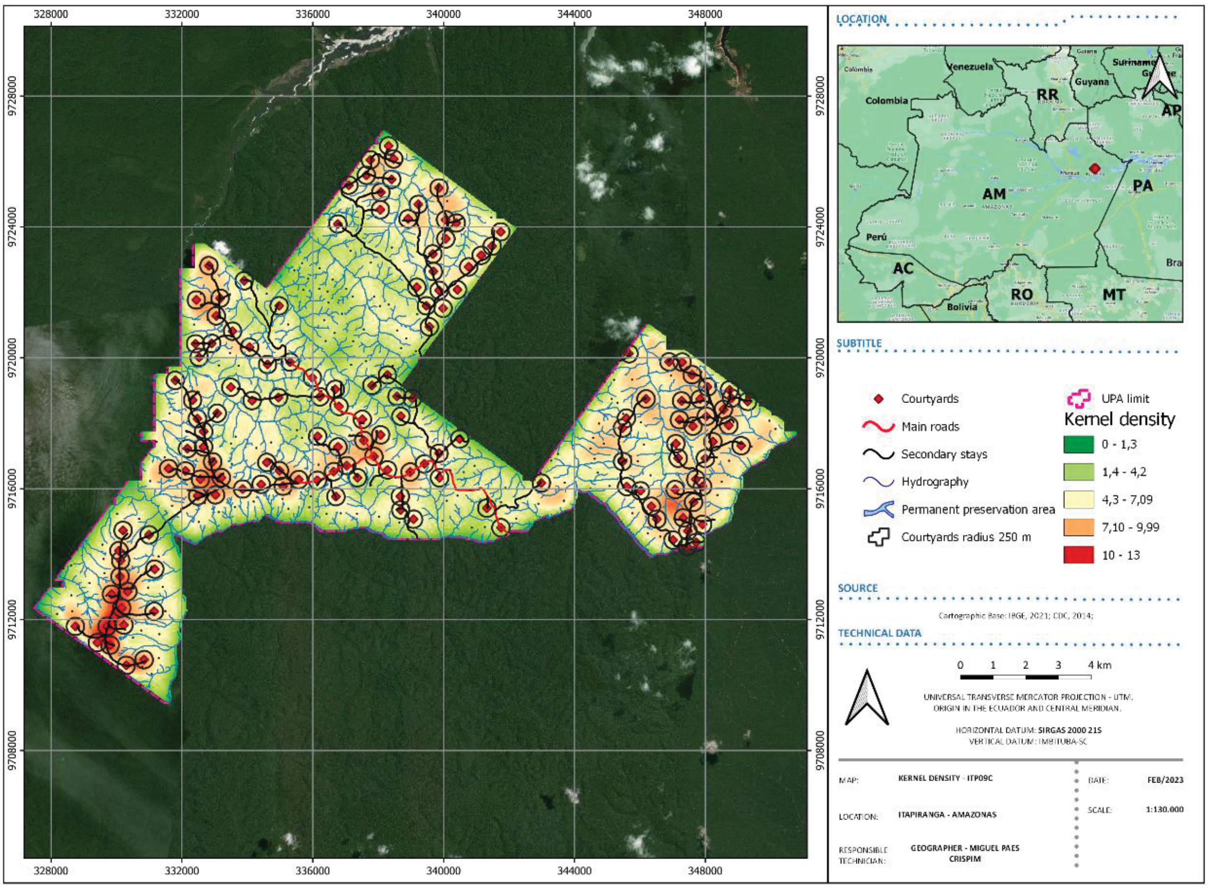
DBH> 50 cm AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 12– IMPROVED SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2015/2016 LOGGING SEASON, HIGHLIGHTING THE DENSITY OF EXPLOITABLE TREES WITH

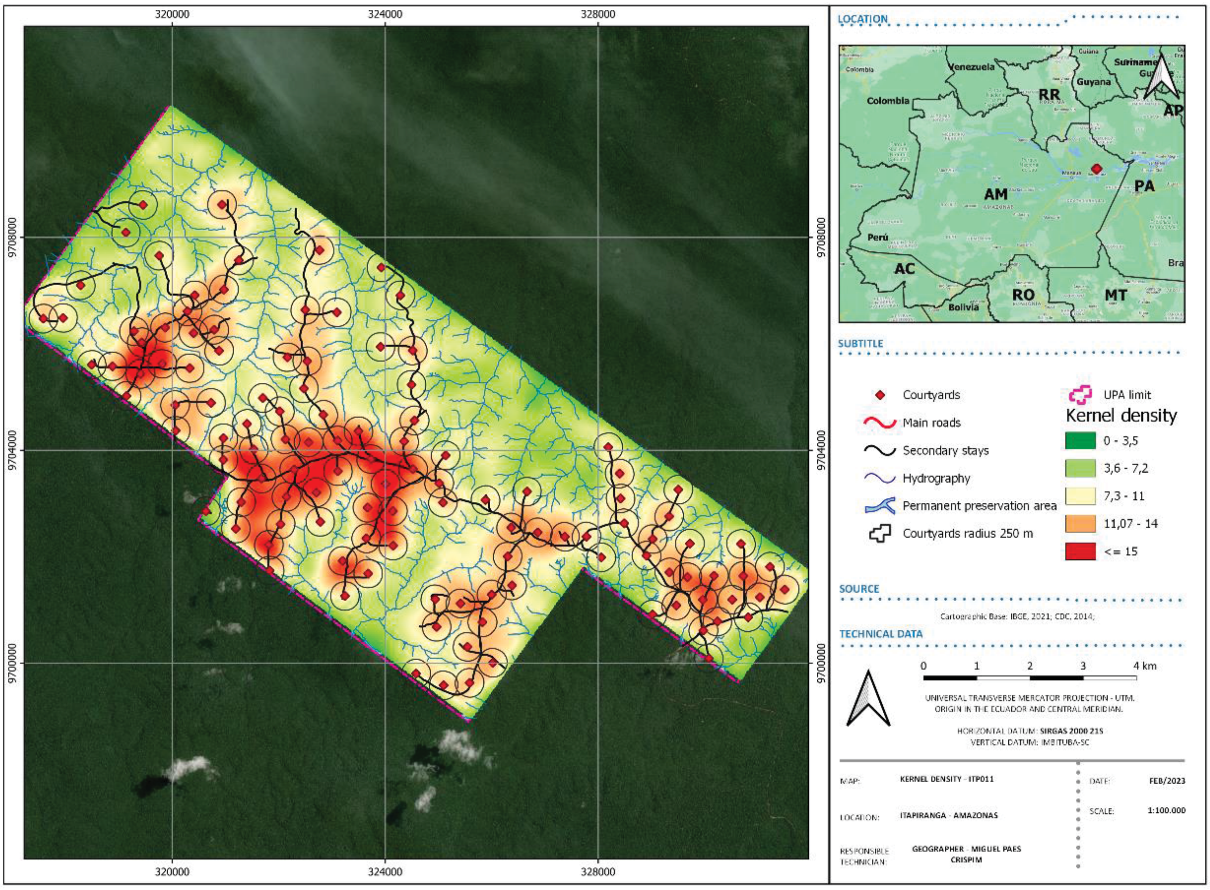
DBH> 50 cm AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 13– IMPROVED SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2016/2017 LOGGING SEASON, HIGHLIGHTING THE DENSITY OF EXPLOITABLE TREES WITH

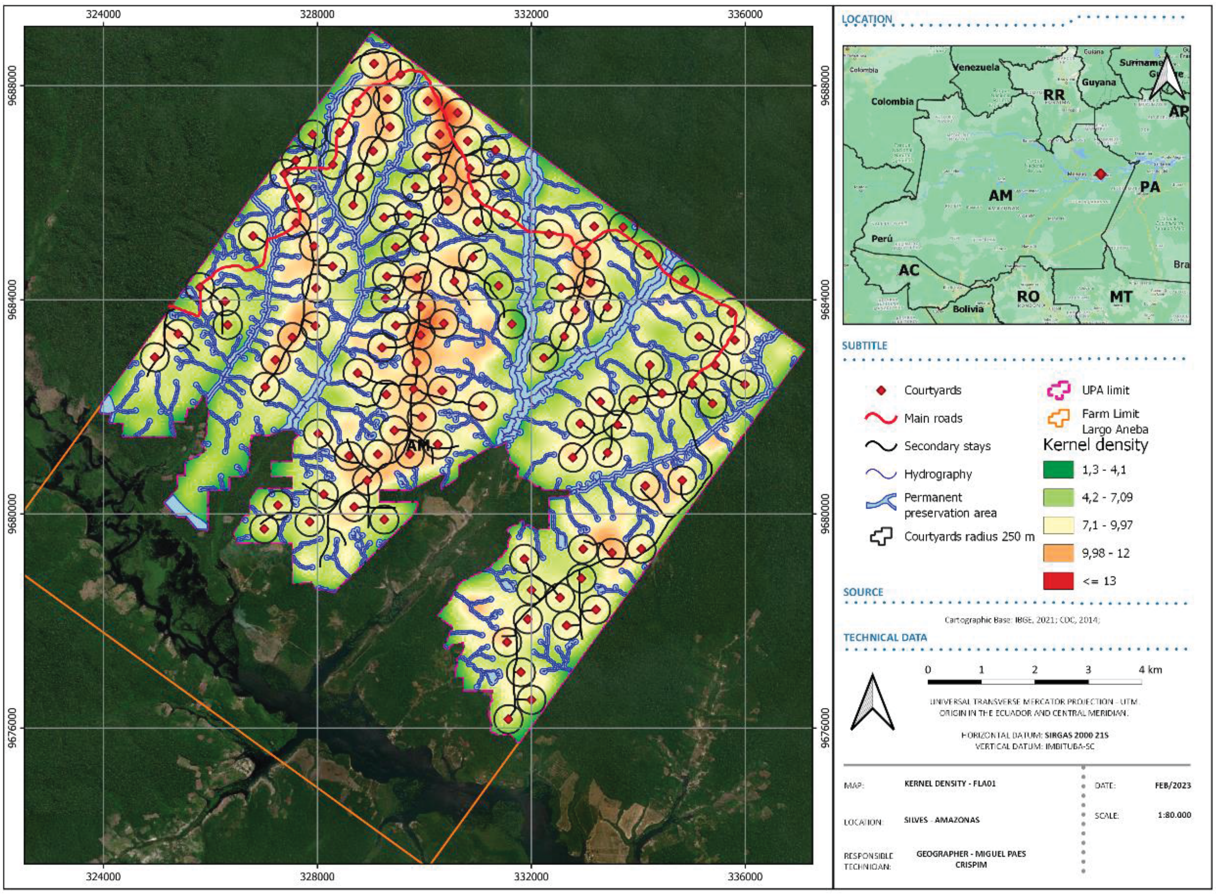
DBH> 50 cm AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 14– IMPROVED SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2017/2018 LOGGING SEASON, HIGHLIGHTING THE DENSITY OF EXPLOITABLE TREES WITH

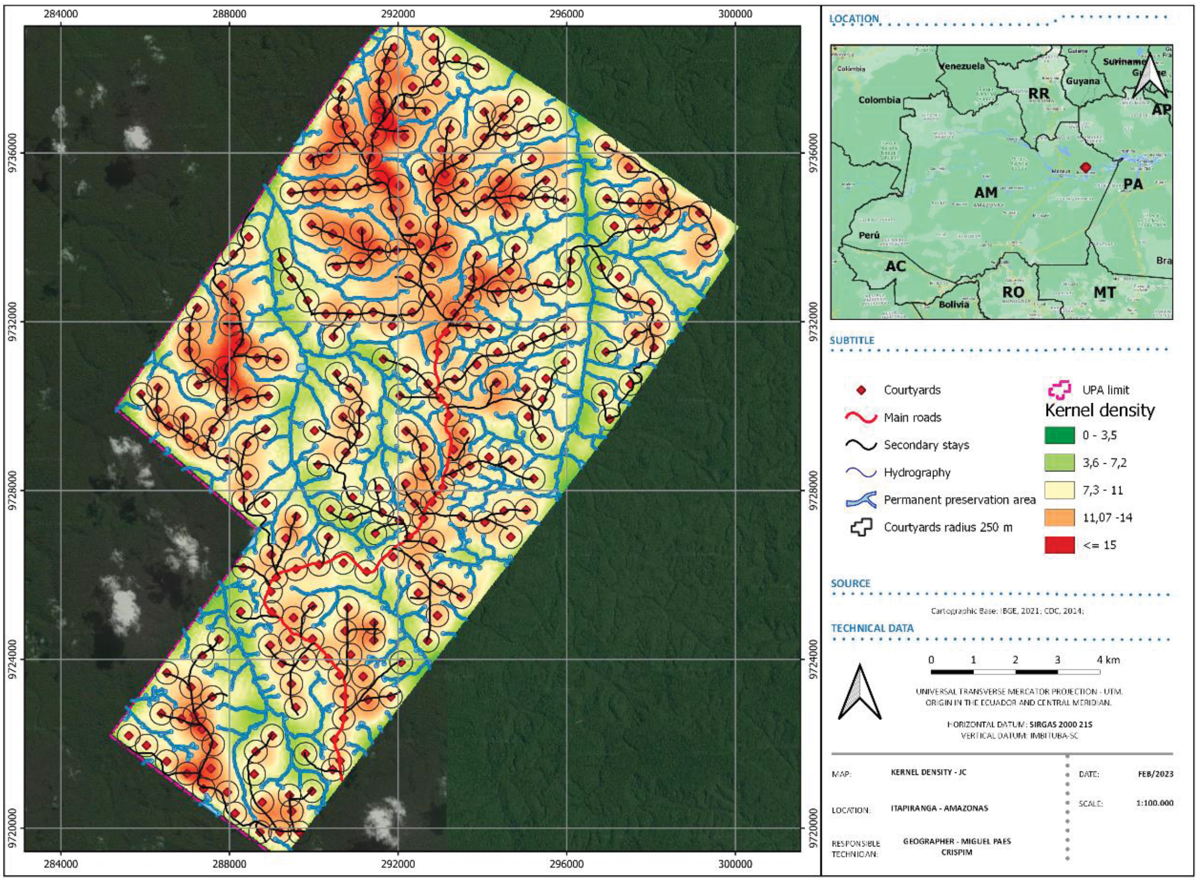
DBH> 50 cm AND HYDROGRAPHY




SOURCE: The Author (2023).

FIGURE 15– IMPROVED SPATIAL PLANNING OF THE INFRASTRUCTURE IN UPA FOR 2018/2019 LOGGING SEASON, HIGHLIGHTING THE DENSITY OF EXPLOITABLE TREES WITH

DBH> 50 cm AND HYDROGRAPHY



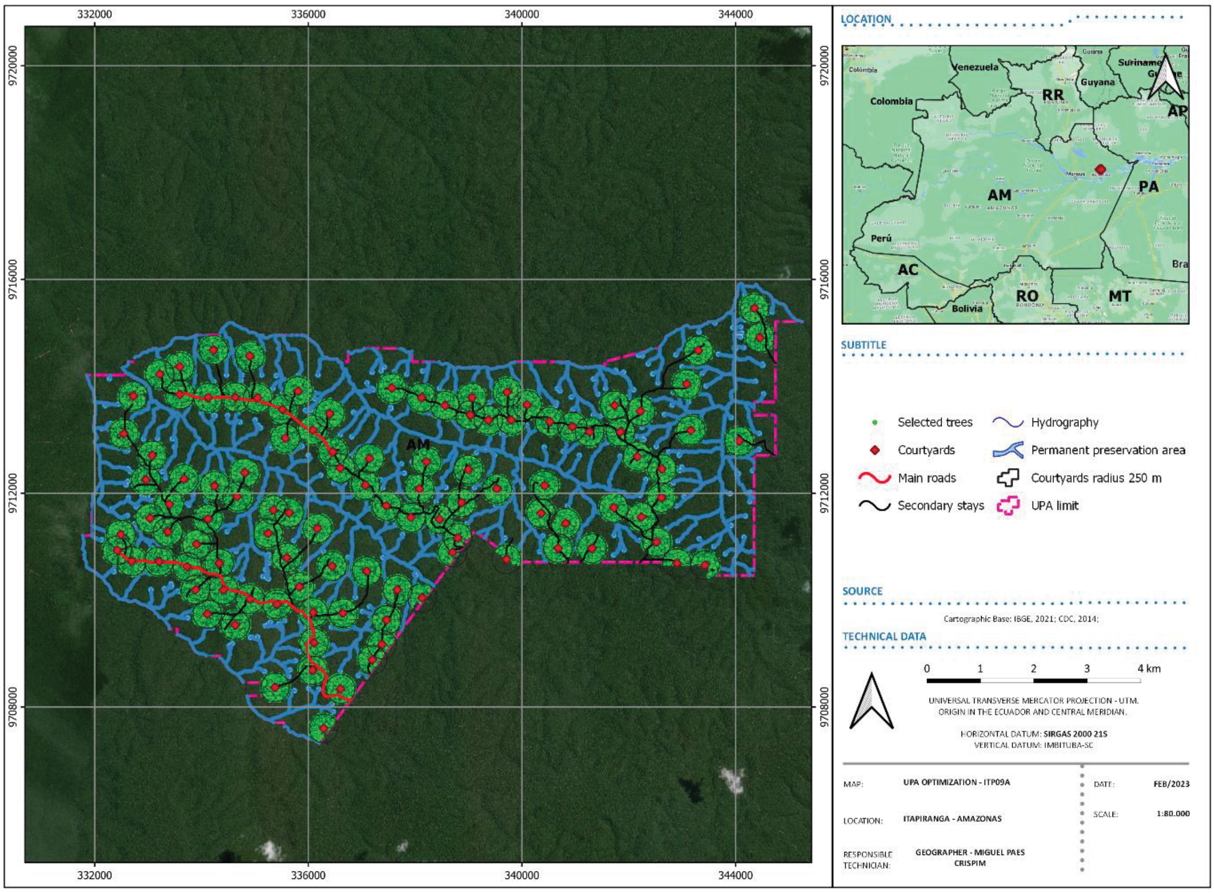

SOURCE: The Author (2023).

In this analysis, with the improved planning of log landings and secondary roads, it was intended to demonstrate the importance of considering the areas with the highest concentration of harvestable commercial trees as a determining factor for the prior planning of the best use of permanent infrastructure (main roads) and the ideal allocation of log landings and secondary roads. In this analysis only trees with DBH above 50cm were considered, as this is the minimum diameter for cutting (DMC) according to Brazilian law.

In the figures below, the improved infrastructure planning of the UPAs are illustrated in a visually clearer way.

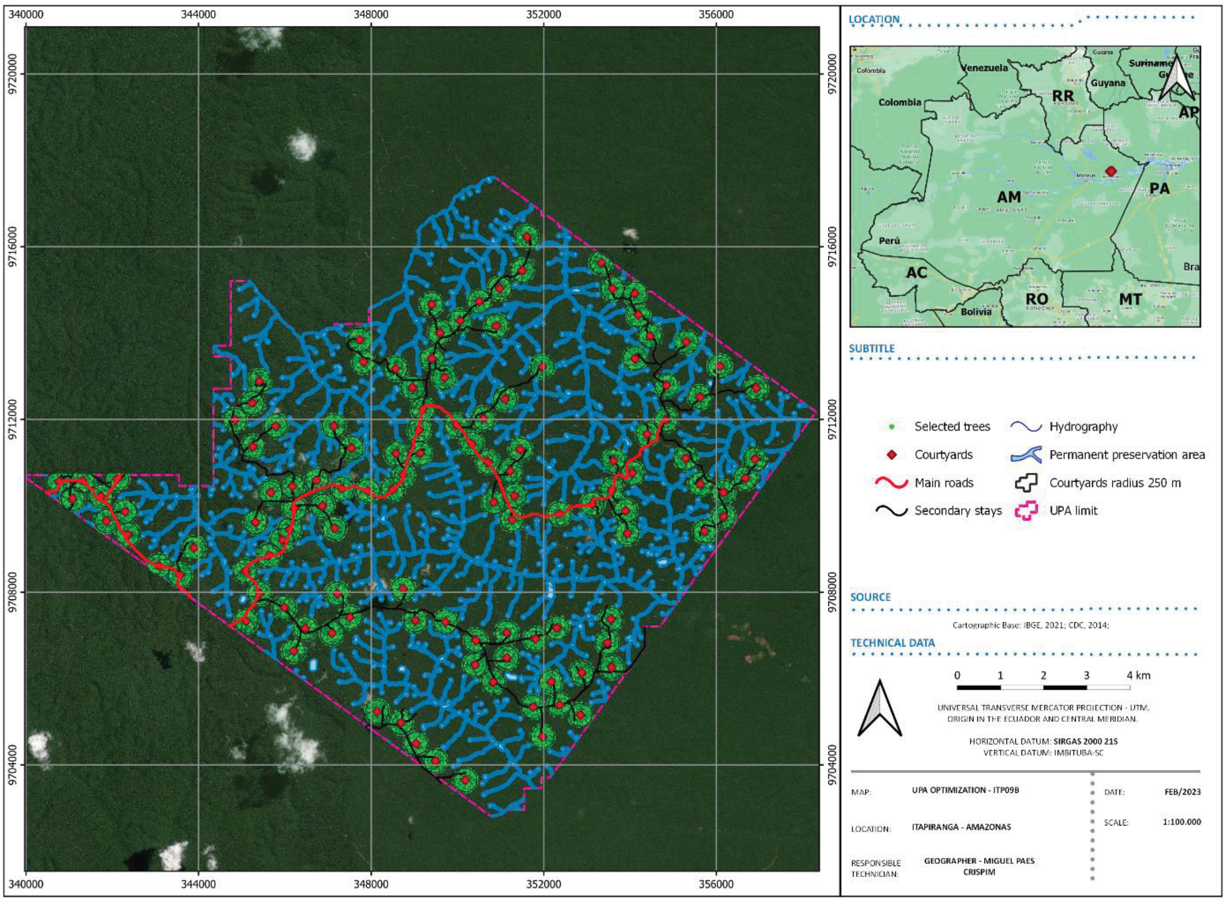
FIGURE 16 – ILLUSTRATION OF IMPROVED INFRASTRUCTURE PLANNING FOR 2013/14 LOGGING SEASON, THROUGH THE REDUCTION AND BETTER REALLOCATION OF LOG

LANDINGS AND SECONDARY ROADS, CONSIDERING THE ESTABLISHED CONSTRAINTS



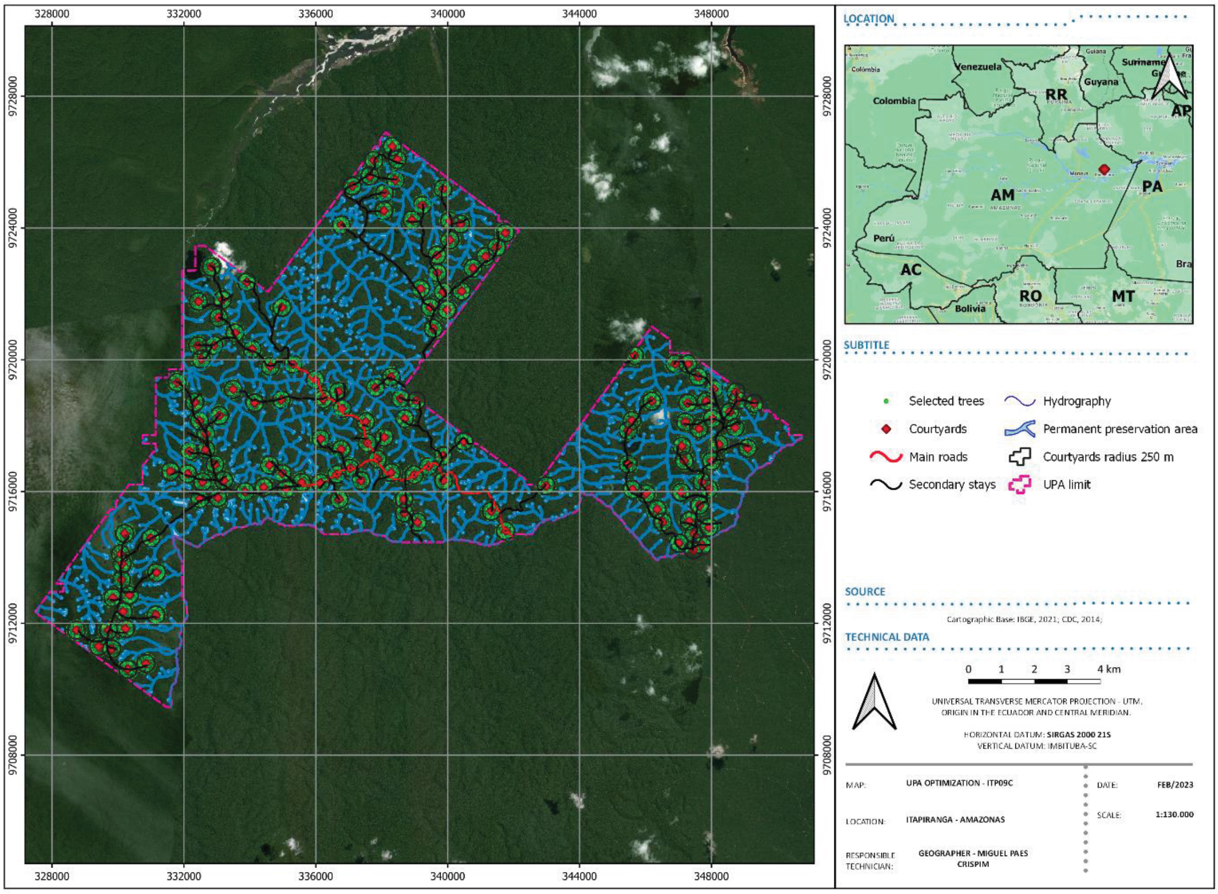

SOURCE: The Author (2023).

FIGURE 17 – ILLUSTRATION OF IMPROVED INFRASTRUCTURE PLANNING FOR 2014/15 LOGGING SEASON, THROUGH THE REDUCTION AND BETTER REALLOCATION OF LOG LANDINGS AND SECONDARY ROADS, CONSIDERING THE ESTABLISHED CONSTRAINTS



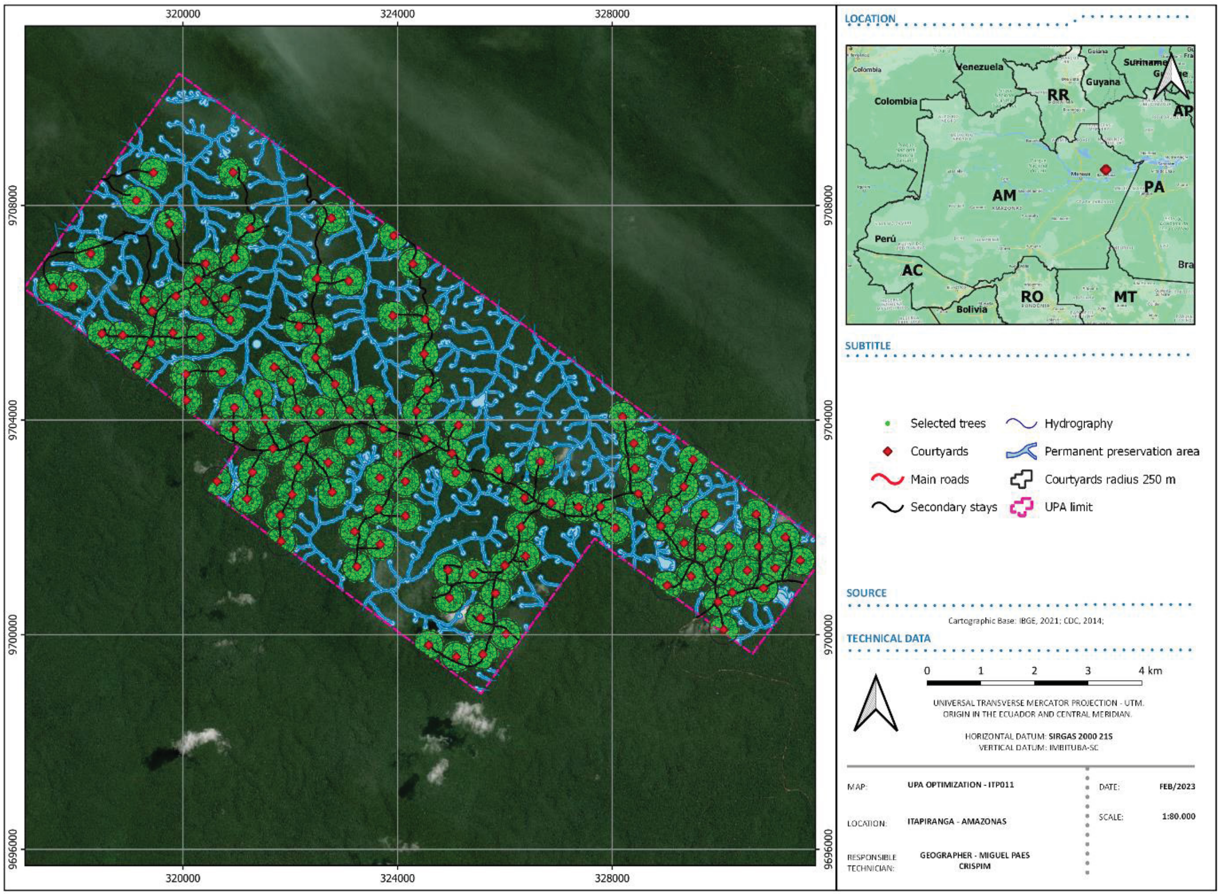

SOURCE: The Author (2023).

FIGURE 18 – ILLUSTRATION OF IMPROVED INFRASTRUCTURE PLANNING FOR 2015/16 LOGGING SEASON, THROUGH THE REDUCTION AND BETTER REALLOCATION OF LOG LANDINGS AND SECONDARY ROADS, CONSIDERING THE ESTABLISHED CONSTRAINTS



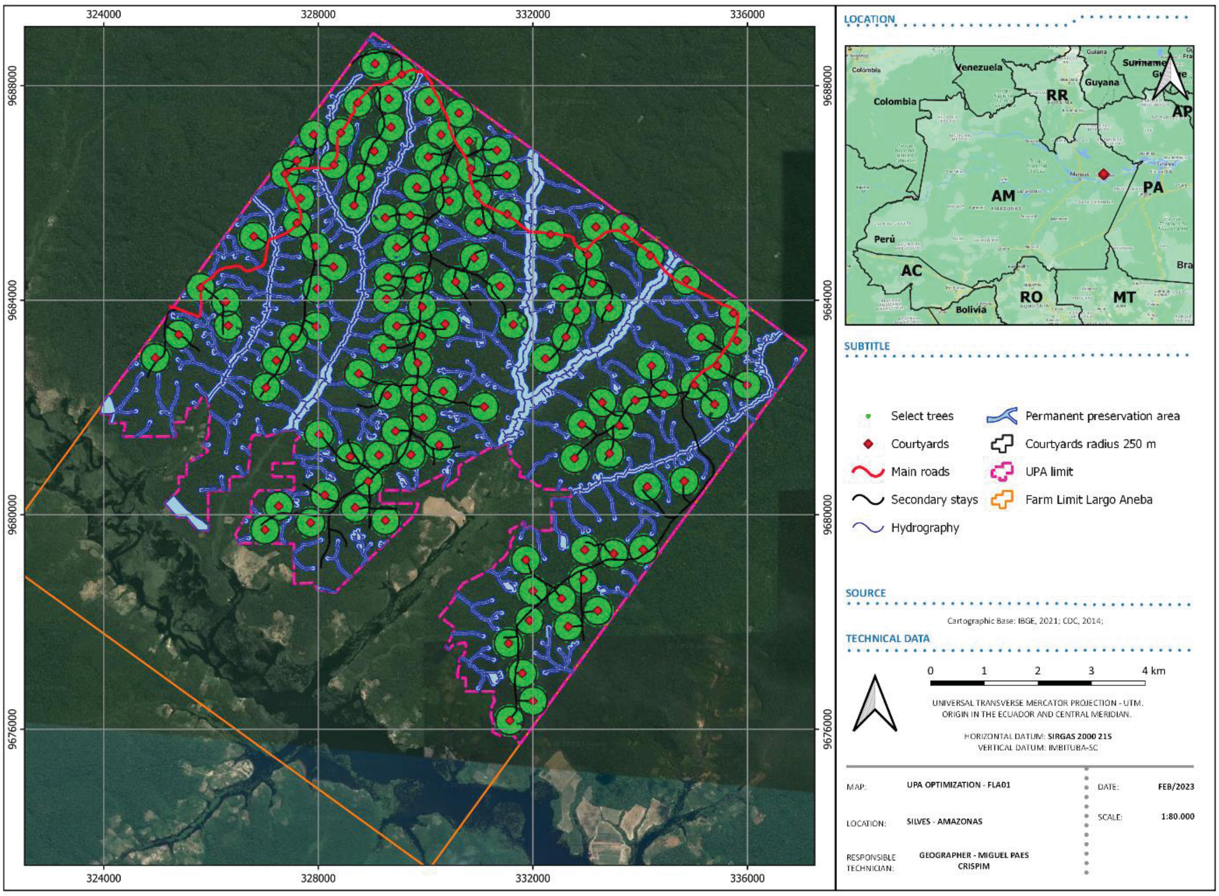

SOURCE: The Author (2023).

FIGURE 19 – ILLUSTRATION OF IMPROVED INFRASTRUCTURE PLANNING FOR 2016/17 LOGGING SEASON, THROUGH THE REDUCTION AND BETTER REALLOCATION OF LOG LANDINGS AND SECONDARY ROADS, CONSIDERING THE ESTABLISHED CONSTRAINTS



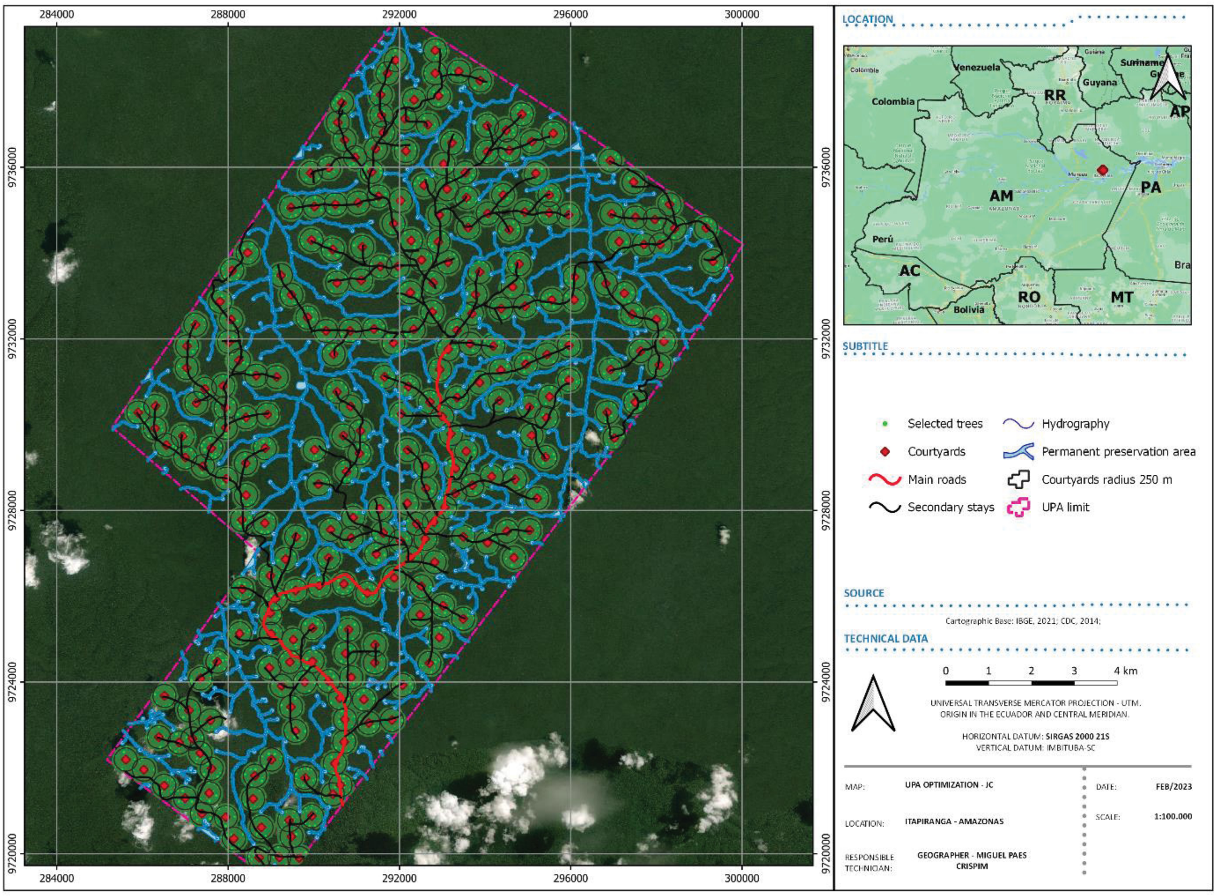

SOURCE: The Author (2023).

FIGURE 20 – ILLUSTRATION OF IMPROVED INFRASTRUCTURE PLANNING FOR 2017/18 LOGGING SEASON, THROUGH THE REDUCTION AND BETTER REALLOCATION OF LOG LANDINGS AND SECONDARY ROADS, CONSIDERING THE ESTABLISHED CONSTRAINTS




SOURCE: The Author (2023).

FIGURE 21 – ILLUSTRATION OF IMPROVED INFRASTRUCTURE PLANNING FOR 2018/19 LOGGING SEASON, THROUGH THE REDUCTION AND BETTER REALLOCATION OF LOG LANDINGS AND SECONDARY ROADS, CONSIDERING THE ESTABLISHED CONSTRAINTS




SOURCE: The Author (2023).

Analyzing the log landings, it was seen that for example the FLA01 area it had 191 log landings, which were not well distributed in the 500m (conventional planning) from each other mentioned (they presented a lot of overlapping area). So it was reduced the number of log landings to 121, and relocated them in the best areas, without overlapping them and avoiding the APPs (permanent protected areas) which took away a lot of available area, and avoiding the valley bottoms.

Thus, 70 log landings from this UPA were removed and some secondary roads were eliminated, while maintaining the production level. On the maps, it shows the distribution of the log landings with radius of 250m, avoiding overlapping radius areas, APP areas and valley bottoms too distant.

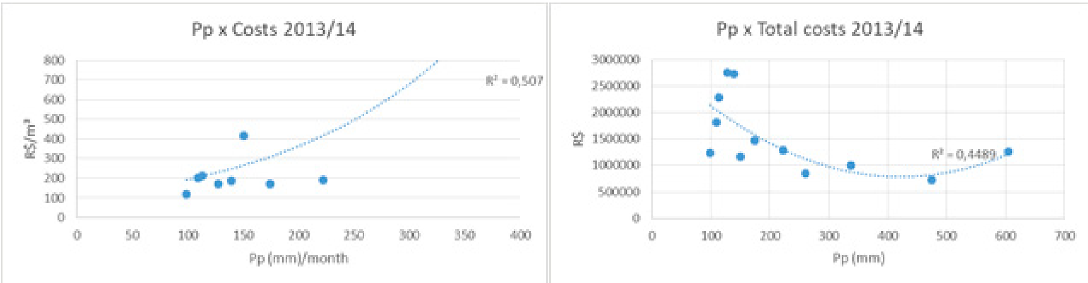
It was averaged the available wood volume per log landing within the radius of 250m, through the column "arv_volume" of the database, that resulted between 800 and 1,200 m³ of wood per radius log landing, then it was concluded that would need a number between 100 and 120 log landings to reach the total volume expected that was around 120,000 $m^3$, the minimum timber production, to reach out the improved planning in FLA01 UPA. Therefore, the amount of log landings varied according to the availability of space within each UPA, and the conformation of the rivers and APPs, so if a place was very closed (rivers very close each other) and could not fit the radius of 250m in full between the rivers, then in these areas log landings were not allocated.

## 4.3 COMPLEMENTARY ANALYSIS

### 4.3.1 Seasonal factors and logging costs

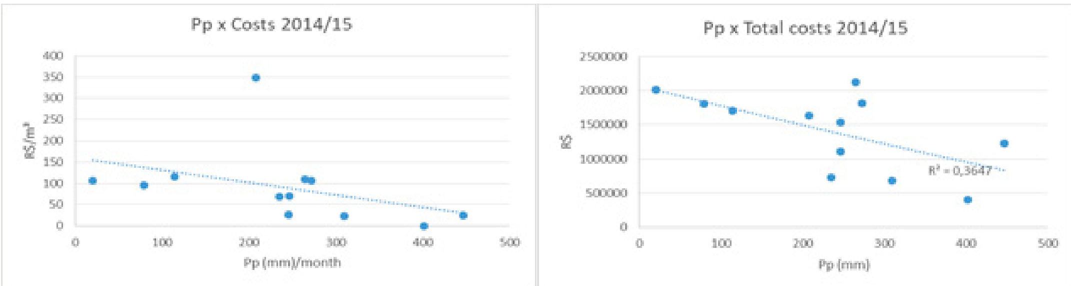
In this complementary analysis, we sought to consider and discuss relevant variables that directly interfere in forest management, but are underestimated in the planning of infrastructure and operations, such as climate factors and soil types.

GRAPHIC 1 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS (TOTAL AND PER M³), THROUGH LOGGING SEASONS (2013/14)



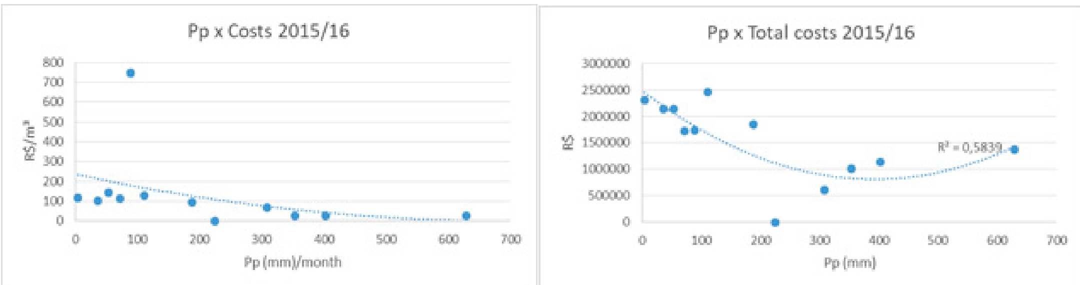

SOURCE: The Author (2023).

GRAPHIC 2 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS (TOTAL AND PER M³), THROUGH LOGGING SEASONS (2014/15)



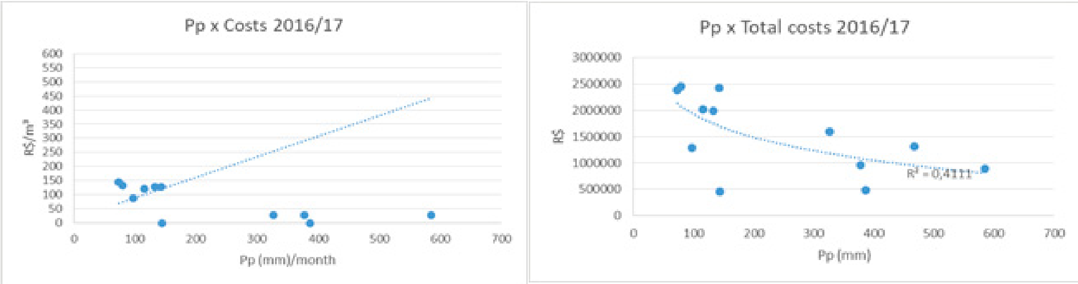

SOURCE: The Author (2023).

GRAPHIC 3 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS (TOTAL AND PER M³), THROUGH LOGGING SEASONS (2015/16)



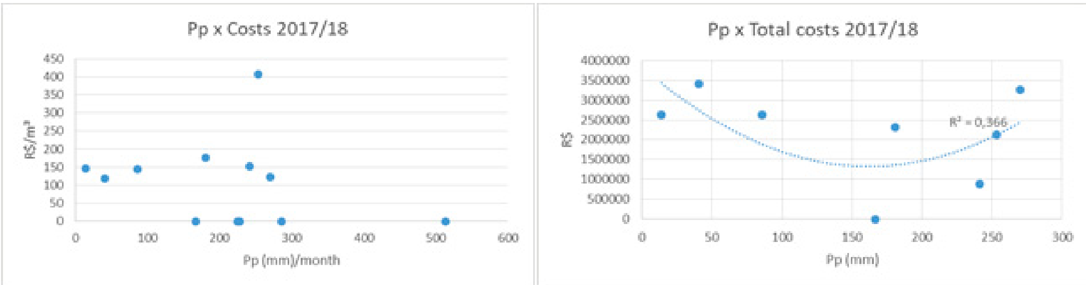

SOURCE: The Author (2023).

GRAPHIC 4 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS (TOTAL AND PER M³), THROUGH LOGGING SEASONS (2016/17)



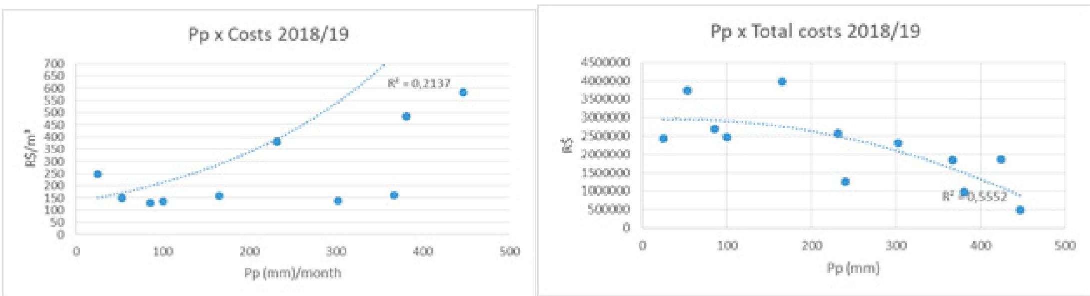

SOURCE: The Author (2023).

GRAPHIC 5 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS (TOTAL AND PER M³), THROUGH LOGGING SEASONS (2017/18)




SOURCE: The Author (2023).

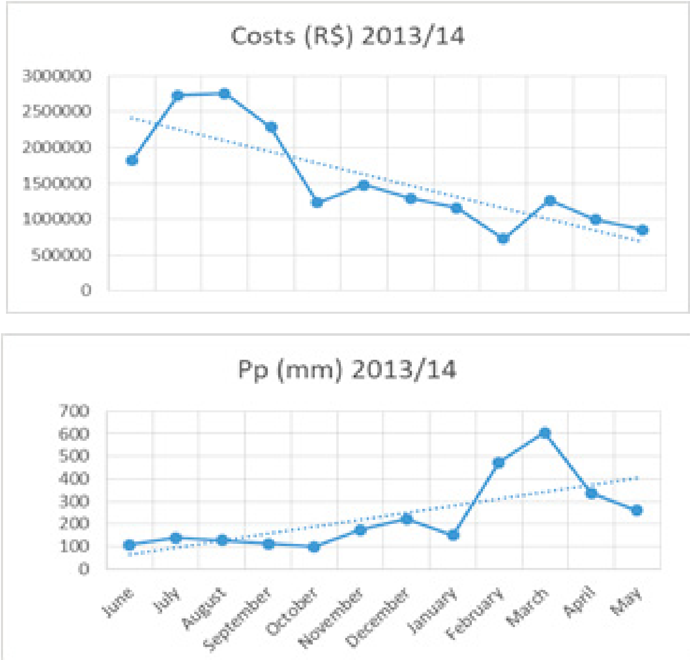
GRAPHIC 6 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS (TOTAL AND PER M³), THROUGH LOGGING SEASONS (2018/19)




SOURCE: The Author (2023).

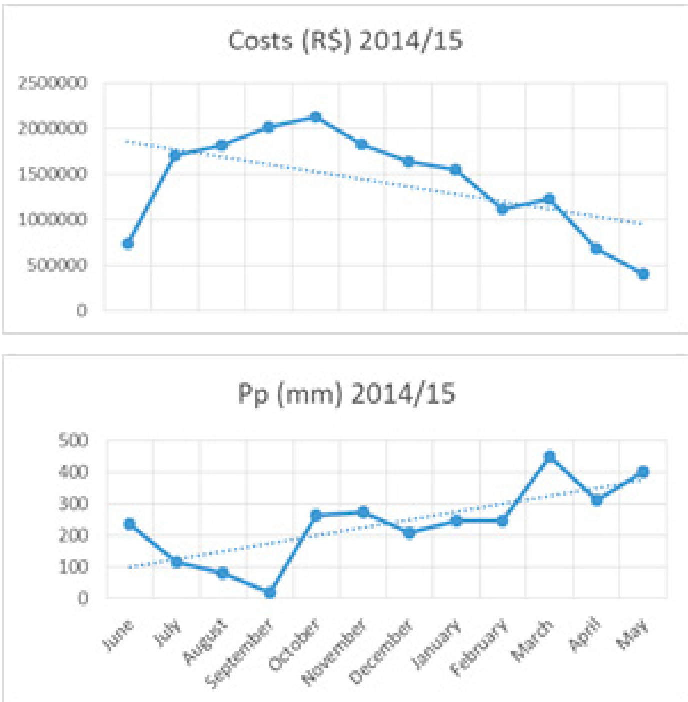
In the graphics below, the correlations between precipitation and operational costs on a monthly basis are presented, in order to analyze the seasonal sensitivity of forest management.

GRAPHIC 7 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS PER MONTH, THROUGH LOGGING SEASONS (2013/14)



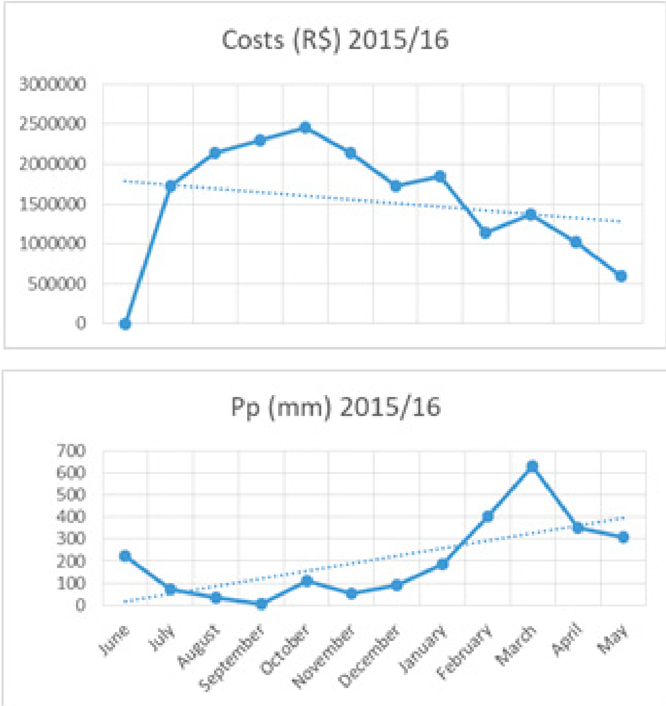

SOURCE: The Author (2023).

GRAPHIC 8 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS PER MONTH, THROUGH LOGGING SEASONS (2014/15)



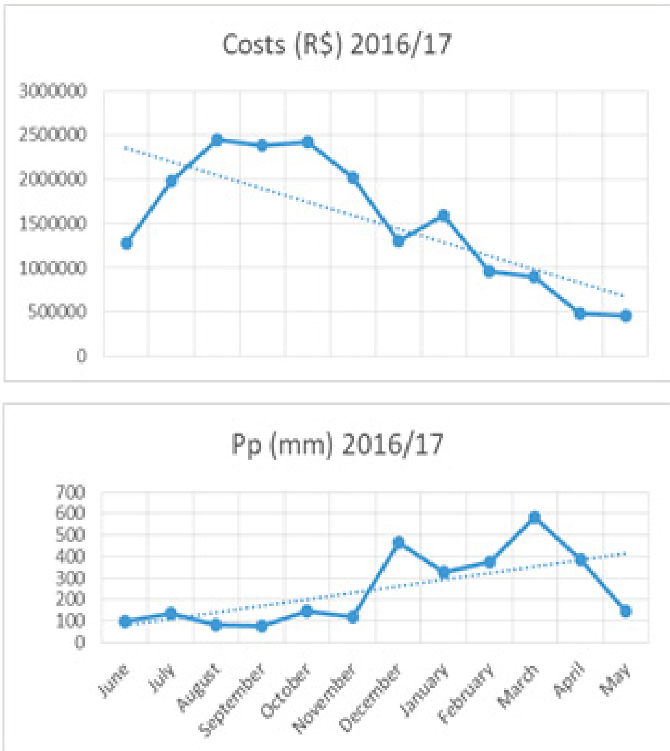

SOURCE: The Author (2023).

GRAPHIC 9 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS PER MONTH, THROUGH LOGGING SEASONS (2015/16)



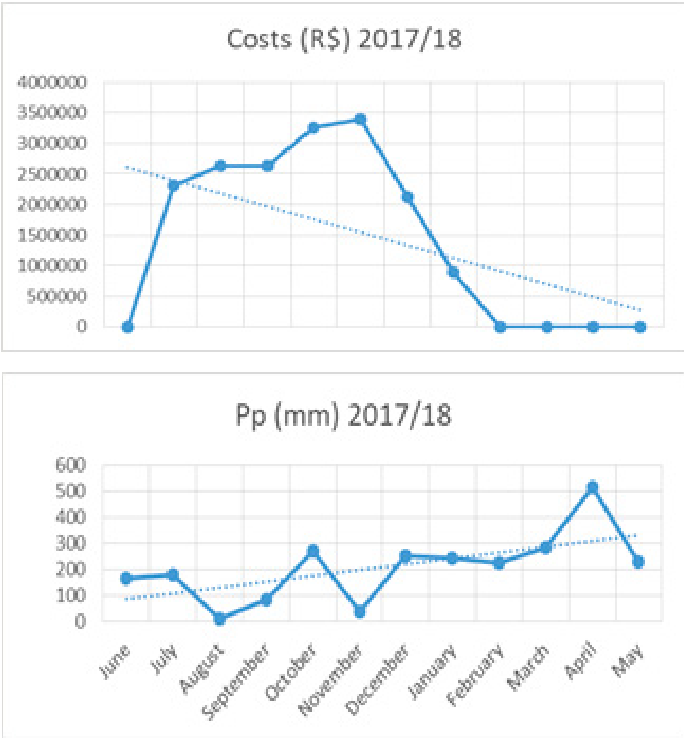

SOURCE: The Author (2023).

GRAPHIC 10 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS PER MONTH, THROUGH LOGGING SEASONS (2016/17)



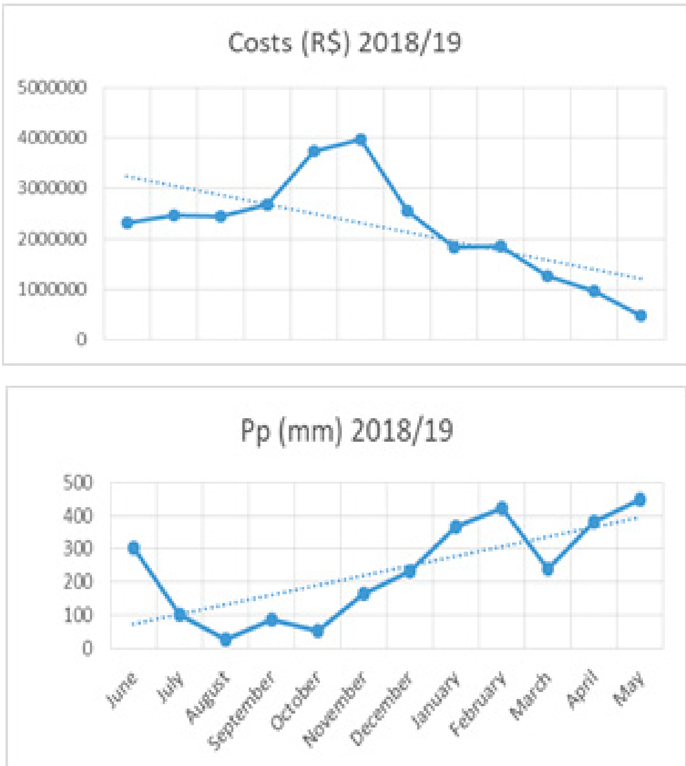

SOURCE: The Author (2023).

GRAPHIC 11 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS PER MONTH, THROUGH LOGGING SEASONS (2017/18)




SOURCE: The Author (2023).

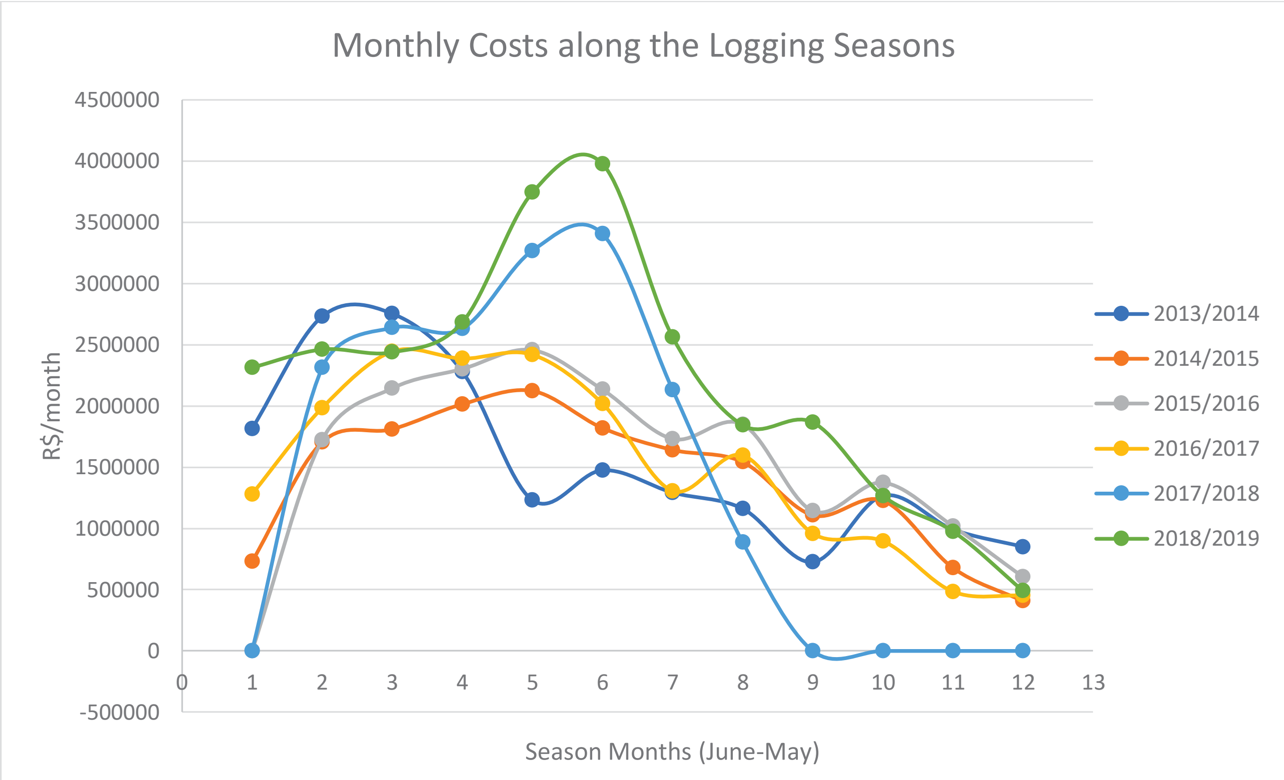
GRAPHIC 12 – CORRELATION BETWEEN PRECIPITATION (PP) AND LOGGING COSTS PER MONTH, THROUGH LOGGING SEASONS (2018/19)




SOURCE: The Author (2023).

In this section, seasonal costs were analyzed throughout the operating seasons, in order to verify possible patterns of months with higher operating costs.

GRAPHIC 13 – TOTAL COSTS OF OPERATIONS OVER THE MONTHS OF THE SEASONS




SOURCE: The Author (2023).

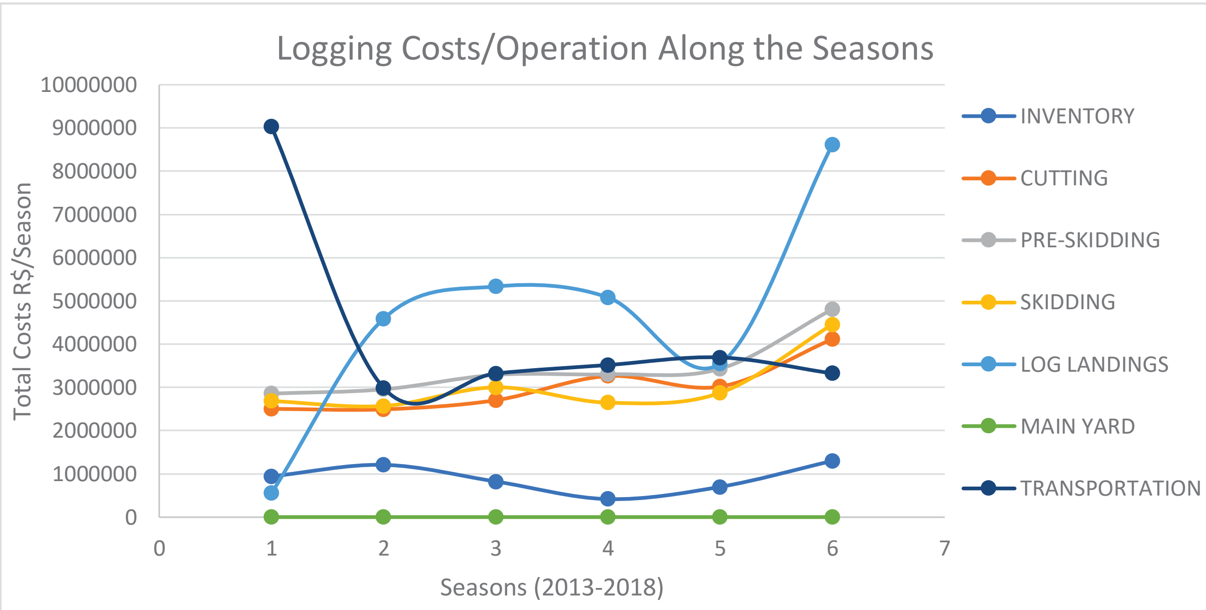
From the graphic, one can see that for all seasons the fluctuation of costs follow the same variation pattern, concentrating the highest expenses between months 2 and 6 of the season (July to November). This is the time when all operations are active. The cutting, which is one of the most crucial stages, ends in November, in order to avoid the beginning of the rains in the region.

### 4.3.2 Operational and roads costs

Additionally, an analysis of costs over the years was carried out in order to verify possible correlations of infrastructure and operating costs with the physical environment of the exploited UPAs, as well as with edaphic-climatic factors in each area.

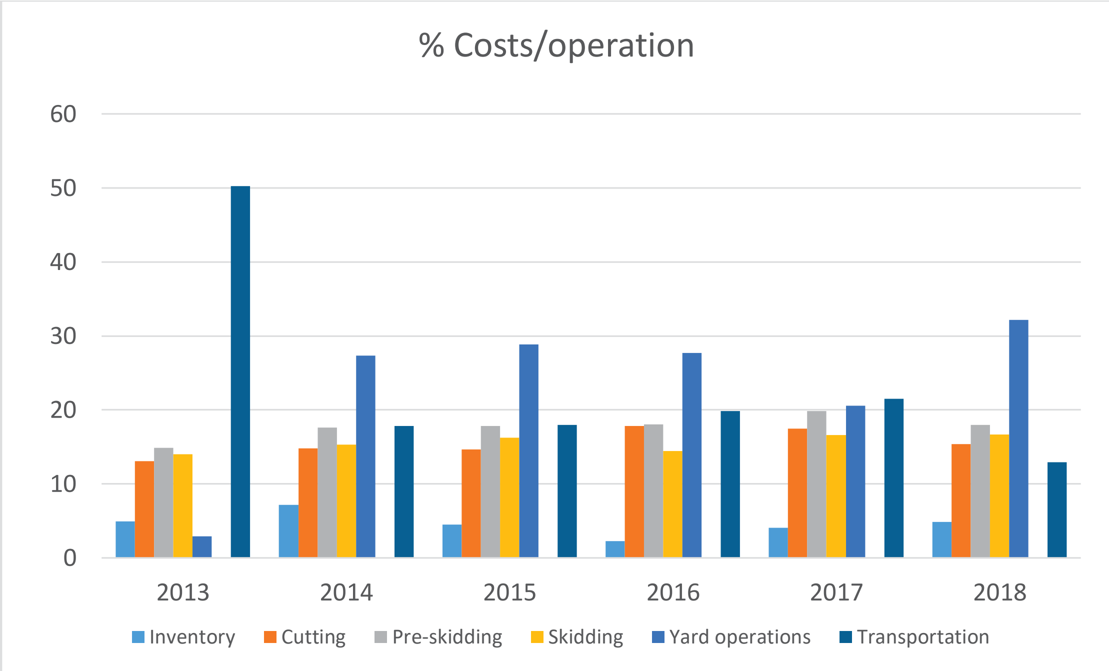
In this section, we sought to analyze the total costs per operation, throughout the seasons, in order to verify the most costly operations for logging.

GRAPHIC 14 –LOGGING COSTS PER OPERATION OVER THE SEASONS




SOURCE: The Author (2023).

GRAPHIC 15 – RELATIVE COSTS PER OPERATION (%) THROUGH LOGGING SEASONS (2013-2018)




SOURCE: The Author (2023).

Based on the graphs presented, it was found that the yard operations (construction and maintenance of log landings) constitutes around 27% of total costs, transport (18%) and pre-skidding operations (18%); were the most costly for the company, respectively.

The table below presents the maintenance/construction costs for the main (A) and secondary (B) roads in the UPAs, in descending order of costs.

TABLE 4 – TOTAL COSTS OF CONSTRUCTION AND MAINTENANCE OF LOGGING ROADS BY SEASON, IN TOTAL COSTS DESCENDING ORDER.

| **Logging season** | **Type A - permanent roads (R$)** | **Type B - secondary roads (R$)** | **Total costs (R$) - descending order** |
|---|---|---|---|
| 2013/2014 | 2,411,383.61 | 741,244.61 | **3,152,628.22** |
| 2017/2018 | 1,323,021.13 | 1,086,792.70 | **2,409,813.83** |
| 2018/2019 | 813,225.00 | 1,387,768.10 | **2,200,993.10** |
| 2014/2015 | 821,209.42 | 651,416.79 | **1,472,626.21** |
| 2015/2016 | 516,038.27 | 695,194.36 | **1,211,232.63** |
| 2016/2017 | 261,800.00 | 526,456.81 | **788,256.81** |

SOURCE: The Author (2023).

According to the results presented in the graphics, during the dry season, operational costs were higher, because it consisted of the periods that most operations took place, thus requiring greater investment in infrastructure and machinery. In the rainy season, there are greater operational constraints, often making operations unfeasible, in addition to generating workers' accidents risks, justifying the lower expenses during this period. The most costly operations for the company (R$/m³) were yard operations (27% of the total), transportation (18%) and pre-skidding (18%), respectively.

During the complete logging season (June to May) and forest operations in UPAs (June to January), for all the years analyzed there was a slight tendency of decreasing operational costs (R$/month) related to increased precipitation (Pp), that is, this correlation was weak and inversely proportional. Therefore, we can conclude that precipitation was essential to decision making in operational planning and scheduling, thus concentrating the most operational and infrastructure expenditures during the dry season, cited by Sessions (2007) and Keller et al. (2015), as key factors for road planning in the region. However, it is evident that Pp was not the main factor to constitute total costs. Probably, other factors such as mechanical availability and operational efficiency of the machines were more relevant for the constitution of these costs, as well as the costs of log book and log storage in the main yard, as well the transport by means of contractors. As for roads costs, it was remarkable from the graphics presented, that precipitation was not determinant for the constitution of investments in roads for different forest management projects (UPAs).

That is, other factors probably related to previous infrastructure (presence/absence), ease of access to the UPA (relief/soils/watersheds) and the distance between the UPA and the main flow routes (forest roads/paved roads). Those were variables much more relevant to constitute the total costs of roads construction/maintenance in the UPAs, corroborating with Sessions (2007) and Keller et al. (2015) studies.

# 5 DISCUSSION

From the preliminary analysis, could be possible to perceive by the conventional planning, that the relief and hydrography were determinant factors for the allocation of roads and log landings within the UPA. In addition, it was possible to perceive that the log landings were systematically allocated along the forest roads, not considering the different patterns of concentration of commercial trees inside the UPAs, also pointed out by Braz (2010).

The preliminary analysis intent to gather important information taken directly from the forest inventory, such as the spatialization of timber volume within the area, in order to better plan the allocation of secondary roads, as well as the number of log landings. In this case, with the spatialization of the commercial trees, new decisions can be made in the planning of logging operations, besides guaranteeing greater efficiency of the process. In addition, other factors arising from the inventory are very relevant for reaching better solutions for planning operations, such as the spatialization of commercial species (in order of economic value) and tree shape quality, corroborating with Braz et al. (2016) and Aguiar et al. (2021) conclusions. The use of information collected in the forest census carried out in the UPAs, generates important subsidies for the strategic planning of forest management operations, also emphasized by Aguiar et al. (2021). However, this important information is often little considered.

According to the improved planning, there was a remarkable reduction in the need for infrastructure for all areas (log landings and secondary roads), maintaining the same production capacity. Thus, the operational costs of maintaining the areas and environmental impacts were consequently reduced, by not remove a noticeable area of vegetation for conversion into infrastructure. The reduction was remarkable for both cases, which is logical, because the relocation and reduction in the number of overlapping log landings consequently reduced the demand for secondary roads connecting to them. In this study, it was not optimized trails, because they are simply a consequence of a good rational planning of main roads, log landings and consequently secondary roads corroborating with Emmert (2014). The author stated manual vectorization of the trails in the GIS software becomes a spending time and inaccurate costly work. These results corroborate with Acosta et al. (2023), in

Peruvian Amazon, that have used similar tools for rational planning infrastructure (Digital Elevation Model and Least Cost Path analysis). The authors observed that the forest road planning using GIS provided better definition (economically and environmentally) of road networks in our forest site than those traditionally defined using conventional mapping techniques; the same results achieved in this research. Also corroborated by Silva et al. (2018a), that optimized the infrastructure planning, reducing the number of forest roads (–6.33%) and trails to extract logs (–15.49%) and costs of infrastructure investment, when compared to traditional planning.

In this study, the reduction of infrastructure demanded in log landings varied between -24.6% and -65.6%, with an average of -40.6%, which is noticeable, considering the agile planning improvement process applied to forest management, results also found in minor reduction by Silva et al. (2018a), using mathematical programming techniques. Emmert (2014) did a research in the same region and optimized the infrastructure in around 15%. On this case, the author have used heuristics model and costs surface to minimize the environmental impacts. These results were smaller than the present study, probably because Emmert (2014) did not use heavy operational constraints as presented on this research (250m maximum skidding distance) and no overlaps between buffers, heavy constraints that determined the better spatial planning in the present study, consequently with more effective results. Silva et al. (2018b) concluded that the mathematical models were able to support forest management planning by estimating a reduction in vegetation damage and guaranteeing timber yield regulation, corroborating with the present study.

The reduction in infrastructure demanded in secondary roads varied between -17.8% and -39.9%, showing an average of -24.2% fewer roads (in meters), which is remarkable when considering the area demanded for road construction (road width and bordering vegetation removal), with great environmental and physical impacts on tropical forests. Acosta et al. (2023) have found a reduction in road construction costs by category (primary, secondary, tertiary) by -23.14%, -19.79% and -12.50%, respectively, for timber extraction compared to conventional planning. According to Silva et al. (2020), using mathematical models to minimize the distances for infrastructure planning, the results demonstrated a higher productivity, a reduction of skidding distance (by an average of 17.16%), and reduced cost of log skidding (by 25.76%), strengthening the assumption of noticeable costs reductions from infrastructure's reduction. Also corroborated by Sales et al. (2019) that concluded reductions in costs and, possibly, environmental impacts of the logging.

The average extraction distance (AED) in the improved planning is 125m, due to the value being half of the (MED) maximum extraction distance (250m). Silva et al. (2018a) concluded that the optimal distance between roads (ROD) was 516 m. In this case MED was defined as half of the ROD, so in this case it was equal to 258 m. However, due to obstacles encountered in the field when extracting trees, as well as location errors, which are common in the practice of harvesting, MED was relaxed from 258m to 342.20m. Therefore, from practical experience obtained in the process of harvesting over time, for a MED of about 350m the volume contained in a circle with that radius is approximately 700m³. Thus, it was assumed that the maximum volume contained in a log landing would be approximately this value, i.e., the yard will be loaded twice (2x) in a time period (SILVA et al. 2018a). These results found corroborate with the MED in this research as well the loading capacity of each log landing. The difference is in the number of loads, 3 times in the case of this study. Finally, according to references and corroborated by Silva et al. (2018a) extracting trees further than around 342m can be economically unviable in addition to damaging soil and flora.

According to the calculations presented in Braz and d'Oliveira (1997), with this AED, the optimal roads density (ORD) becomes 20m/ha. According to the authors, there is a minimum cost optimum point between 100m and 1000m average skidding distance, from the sum of AED + ORD values. In conventional planning, with the exception of the 2016/2017 UPA (24.32 m/ha), they presented lower values of road densities compared to the optimized planning (20m/ha), which generated a considerable increase in the average skidding distance. The secondary roads density in conventional planning was too low, generating an imbalance in the AED x ORD ratio, according to the classification of this relationship presents in costs the minimum optimal equilibrium point (BRAZ, 1997).

According to the complementary analysis, during the dry season, operational costs were higher, because it consisted of the periods that most operations took place, thus requiring greater investment in infrastructure and machinery. In the rainy season, there are greater operational constraints, often making operations unfeasible, in addition to generating workers' accidents risks, justifying the lower expenses during this period, corroborating with Fernandes et al. (2013) and Braz et al. (2016) that considered the seasonality in Amazon a determinant factor for scheduling the forest management and reinforce that is underestimated by managers. The most costly operations for the company (R$/m³) were yard operations (27% of the total), transportation (18%) and pre-skidding (18%), respectively. With optimized planning, here is a tendency to increase pre-skidding costs, due to the likely increase of skidding trails distances, as well as the cost reduction of yard operations, due to the planned reduction, generating less yards construction and maintenance costs.

During the complete logging season (June to May) and forest operations in UPAs (June to January), for all the years analyzed there was a slight tendency of decreasing operational costs (R$/month) related to increased precipitation (Pp), that is, this correlation was weak and inversely proportional. From the cost analysis for all seasons analyzed (2013-2018), there was a pattern of higher expenditures between the months of July and November, the period when all forest operations are active. This also coincides with the end of the cutting operation schedule, the most critical operation (bottleneck), for demanding a large contingent of workers and resources, besides being the most dangerous activity in the production process.

Therefore, we can conclude that precipitation was essential to decision making in operational planning and scheduling, thus concentrating the most operational and infrastructure expenditures during the dry season, cited by Sessions (2007) and Keller et al. (2015), as key factors for road planning in the region. However, it is evident that Pp was not the main factor to constitute total costs. Probably, other factors such as mechanical availability and operational efficiency of the machines were more relevant for the constitution of these costs, as well as the costs of logbook, log storage in the main yard and the transport by means of contractors, corroborating the conclusions found by Emmert (2014) that did a research in the same company.

As for roads costs, it was remarkable from the graphics presented, that precipitation was not determinant for the constitution of investments in roads for different forest management projects (UPAs). That is, other factors probably related to previous infrastructure (presence/absence), ease of access to the UPA (relief/soils/watersheds) and the distance between the UPA and the main flow routes (forest roads/paved roads). Those were variables much more relevant to constitute the total costs of roads construction/maintenance in the UPAs, corroborating with Sessions (2007) and Keller et al. (2015) studies.

# 6 CONCLUSION

Based on the results found, it can be concluded that the study brought sensible contributions to the planning of logging in the Amazon, by minimizing the necessary infrastructure, while maintaining the same productive capacity. This work brings subsidies for the improvement of processes in this activity in the Amazon, as well as stimulates the replication of methods and contributes to new management enterprises in the region. Therefore, it highlights the importance of deepening the technical knowledge of the use of geospatial processing tools, with the tendency of increasing demand for professionals with this specialty, being strategic in forest management companies.

- The total infrastructure of yards and secondary roads has been minimized to a significant extent, maintaining production capacity and making maximum use of the planned improved structure. This tends to generate appreciable cost savings in the construction and maintenance of yards and roads, which are the largest cost drivers of logging operations (27% of operating costs). However, with the probable increase of skid trails and tertiary roads due to the MED restriction (250m), the pre-skidding operation tends to present cost increases. In general, optimizing the use of infrastructure brings benefits to the improvement of processes in the sector, in order to increase the competitiveness of the forestry business in relation to other enterprises in the decision making process of entrepreneurs.
- The rigid restriction of the log landings skidding radius proved to be fundamental to guarantee the optimization of the infrastructure use, as well as the best organization and control of the activity in the field, besides minimizing the environmental damage of permanent structures. Different skidding radius can be tested in the field for each case, in order to perform a sensitivity analysis and ensure the optimization of logging for each specific situation (machinery, relief and forest), so as guarantee the optimization of the process.
- The process created and tested on a large mass of data and for several different UPAs, proved to be robust and efficient, which is essential to enable the replication of the process in other forests,

operations, and forest enterprises in the Amazon. This process can be used for any forest harvesting plan, changing, for each case, the values of the predictor variables (minimum production level, storage capacity of log landings, maximum skidding distance, among other variables).

It is important to emphasize that none of the studies conducted in the Brazilian Amazon to improve infrastructure planning of forest management, have used such large areas, so many UPAs and such a large inventory database, making this study unprecedented.

## 6.1 RECOMMENDATIONS

It is recommended to use, replicate, and disseminate these rational methods presented here for different logging contexts in the Amazon, testing if possible different values of variables, especially those related to the maximum skidding radius, which are more sensitive to the local effect of the operation, that is, they vary specifically within the context of that activity.

# APPENDIX

REPRODUCING THE ANALYSIS ROUTINE IN QGIS SOFTWARE (PORTUGUESE LANGUAGE)

1. Organização da base cartográfica (download, geração ou descompactação dos arquivos recebidos).
2. Homogeneização do sistema de referência cartográfica – SRC. Ou seja, transformar todos os arquivos para o mesmo sistema de coordenada "Datum", assim como o SRC do projeto, também deve ser o mesmo.

Para este projeto utilizamos o software Qgis e os seguintes dados:

**Arquivos shape file**

- Pontos das arvores
- Hidrografia
- Áreas de APP
- Limite da fazenda
- Pátios
- Estradas principais
- Estradas secundárias
- Trilhas

**Arquivos raster (imagem)**

- Modelo Digital de Elevação (MDT) – imagem SRTM, resolução espacial 30m.

**Passo a passo**

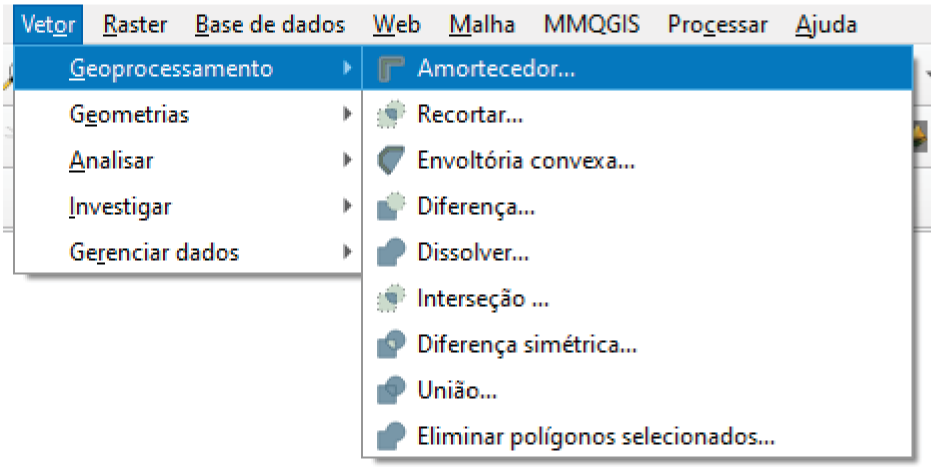
Análise do volume de pátios, tendo em vista um raio de 250m a partir do ponto central e o volume de madeira disponível naquela área.

**1.** Abrir o Software Qgis

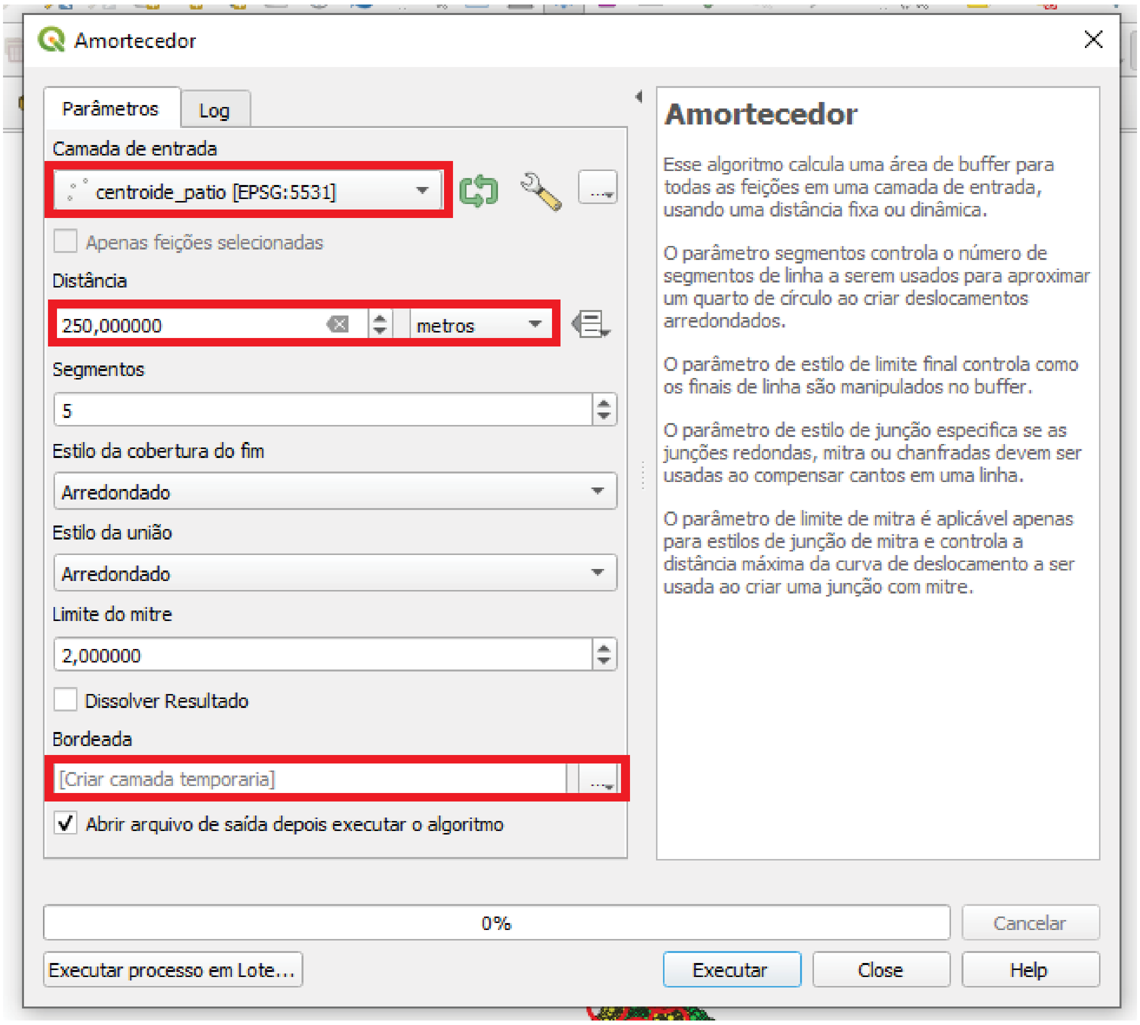
**2.** Abrir os dados

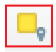
**3.** Deixar todos os dados no mesmo sistema de coordenadas, assim como o projeto.

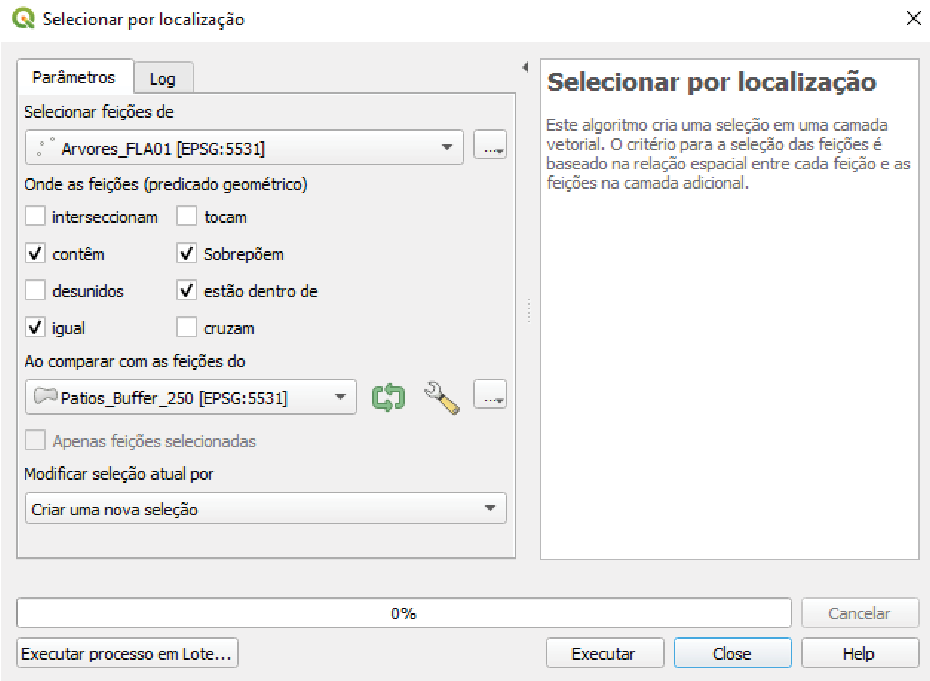
**4.** Procurar a aba Vetor, item Geoprocessamento e opção amortecedor.



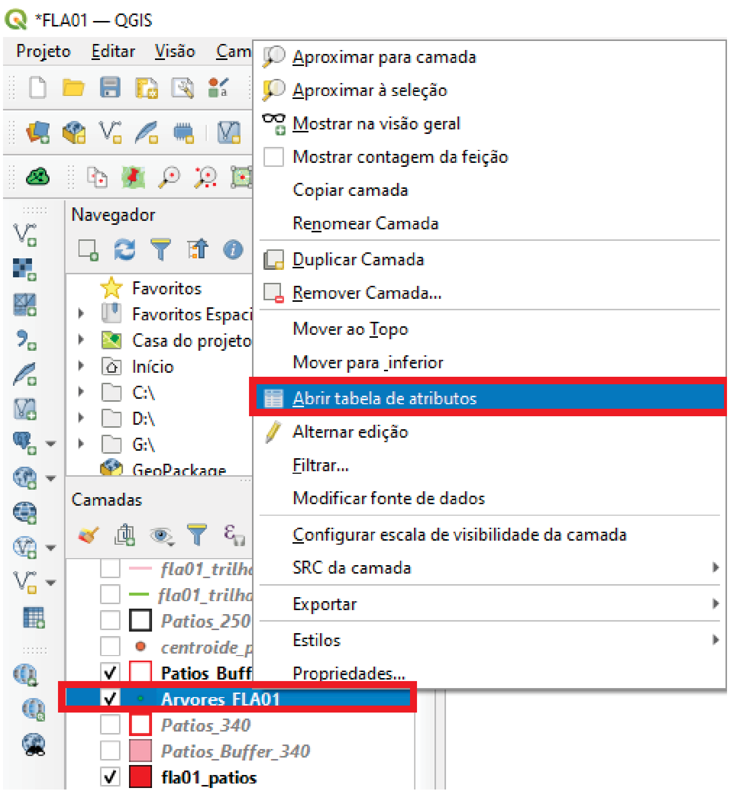

**5.** Escolha o arquivo do centroide dos pátios, determine o raio desejado, neste caso 250m e escolha uma pasta onde salvar.



**6.** Procure o ícone  da Seleção por localização, e selecione as arvores, a partir do raio de 250m dos pátios.

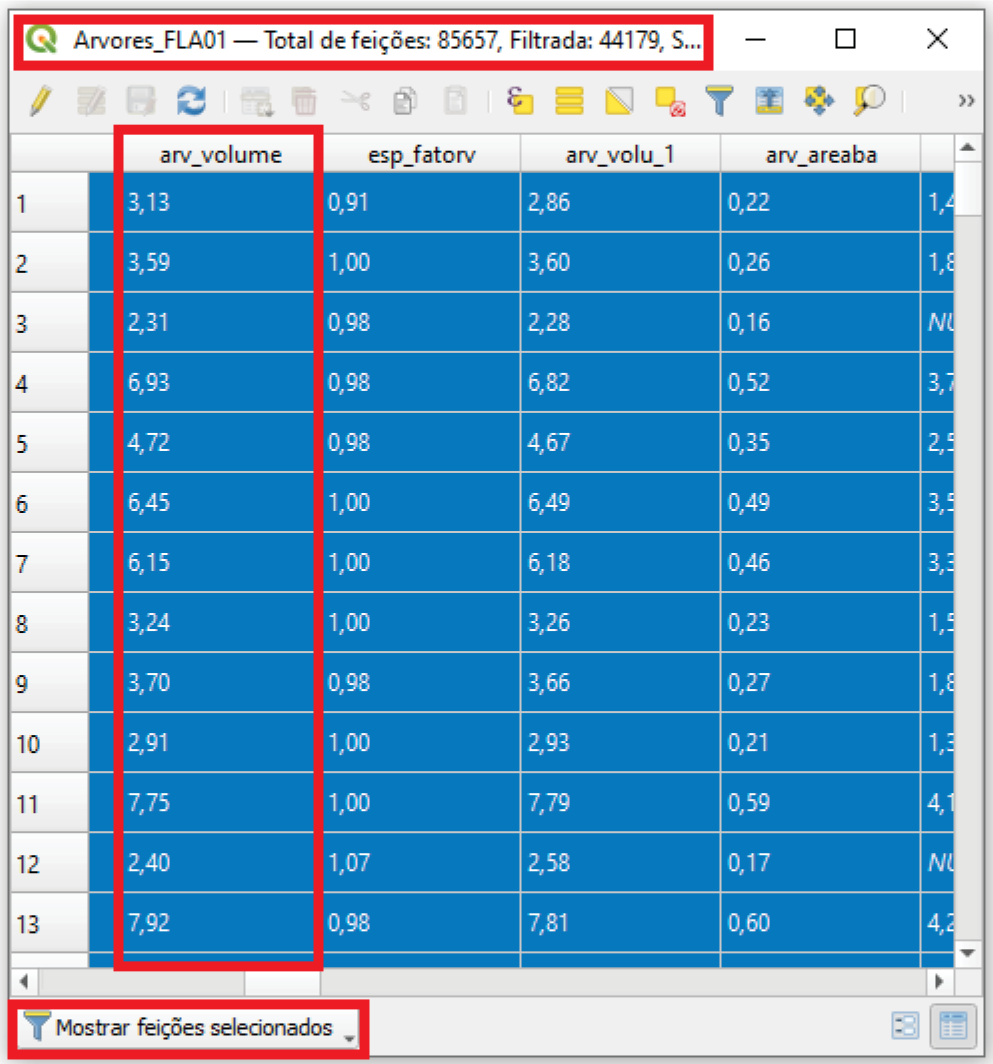


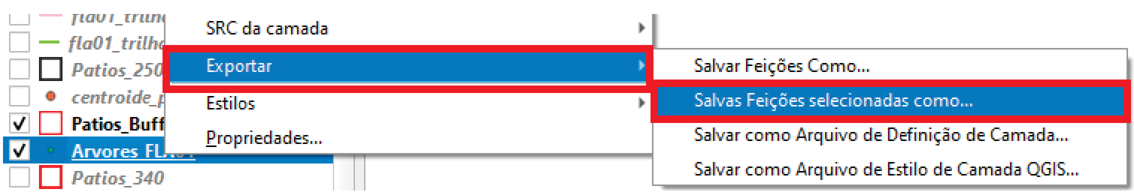

**7.** Abra a tabela de atributos do arquivo das arvores.

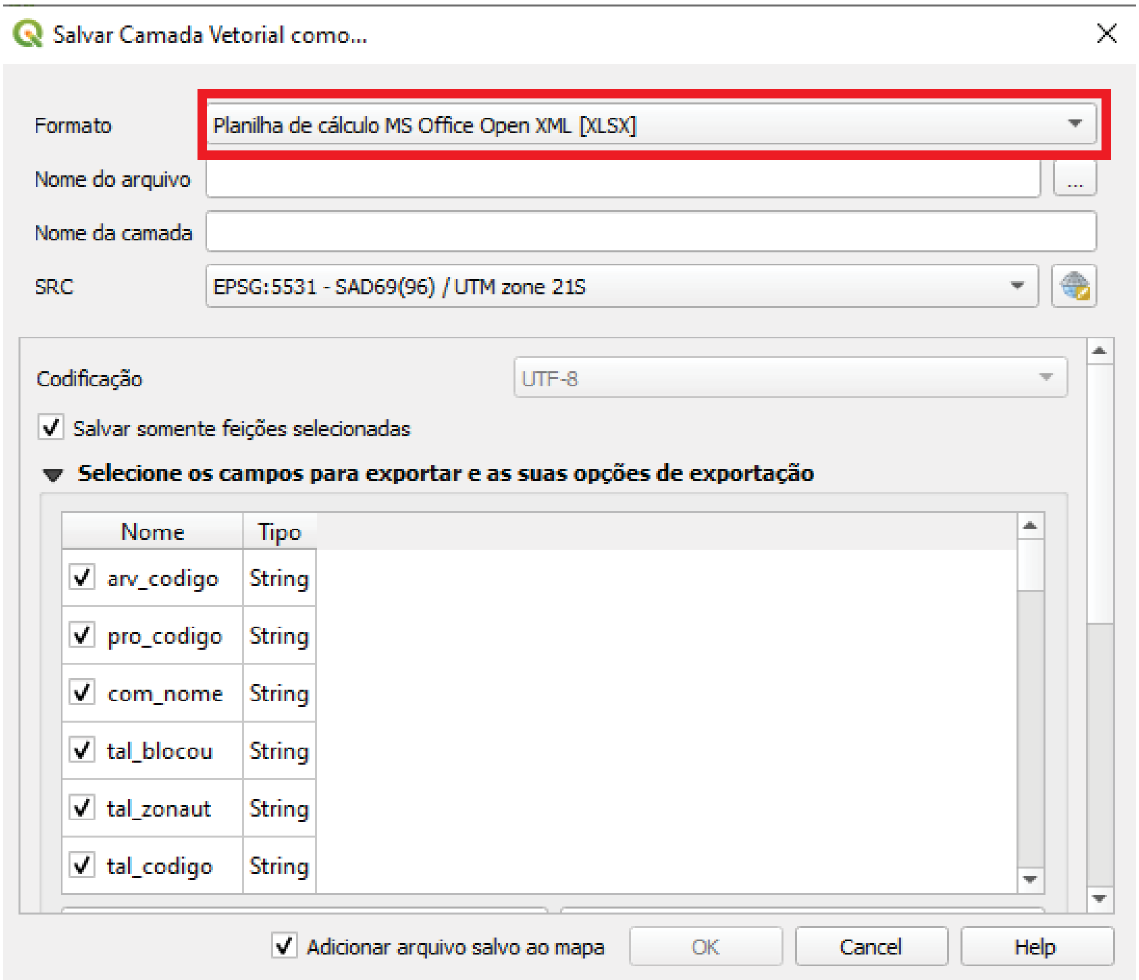


**8.** Procure a opção “Mostrar feições selecionadas” e então procure a coluna “arv_volume” – agora temos o volume de todas as arvores selecionadas dentro do raio de 250m dos pátios, e o total de arvores selecionadas.

Exportando as feições selecionadas na extensão XLSX, é possível abrir o Excel a planilha das arvores com apenas as árvores que estavam no raio de 250m e calcular o volume potencial dentro dos pátios.

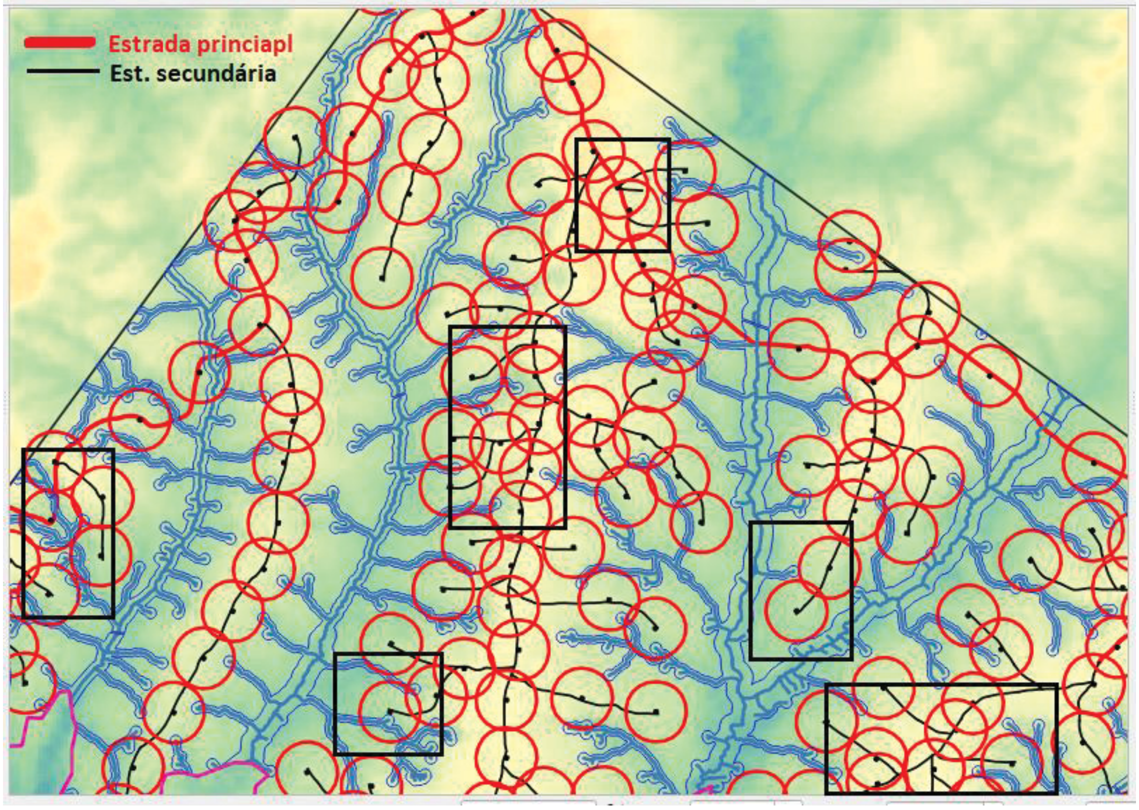


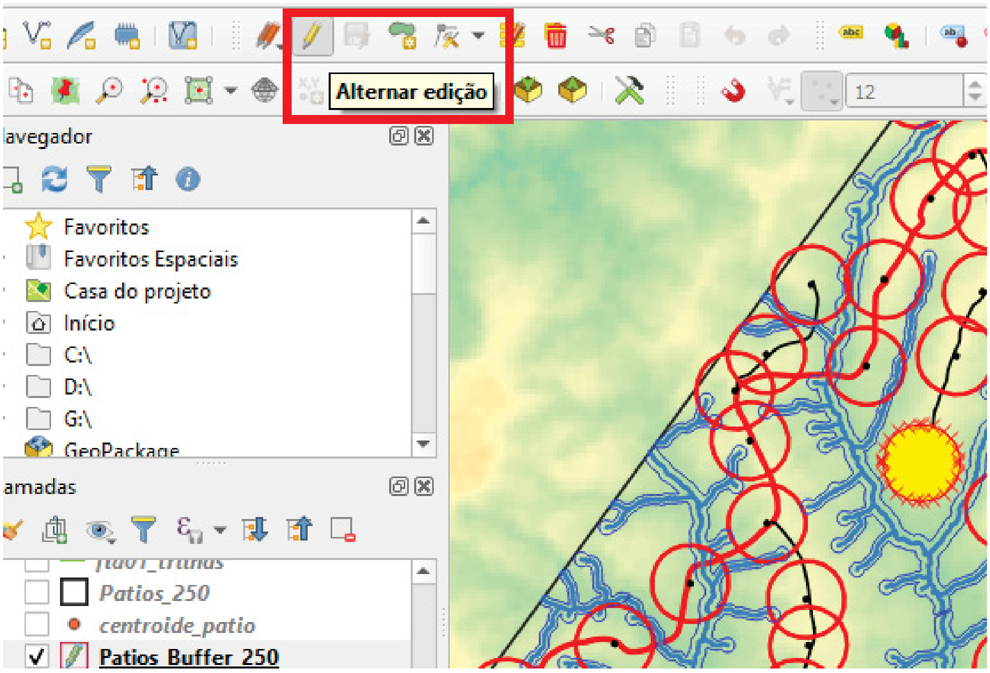



**9.** Avaliando o volume potencial de madeira computado dentro dos raios e o volume estipulado pela norma, podemos avaliar a possibilidade de realocação e diminuição do número de pátios, se levando em consideração as características físicas do meio e ambientais/legislativas (altitude, proximidade com as áreas de APPs e córregos).

- Na imagem abaixo conseguimos observar através da distribuição do raio dos pátios, que eles poderiam estar melhor distribuídos. Pois eles apresentam sobreposição de área, áreas sobre APP, áreas sobre nascentes, áreas sobre rios de 2 ordem, em fundos de vale onde predominam altitudes mais baixas, vou seja pressupõe uma subida mais onerosa ao caminhão de transporte, e além de estar longe da estrada principal.



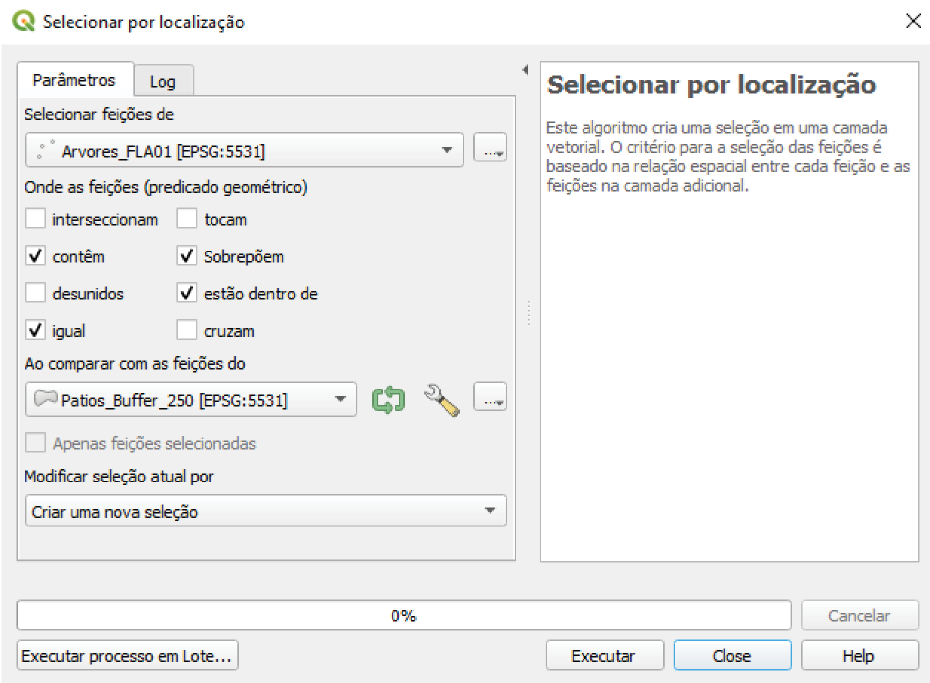

**10.** Através da ferramenta Alternar edição, conseguimos deletar, editar, deslocar e alterar a localização dos pátios. Neste caso dos raios, que usaremos como guia, e posteriormente pode-se gerar novos pontos do centróide onde se localizará o pátio propriamente dito. Utilizar a ferramenta “Mover feição” para deslocar o posicionamento dos polígonos.

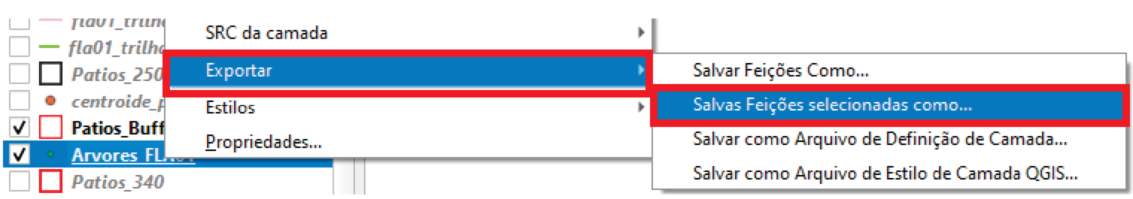



**11.** Neste passo é realizada uma análise da malha na extensão qneat, tem de ir diminuindo o número de pátios conforme o que diz respeito a norma e visando uma otimização e redução dos custos, que se dá principalmente ela diminuição dos pátios que contém área sobrepostas, ou seja, que estão a menos de 500m um do outro.

**12.** Após a determinação do número de pátios e o volume de madeira estipulado por área e por pátio, aproximadamente 900m³ por pátio, realiza-se o mesmo procedimento do passo 6 e 8.

A Partir da nova quantidade de pátios, selecione as árvores dentro dos novos raios realocados, e em seguida exporte as feições selecionadas, assim separando as árvores de interesse dentro da área de interesse.



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