

Analysis of the efficiency of delineating work units in sustainable forest management using remote sensing

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FOREST MANAGEMENT

ABSTRACT

Background: Forest microzoning is fundamental to the efficiency of sustainable forest management plans in the Amazon because it guides the delineation of work units. Traditionally, this process was based on field collections and required a significant amount of time, human resources, and financial resources. Thus, remote sensing emerges as an alternative that can optimize this stage, reducing costs and increasing operational efficiency. The objective of this study was to evaluate the quality of Work Unit delimitations in management areas in the state of Pará by comparing three scenarios: field data, remote sensing data, and integrated data. To this end, geographic data were collected in the field, and then delimitations were generated using geospatial data. Finally, a model combining both types of data was tested. Quality was assessed using an index proposed in the study.

Results: The scenario based solely on remote sensing identified a greater number of watercourses, expanding the Permanent Preservation Areas and reducing the Effective Management Area. The field model had methodological limitations in the first area analyzed, but the integrated model overcame these limitations. The integrated model kept the area of the work units close to ideal and respected the hydrography. In the second area, the integrated model achieved a higher quality index.

Conclusions: The exclusive use of remote sensing overestimates the drainage network, whereas the field model ensures greater accuracy, albeit at a high cost. Therefore, integrating both methods proved to be the most efficient and accurate methodology for forest planning and exploitation.

Keywords: Forest management; Land use planning; Environmental conservation; Spatial monitoring.

HIGHLIGHTS

Field integration and sensing improve the delineation of work units.
Remote sensing overestimates drainage and reduces the effective management area.
The integrated model keeps work units close to 100 ha and respects natural resistance.
Integration ensures greater efficiency in sustainable forest planning.

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INTRODUCTION

In the Amazon, Sustainable Forest Management (SFM) is a fundamental strategy for conserving standing forests and establishing a direct relationship between exploiting natural resources and protecting environmental quality (Oliveira et al., 2024; Rodrigues et al., 2020; Schulze et al., 2008). According to Brazil's new Forest Code (Brasil, 2012), SFM is defined as managing natural vegetation to obtain economic, social, and environmental benefits while respecting the mechanisms that sustain the managed ecosystem. (Brasil, 2012; Kazama et al., 2021; Miranda et al., 2020).

To promote the use of SFM techniques, the Brazilian government created a forest concession policy through Law No. 11,284 in 2006. This policy allows for the sustainable production of public forests. The concession process involves competitive bidding and may result in a fixed-term administrative contract. If a company is awarded a concession, it has the right to practice sustainable forest management in public forests (Brasil, 2006b; Silva et al., 2023; Sist et al., 2021).

After approval, the selected company must conduct a microzoning study of the area. This study involves a detailed survey to identify watercourses, drainage channels, ravines, steep slopes, areas prone to landslides, the floristic composition, and Permanent Preservation Areas (PPAs) (Brasil, 2006a). It is imperative that microzoning be executed properly because it is decisive in determining the location, distribution, and arrangement of Work Units (WUs) within annual Production Units (APUs) (Aguar et al., 2021; Gouveia et al., 2024; Martorano et al., 2025).

Microzoning methodologies are mainly based on field collections using GNSS (Global Navigation Satellite System) receivers. However, its application in large areas requires substantial operational effort, including personnel mobilization, field-related costs, execution time, and exposure to accident risks. Additionally, altimetric data derived from GNSS navigation is limited, preventing a detailed analysis of the terrain (Khan et al., 2025).

In this scenario, tools from the field of geotechnologies, such as remote sensing, allow us to collect and analyze geospatial data efficiently and effectively. For example, in preparing the initial hydrography, active RADAR (radio detection and ranging) sensor products are used to characterize the relief, identify the hydrographic network, and extract it through flow analysis (Alves Sobrinho et al., 2010; Datta et al., 2022). In addition, remote sensing can easily identify PPAs on slopes, hilltops, rivers, and special areas.

This technique allows for multi-criteria analysis, including topography, land use, and drainage. However, GNSS alone is limited to location data (Hugo and Viertel, 2024). Moreover, these techniques have limitations, such as the inability to adequately represent fine-scale topographic variations, particularly when low-spatial-resolution data are used, which may result in sampling errors that affect terrain attribute extraction and compromise the reliability of the analysis.

Therefore, this study aimed to evaluate the quality of WU delimitation in management areas in the state of Pará by comparing three scenarios: (i) delimitation based exclusively on field data, (ii) delimitation based exclusively on remote sensing data, and (iii) delimitation based on the integration of field and remote sensing data. The guiding hypotheses were that: (1) the remote sensing-based method has limitations and always requires field validation, and (2) the integrated model of remote sensing and field data is more accurate because it ensures greater data reliability.

MATERIALS AND METHODS

Study area

The study area is a Sustainable Forest Management Unit (SFMU) covering 4,159.17 ha located in the municipality of Almeirim, in the Lower Amazon mesoregion of the state of Pará (Figure 1).

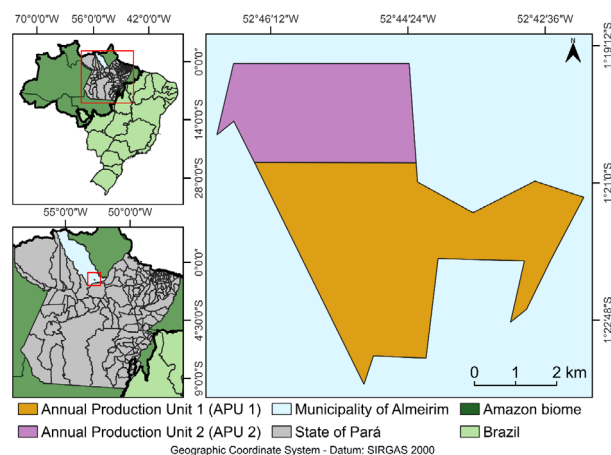


Figure 1: Location map of the study area.

The area has a humid tropical climate of the Am type, with average temperatures above 18 °C year-round, a short dry season, and high annual precipitation (Alvares et al., 2014). The vegetation consists primarily of tropical broadleaf forests, with variations including dense submontane, plateau, and terrace forests, as well as alluvial and field forests near the Amazon River (Amorim et al., 2010). The hydrography is characterized by the Paru and Jari rivers, which are significant tributaries on the left bank of the Amazon.

Description of the Sustainable Forest Management Unit (SFMU)

As described in Table 1, the SFMU is composed of three Annual Production Units (APUs).

Data related to APU 1, with an area of 2,052.57 ha, were obtained in 2022, with forest harvesting taking place in the following year. APU 2 has an area equivalent to one quarter of the total FMU area (1,045.58 ha). Both

Table 1: Description of the Annual Production Units (APU) that comprise the Sustainable Forest Management Unit.

Label	Área (ha)
APU 1	2.052,5663
APU 2	1.045,5753
APU 3	1.061,0262

APUs were delineated in accordance with the provisions established by Normative Instruction No. 05 of 2017 of the State Secretariat for Environment and Sustainability (Pará, 2015), and the pre-harvest phase of APU 2 was carried out in June and July 2024. As management activities in APU 3 had not yet begun, the present study was conducted using data from APUs 1 and 2.

Methodological Procedures

The following steps were implemented: (1) collecting field data and distributing work units, (2) collecting geospatial data and optimizing the distribution of work units, (3) optimizing the distribution of work units with merged geospatial and field data, and (4) evaluating the accuracy of the proposed models.

Step 1: Field data collection and distribution of work units.

Two teams (two GPS operators and two assistants) were needed to collect the microzoning data in the field at APU 1, and one team (one GPS operator and one assistant) was needed at APU 2. Over a period of 14 days, the collaborators covered the entire area, identifying important structures and variables such as clearings, flooded areas, steep slopes, and hydrography.

Employees carried out the hydrography layout using the walking method. They walked along the banks of the watercourses equipped with Garmin GPSMAP 66i GNSS navigation devices with an accuracy of three meters. They used the route recording function in vector line format.

Then, the collaborators marked the locations of the springs and walked back along the other bank of the watercourse to create a polygon that could be measured for the subsequent identification of Permanent Preservation Areas (PPA) based on the legal delimitations of Law No. 12,651 of 2012 (Brasil, 2012).

After collecting field data, it was imported into GPS TrackMaker software (version 5.1) to smooth the lines delineating the rivers and subsequently create the PPAs. After analyzing the average width of the watercourses, it was determined that they did not exceed seven meters. This made it necessary to delimit a 30-meter PPA strip (Brasil, 2012) (Table 2).

The Buffer tool in Quantum GIS (QGIS) software, version 3.34, was used to determine the PPA ranges in the study area. Since the average width of the watercourses was less than 10 meters, a 30-meter buffer was applied

Table 2: According to the new Forest Code, the minimum size of an PPA for each specification.

River width	PPA Range
≤ 10 meters	Minimum strip of 30 meters on each bank
> 10 e ≤ 50 meters	Minimum strip of 50 meters on each bank
> 50 e ≤ 200 meters	Minimum strip of 100 meters on each bank
> 200 e ≤ 600 meters	Minimum strip of 200 meters on each bank
> 600 meters	Minimum strip of 500 meters on each bank
Hilltop	Full protection above the upper third, provided the height is greater than 100 meters and the average slope is greater than 25°
Slope	Slope above 45°, equivalent to 100%
Spring	minimum radius of 50 meters around

Source: Adapted from (Brasil, 2012).

using the vector hydrography layers collected in the field as input files. Additionally, 50-meter buffers were applied to delineate the PPAs of springs using the point vector layers of springs as the input files. To determine the applicability of Permanent Preservation Areas (PPAs) associated with slopes and hilltops, the study area was evaluated according to the Brazilian Forest Code No. 12,651 of 2012 (Brasil, 2012). This assessment was used as a methodological criterion for defining regulatory constraints within the GIS-based analysis. The geomorphological conditions of the study area did not meet the legal thresholds, as elevation did not exceed 100 m and slope gradients remained below 27°.

After identifying areas legally unsuitable for management, the Effective Management Area (EMA) extent was determined for each APU. Then, the work units were delineated using the rectangle creation tool in the GPS TrackMaker software. This methodology requires distributing areas with magnification, so that each rectangle on the interface is 100 hectares. Thus, planning is carried out according to the forest manager's decision, which may result in subjective delineation of work units.

For this delimitation, the boundaries of the PPA and the size of a Work Unity (WU) of 100 hectares were taken into account. This methodology, which follows natural barriers, facilitates forest inventory. Teams can walk through the area without crossing watercourses, and duplication of individuals at the boundaries between one WU and another is avoided. It also shapes infrastructure management for extraction.

Step 2: Collection of geospatial data and optimized distribution of work units

Digital processing techniques were used to collect data for geospatial analysis from the Digital Elevation Model

(DEM) of the RADAR (Radio Detection and Ranging) ALOS (Advanced Land Observing Satellite) topographic mission of the Japan Aerospace Exploration Agency (JAXA), which has a spatial resolution of 12.5 meters and was acquired on the ASF Data Search platform (2024).

The DEM files were pre-processed to remove spurious depressions and create a hydrologically consistent DEM. The “Fill” and “Sink” tools in QGIS were used for this purpose. To ensure spatial conformity between the DEMs and the APUs’ boundaries, the matrix file was cropped. This generated two independent files: one referring to the corrected DEM within the boundaries of APU 1, and the other referring to the corrected DEM within the boundaries of APU 2.

Next, the methodology proposed by Conrad (2003), was used to identify watercourses and springs in the area. The “Channel Network and Drainage Basins” tool was applied using the DEM as the input variable. This tool identifies drainage networks (rivers) and delimits watersheds from an DEM. Then, vector files of lines (watercourses) and points (springs) were generated. Since the watercourses in the study area do not exceed an average width of seven meters, 3.5-meter buffers were applied to the river vectors using the water grids as input variables.

To determine the PPA ranges, 30-meter buffers were applied using the hydrography vector layers generated in the previous step. Additionally, 50-meter buffers were applied to delineate the PPAs of springs using the point vector layers of springs as the input files. As mentioned when delimiting WUs with field data, there are no PPAs on slopes and hilltops.

Given the effective management area of both APUs minus the PPAs, it was possible to automatically divide the WUs using the “Polygon Divider” complement in QGIS. This tool divides polygons into smaller areas of a defined size and/or shape. The criterion used was the size of the WUs (100 hectares), in accordance with State Secretariat for Environment and Sustainability of the state of Pará (SEMAS) Ordinance No. 39 of 2025 (Pará, 2025).

The add-on requests the subdivision direction, which can be from left to right, from right to left, from top to bottom, or from bottom to top. To ensure a better fit for the polygons, the ones that best suited the specified delimitation methodology were tested. Thus, with adjustments to the automatic delimitation, the WUs were generated.

It is important to note that this configuration creates polygons that are at least 100 hectares in size. In certain isolated situations, however, smaller polygons may be necessary. Specific adjustments were made whenever this occurred to ensure adequate results.

Step 3: Optimization of work units through integrated processing in a GIS environment

The final method evaluated consisted of an automated GIS-based processing approach using field data for work unit delineation. Thus, the field data was combined with automated GIS processing for the division of the WUs.

The PPA data used in this step came from the teams’ field hydrography obtained via GPS. It was then

plotted in QGIS for the automatic redrawing of the work units. The “Polygon Divider” tool was applied to divide the APUs’ polygons into WUs, using the aforementioned 100-hectare criterion.

Step 4: Assess the assertiveness of the proposed models

Three criteria were proposed to evaluate the efficiency and adequacy of the three scenarios for defining WUs. These criteria were assigned weights to indicate their importance in the assessment process. Variations were developed for each criterion, each of which is associated with a specific weight (Table 3).

Table 3: Criteria for Optimized Delimitation of Work Units by Level of Importance for Each Scenario.

Criteria	WC	Description	Variations	WV
1	0,6	Size of WUs	Less than 40% of WUs > 85 ha and < 110 ha	1
			40% to 55% of WUs > 85 ha and < 110 ha	2
			55% to 70% of WUs > 85 ha and < 110 ha	3
			70% to 85% of WUs > 85 ha and < 110 ha	4
			More than 85% of WUs > 85 ha and < 110 ha	5
2	0,8	Rivers crossing WUs	More than 50% of WUs are crossed by rivers	1
			40% to 50% of WUs are crossed by rivers	2
			20% to 40% of WUs are crossed by rivers	3
			0% to 20% of WUs are crossed by rivers	4
			0% of WUs are crossed by rivers	5
3	1	EMA per APU	< 50%	1
			>50% and <70%	2
			>70% and <80%	3
			> 80% and <90%	4
			> 90%	5

Where: WC are the weights of the criteria, and WV are the weights of the variations.

The delimitation of these variables, as well as the weights used, was based on conversations with area managers and requests for information about the main criteria used in the field. This interaction with professionals working in the field was providential, with the aim of ensuring that the methodology was appropriate to the realities of the field.

The criteria and variations within the criteria were developed with the level of importance of the assessment

of the Work Units. The optimal size of the WUs varies around ha, which can influence logistics at the time of forest exploitation, compliance with the requirements of Ordinance No. 39 of January 14, 2025, of the State Secretariat for the Environment and Sustainability of the Government of the State of Pará (Pará, 2025), as well as standardization for the forest inventory itself.

The second criterion regarding rivers crossing the WUs was analyzed in an environment where the best scenario is one with the fewest hydrographic networks crossing the WU from side to side. This variation was therefore given maximum weight. Based on the percentage of areas under effective management within the APUs, the APU with the largest proportion of suitable areas was given the highest weight.

Given this, a Work Unit Quality Index (WUQI) (Equation 1) was proposed to assess the efficiency and suitability of the WUs in relation to the criteria mentioned above. The result obtained ranges from 0% to 100%, with values closer to, where: WUQI represents the Work Unit Quality Index, V represents variations, C represents evaluation criteria and represents the maximum score that can be assigned to a variation for a given criterion.

$$WUQI = \frac{\sum_{i=1}^n (V_i \times C_i)}{P_{\max} \times \sum C_i} \times 100$$

RESULTS

According to the information presented in Table 3 and illustrated in Figure 2, 53.10 km of hydrography were identified in APU 1 and 16.23 km in APU 2 in the scenario with field data. These values increased substantially in the scenario with remote sensing data, to 108.35 km in APU 1 and 54.20 km in APU 2. Consequently, the PPA ranges were higher with remote sensing data, reducing the Effective Management Areas of APUs 1 and 2 by 17.94% and 16.92%, respectively. With field data, the reduction in the effective management areas of APUs 1 and 2 was 9.28% and 5.11%, respectively.

Table 4: Reduction of the Effective Management Area based on hydrography by Annual Planning Unit.

	APU 1			APU 2		
	Area (ha)	PPA (ha)	Reduction of the EMA (%)	Area (ha)	PPA (ha)	Reduction of the EMA (%)
Field data	2,052.57	190.58	9,28	1.045,58	53.44	5,11
Remote Sensing	2,052.57	347.35	17,94	1.045,58	187.59	16,92

WU delimitation maps were generated for the three scenarios described above based on field hydrography data and remote sensing analysis (Figure 3). The results show that 17 WUs were delimited in the field data scenario in APU 1, 15 in the remote sensing scenario, and 17 in the integrated scenario. In APU 2, nine WUs were delineated in the field data scenario, eight in the remote sensing, and nine in the integrated scenario.

Given the criteria and variations, in APU 1, to identify the WUQI in the three scenarios, the weights for each variation were calculated (Table 5). The model that stood out most in the WUQI was the one that integrated field and sensing data (76%). This division met the criteria for delimiting the WUs well, following natural resistances, with few rivers cutting through the units. For APU 2, the scenarios that stood out most were the one with field data and the integrated one, with 90.4% accuracy.

Table 5: Reduction of the Effective Management Area based on hydrography by Annual Planning Unit.

Criteria	APU 1			APU 2		
	Field data (V)	Remote Sensing (V)	Field data + Remote Sensing (V)	Field data (V)	Remote Sensing (V)	Field data + Remote Sensing (V)
C1	1	2	3	3	2	3
C2	1	1	3	5	4	5
C3	5	4	5	5	4	5
WUQI %	52,0	48,8	76,0	90,4	70,4	90,4

DISCUSSION

The results obtained in this study reinforce the complexity inherent in forest microzoning and highlight substantial differences between the scenarios analyzed. These variations underscore the need for methodologies that ensure greater assertiveness in planning in SFM areas, where the accuracy of WU delimitation directly influences operational efficiency and environmental conservation.

Several authors in the literature have highlighted the limitations of models based solely on geospatial data. For example, Wu and Xia (2014) and Costabile et al. (2022) explain that analyses based solely on Digital Elevation Models (DEMs) can misinterpret low-lying areas as water bodies. This results in a simulated network that is larger than the actual network, primarily due to the way topographic depressions are treated. Consequently, simulations of non-existent water bodies arise, resulting in a higher drainage density than verified in the field.

This limitation is particularly relevant, as overestimating the hydrographic network can impact the definition of PPA, artificially reducing the EMA, as occurred in this study. In the scenario based exclusively on remote sensing, a greater number of watercourses were identified, expanding the PPAs and reducing management effectiveness. This result confirms that remote sensing, although valuable for automation and spatial coverage, has limitations in distinguishing between perennial, intermittent, and ephemeral drainage. Reliable distinction of these flows requires on-site analysis during a complete hydrological cycle.

In APU 1, the scenario with field data had methodological limitations because the WUs were delimited without considering natural resistance, which resulted in drainage cuts. Although the same methodology

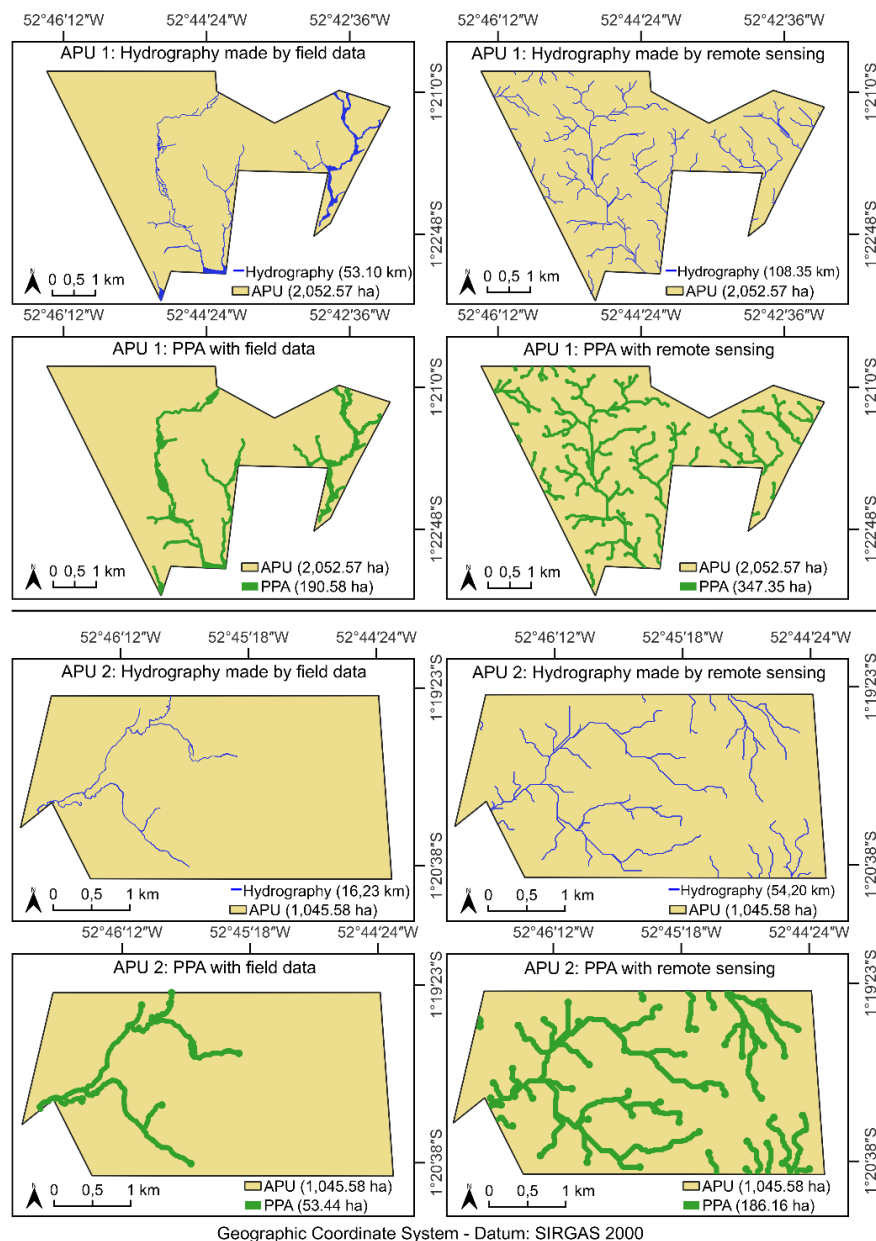


Figure 2: Hydrographic network in both APUs in the analysis scenarios.

was applied in both APUs, the results differed due to variations in the hydrographic network configuration and the subjectivity inherent to the forest manager's decision-making process during WU delineation. Processing the same physical microzoning data in a geospatial environment in the integrated scenario optimized the delimitation, producing WU close to 100 hectares that respected the layout of watercourses. This result reinforces the idea that combining field surveys with remote sensing data reduces methodological flaws and ensures greater reliability.

It was also observed that an increase in PPAs in the remote sensing data scenario led to a reduction in the number of WUs and consequently lower WUQIs. This reduction is associated with the difficulty of maintaining

standardization at 100 hectares when drainage channels cut through the units due to an overestimation of the hydrographic network. Thus, while a model based solely on remote sensing data is efficient on a regional scale, directly applying it to SFM operational planning may compromise productivity and logistical efficiency.

Other studies corroborate the importance of integrating different data sources. Papa *et al.* (2018), when proposing a microzoning model with a GNSS receiver combined with RADAR data, demonstrated that the combination of parameters reduces uncertainties and allows for the delimitation of WUs that are better adjusted to environmental heterogeneity, enabling better allocation of resources and infrastructure. (Rocha *et al.*, 2024) also

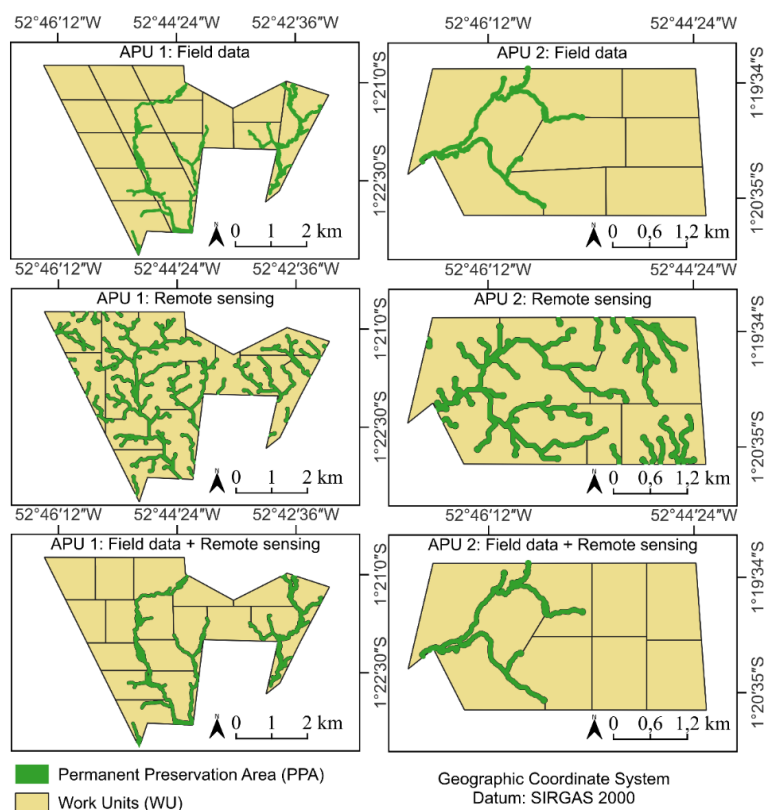


Figure 3: Map showing the boundaries of the Work Units in the three scenarios for APUs 1 and 2.

showed gains in production quality and homogeneity in the distribution of commercially valuable species by reorganizing WUs according to natural resistance.

In the context of this study, the definition of WUs around 100 hectares proved to be adequate, in line with CONAMA Resolution No. 406/2009 (Brasil, 2009), and SEMAS-PA Ordinance No. 39/2025 (Pará, 2025) to ensure sustainable forest management and regeneration. This standardization not only facilitates inventory and exploration logistics but also allows for the optimized planning of roads and yards with less environmental impact and an adequate distance from PPAs.

Field validation of the model is crucial to avoid discrepancies. In this study, we initially assume that the data collected by the microzoning teams is correct. However, the possibility of bias or human error is acknowledged. Therefore, future research is recommended to include a new visit to the area. This is because teams may have misclassified lower points in the terrain that could be intermittent watercourses as “dry grotas” (lower parts of the terrain not subject to PPAs or ephemeral rivers).

CONCLUSION

The exclusive use of remote sensing overestimates the drainage network and reduces the effective management area. In contrast, the approach using only field data ensures greater accuracy, resulting in larger effective management areas;

The automated approach in a GIS environment, using field data, produced the best results by combining efficiency and accuracy in delimiting work units;

Field validation is essential to support the accurate representation of drainage features and to reduce errors in the delineation of Permanent Preservation Area;

The integration of methods ensures greater sustainability and productivity in forest planning and exploitation.

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