UFJ
Universidade Federal de Jataí
Revista Eletrônica do curso de Geografia
Graduação e Pós-Graduação
Jataí-GO | n 55 | maio-agos/2026
GEO AMBIENTE on-line
ISSN 1679-9860

MAPPING OF RURAL PROPERTIES WITH REMOTELY PILOTED AIRCRAFT TO COMPLY WITH THE RURAL ENVIRONMENTAL REGISTRATION

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Abstract: This study evaluates the feasibility of using Remotely Piloted Aircraft (RPA) in mapping rural properties to comply with the Rural Environmental Registry (CAR), emphasizing the positional quality of cartographic products and the methodological standardization of environmental mapping. The survey was conducted on a 21.95-hectare rural property using aerial photogrammetry with RPA, implementation of Control and Verification Points by GNSS/RTK, and photogrammetric processing using open-source software. The cartographic products generated were an orthomosaic, a Digital Elevation Model (DEM), land use and land cover maps, slope maps, and CAR environmental unit maps. Positional accuracy was evaluated based on the Positional Accuracy Standard for Digital Cartographic Products (PAP-PCD), using seven independent verification points. The results showed a Root Mean Square Error (RMSE) of 0.203 m in planimetry and 0.160 m in altimetry, placing the products in Class A for the 1:2000 and 1:1000 scales, respectively. The results demonstrate that the integration between UAV, GNSS/RTK, and normative evaluation constitutes a robust and applicable approach to CAR (Rural Environmental Registry), contributing to greater precision, reliability, and standardization of rural environmental mapping.

Artigo recebido para publicação em 26 de fevereiro de 2026
Artigo aprovado para publicação em 06 de junho de 2026

Keywords: Georeferencing, photogrammetry, environmental monitoring.

MAPEAMENTO DE IMÓVEIS RURAIS COM AERONAVE REMOTAMENTE PILOTADA (ARP) PARA ATENDIMENTO AO CADASTRO AMBIENTAL RURAL

Resumo: O presente estudo avalia a viabilidade do uso de Aeronave Remotamente Pilotada (ARP) no mapeamento de imóveis rurais para atendimento ao Cadastro Ambiental Rural (CAR), com ênfase na qualidade posicional dos produtos cartográficos e na padronização metodológica do mapeamento ambiental. O levantamento foi realizado em uma propriedade rural de 21,95 hectares, utilizando aerofotogrametria com ARP, implantação de Pontos de Controle e Verificação por GNSS/RTK e processamento fotogramétrico em software livre. Como produtos cartográficos, foram gerados ortomosaico, Modelo Digital de Elevação (MDE), mapas de uso e ocupação do solo, declividade e unidades ambientais do CAR. A acurácia posicional foi avaliada com base no Padrão de Acurácia Posicional de Produtos Cartográficos Digitais (PAP-PCD), utilizando sete pontos independentes de verificação. Os resultados apresentaram Erro Médio Quadrático (EMQ) de 0,203 m na planimetria e 0,160 m na altimetria, enquadrando os produtos na Classe A para as escalas 1:2000 e 1:1000, respectivamente. Os resultados demonstram que a integração entre ARP, GNSS/RTK e avaliação normativa constitui uma abordagem robusta e aplicável ao CAR, contribuindo para maior precisão, confiabilidade e padronização do mapeamento ambiental rural.

Palavras-Chave: Georreferenciamento, fotogrametria, monitoramento ambiental,

MAPEO DE INMUEBLES RURALES CON AERONAVE REMOTAMENTE PILOTADA (ARP) PARA EL CUMPLIMIENTO DEL CATASTRO AMBIENTAL RURAL

Resumen: El presente estudio evalúa la viabilidad del uso de Aeronaves Remotamente Pilotadas (ARP) en el mapeo de inmuebles rurales para el cumplimiento del Cadastro Ambiental Rural (CAR), con énfasis en la calidad posicional de los productos cartográficos y en la estandarización metodológica del mapeo ambiental. El levantamiento fue realizado en una propiedad rural de 21,95 hectáreas, utilizando aerofotogrametría con ARP, implantación de Puntos de Control y Verificación mediante GNSS/RTK y procesamiento fotogramétrico en software libre. Como productos cartográficos, se generaron ortomosaico, Modelo Digital de

Elevación (MDE), mapas de uso y ocupación del suelo, declividad y unidades ambientales del CAR. La exactitud posicional fue evaluada con base en el Patrón de Exactitud Posicional de Productos Cartográficos Digitales (PAP-PCD), utilizando siete puntos independientes de verificación. Los resultados presentaron un Error Cuadrático Medio (ECM) de 0,203 m en la planimetría y 0,160 m en la altimetría, clasificando los productos en la Clase A para las escalas 1:2000 y 1:1000, respectivamente. Los resultados demuestran que la integración entre ARP, GNSS/RTK y evaluación normativa constituye un enfoque robusto y aplicable al CAR, contribuyendo a una mayor precisión, confiabilidad y estandarización del mapeo ambiental rural.
Palabras clave: Georreferenciación, fotogrametría, monitoreo ambiental.

Introduction

Given the growing environmental challenges, it is essential to preserve, conserve, and promote the recovery of ecosystems. In this context, understanding the impacts of human activities and identifying priority natural areas has demanded the development of increasingly accurate and reliable environmental databases. With the expansion of the carbon market and the increase in transactions involving emission reduction credits, the spatial delimitation of these areas has taken on a strategic character, requiring greater technical rigor in the generation of geospatial information (Kruse, 2023).

In Brazil, the Rural Environmental Registry (CAR), established by Law No. 12,651/2012 (Forest Code), is one of the main instruments for environmental management of rural properties, requiring the delimitation of Permanent Preservation Areas (APP), Legal Reserve (RL), remnants of native vegetation, and the perimeter of the properties (Brazil, 2012). This information feeds into the National Rural Environmental Registry System (SICAR), serving as a basis for environmental monitoring, planning, and enforcement (Brazil, 2012). In this sense, the CAR contributes to the consolidation of a national geospatial database and to the fulfillment of the socio-environmental function of rural property (Tybusch; Bertoncelli, 2022; Nogueira; Martins, 2022; Beneventi; Oliveira, 2025; Carvalho; Barbosa, 2019; Bittar et al., 2024).

Despite the relevance of the CAR, recent studies have highlighted geometric inconsistencies in SICAR, such as overlapping areas and discrepancies in the delimitation of APPs, compromising the effectiveness of the registry as a territorial management tool (Garcez;

ISSN 1679-9860

Bono, 2023). In certain regions, such inconsistencies can reach significant percentages, highlighting structural limitations in the database (Valente; Viera, 2025). In addition, analyses applied to the CAR indicate that, although the system has high potential for environmental planning, its effectiveness depends directly on the quality of the information entered (Menezes; Dias, 2019).

However, recent advances in the use of geotechnologies have demonstrated potential for overcoming these limitations, especially through the integration of different tools and techniques for acquiring geospatial data. In this context, Souza and Cunha (2020) highlight that the combined use of GNSS, Geographic Information Systems (GIS), and aerial surveys with Remotely Piloted Aircraft (RPA) expands the capacity for environmental analysis, providing greater precision in the delimitation of territorial features and more efficient support for environmental planning and management. Similarly, Gomes et al. (2026) demonstrated the potential of using RPA integrated with GNSS and satellite communication in rural cadastral mapping, including the possibility of dispensing with field control points, achieving products with high precision and accuracy. Similar results were observed by Costa et al. (2023), who identified greater detail in the delimitation of sensitive environmental features. Complementarily, Ramos et al. (2025) showed that the use of UAVs associated with GNSS/RTK provides significant operational gains, with reduced costs and increased efficiency in data processing.

From a scientific point of view, the use of aerial photogrammetry with UAVs associated with GNSS positioning has become established as a promising alternative for obtaining high spatial resolution data and high positional accuracy (Westoby et al., 2012; Nex; Remondino, 2014; Colomina; Molina, 2014). Recent applications demonstrate the potential of these technologies in geomorphological mapping and environmental analysis, allowing the identification of spatial patterns and support for the management of natural resources (Santos et al., 2023).

Therefore, it is observed that the use of UAVs in environmental mapping for the CAR takes advantage of the potential of this geotechnology in these applications, such as good positional accuracy, high spatial resolution, operational simplicity, productivity and low cost. Furthermore, temporal resolution allows for the mapping of environmental areas to be carried out at the time of registration, enabling an up-to-date environmental registry; in addition, this technology allows for periodic registration updates.

Despite these recent advances in the use of geotechnologies applied to mapping environmentally protected areas, gaps persist related to positional quality and the reliability of declarative data, often associated with the absence of detailed technical surveys and the dependence on medium-resolution images (Melo, 2020; Oliveira et al., 2020). These gaps are mainly due to the lack of standardization of procedures for the use of geotechnologies in mapping environmental areas, the level of positional accuracy required, and the definition of instruments for controlling the positional quality of the cartographic products used. Thus, this lack of standardization has contributed to the occurrence of geometric inconsistencies, such as overlapping areas and discrepancies in the delimitation of APPs, compromising the reliability of the cadastre as a territorial management tool.

Regarding the quality of environmental mapping, it is noted that the Accuracy and Precision Standard for Digital Cartographic Products (PAP-PCD), established by the Technical Specification for Quality Control of Geospatial Data (ET-CQDG) (Brazil, 2016), in accordance with Decree-Law No. 89,817/1984 (Brazil, 1984), remains underutilized, despite its ability to guarantee traceability, comparability, and reliability of cartographic products.

In this context, this work aims to evaluate the feasibility of using UAVs in mapping rural properties to meet the requirements of the CAR (Rural Environmental Registry), with an emphasis on analyzing the positional accuracy of the generated cartographic products, integrating aerial photogrammetry with UAVs, GNSS/RTK positioning, and normative evaluation based on the PAP-PCD. Additionally, it seeks to contribute to the standardization of procedures for mapping environmental areas for the CAR, given the potential of mapping with UAVs.

Methodological approach

The mapping involved the following steps: i) planning the aerial survey; ii) establishing control and verification points; iii) capturing and processing UAV images; iv) quality control of cartographic products.

Aerial Survey Planning

The study area corresponds to a rural property of 21.95 hectares, with a perimeter of 1,933.55 meters, located in the Ribeirão da Laje region, municipality of Coaraci, Bahia, Brazil (Figure 1). Located in the Southern Coastal territory, composed of 27 municipalities within the Atlantic Forest, Pre-Coastal Plateau, Coastal Plateau, and Recôncavo-Tucano Sedimentary Basin biomes (Mota, 2022), the site was selected due to the presence of native vegetation, Legal Reserves, Permanent Preservation Areas, and agricultural areas. The choice also considered easy access, proximity to the urban area (~4 km), and the fact that it complies with the legislation on airspace use (DECEA, 2020). Furthermore, it is a property with occupation prior to the temporal landmark of July 22, 2008, the date established in the Federal Constitution for the characterization of consolidated rural areas (Brazil, 2012).

The UAV used in this study was the DJI Phantom 4 Pro model, classified as Class 3 by the National Civil Aviation Agency (ANAC), with a maximum takeoff weight of up to 25 kg. Operations were performed in VLOS (Visual Line-of-Sight) mode, ensuring that the pilot maintained direct visual contact with the UAV, without the use of lenses or other devices (ANAC, 2017). The documentation required for the flight included aircraft registration with ANATEL, pilot registration with DECEA, and a flight authorization request via SARPAS. The flight request included the submission of the area polygon in .KML format, indicating the date, time, flight altitude (up to 120 m) and operating radius (400 m) (DECEA, 2020). The flight plan was generated in the DJI Pilot application (version 2.5.1.15) (DJI, 2022), where the parameters for image capture were defined: altitude of 120 m, flight line azimuth of 0°, takeoff and landing points, longitudinal overlap of 80% and lateral overlap of 70%, and a buffer of 20 m.

Implementation of Control and Verification Points

To ensure accuracy and quality control of the aerial survey cartographic products, Control Points (CPs) and Verification Points (VPs) visible in the images were established in the field. Figure 1 shows the spatial distribution of these points, and Figure 2 illustrates the steps involved in establishing the CPs and VPs, which consisted of materializing and positioning the points.

The materialization was provisionally performed with ~100 grams of plaster in the shape of a cross, to ensure adequate visual contrast (white on the green of the grass). The

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ISSN 1679-9860

positioning was performed by the GNSS/RTK system, in which two receivers collect data from GNSS satellites simultaneously, one installed at a base station with known coordinates, and the other at a mobile station (CPs and VPs) where the coordinates are to be determined; in real time, error corrections sent from the base station to the mobile station ensure high accuracy in positioning.

Figure 1 - Location map of the study area with the distribution of Control Points (CPs) and Verification Points (PVs) used in the Aerial Survey with ARP, Coaraci/BA – Brazil. UTM Coordinate System, Time Zone 24 South.

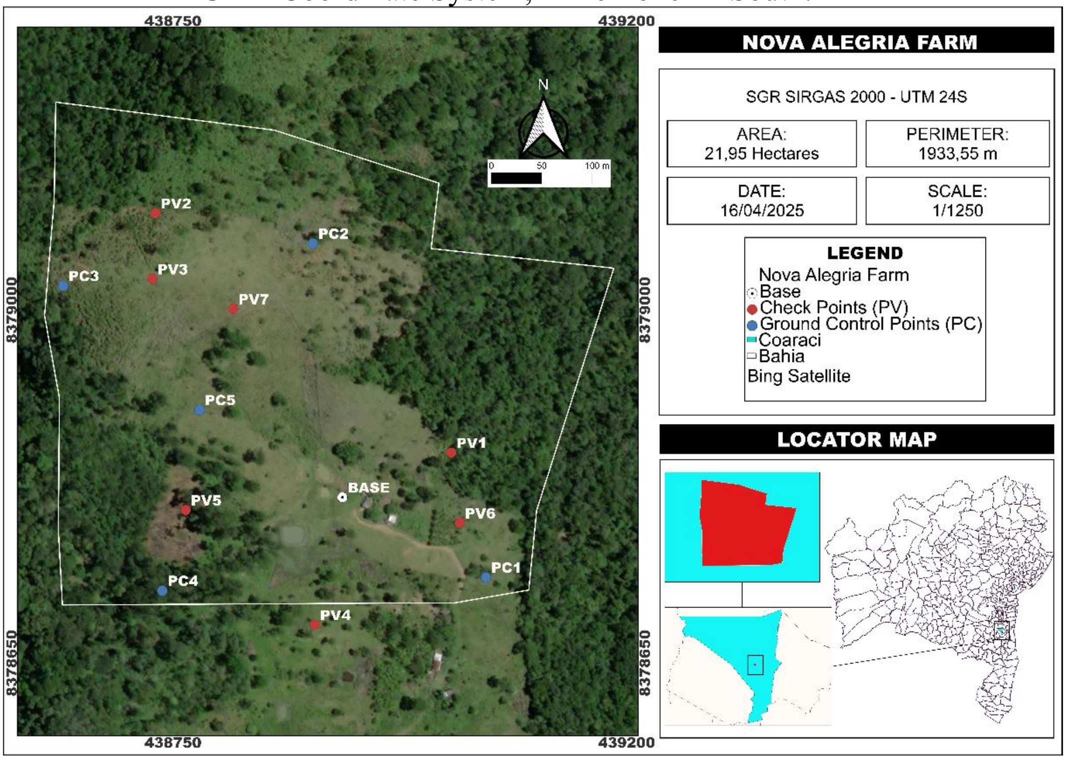
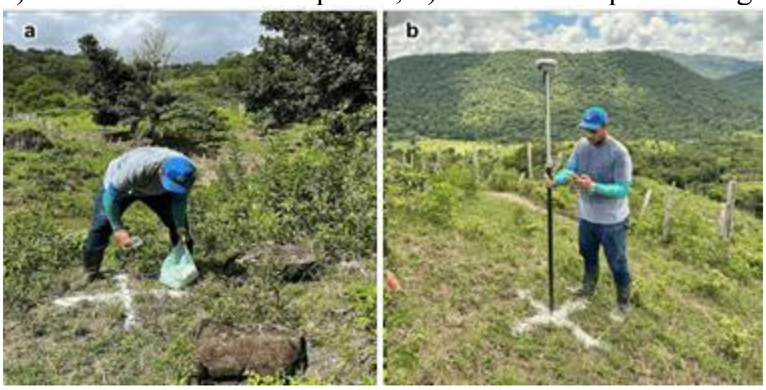


Figure 2 - Illustration of the implementation steps of Control Points - PC and Verification Points - PV: a) materialization of the points; b) GNSS/RTK positioning of the points.



The base station was materialized in the area and its coordinates were determined using the IBGE's Precise Point Positioning method (IBGE-PPP), being georeferenced to the SIRGAS2000 system. In the field, two CHC i90 model GNSS/RTK receivers were used, with dual frequency and nominal horizontal accuracies of 8 mm ± 0.5 ppm RMS and vertical accuracies of 15 mm ± 0.5 ppm RMS.

The geometric heights (h), obtained by the GNSS/RTK system, were converted into normal heights (H), referenced to the Mean Sea Level (MSL) of the Brazilian Geodetic System (SGB), by the IBGE's hgeoHNOR2020 (N) geoid model, by:

$$H = h - N \tag{1}$$

The normal height error (s_H) was estimated by the variance propagation of the geometric height error (s_h), determined in the GNSS/RTK positioning, and the geoidal height error (s_N), estimated in the geoidal model, by:

$$s_H = \sqrt{s_h^2 + s_N^2} \tag{2}$$

ARP image capture and processing

The aerial survey operation for capturing images used the DJI Pilot application (version 2.5.1.15), into which the flight plan with the parameters previously defined in the aerial survey planning stage was imported. Image acquisition was carried out under favorable weather conditions, with sunny weather, low cloud cover, and reduced wind intensity, seeking to minimize atmospheric interference and aircraft oscillations during flight. In addition, the survey was conducted during a period of good solar incidence, reducing the presence of excessive shadows and favoring the radiometric uniformity of the captured images. These conditions are important to ensure higher visual quality of the images, better correspondence between homologous points, and greater precision in photogrammetric processing. During the operation, operational safety procedures and flight protocols established for UAVs were observed, ensuring aircraft stability and the continuity of image acquisition throughout the entire study area.

Aerial photogrammetric processing was performed using the free software WebODM, which allows for the visualization, storage, and analysis of data (Vacca, 2020; Patel et al., 2024).

Initially, the images underwent photogrammetric alignment and automatic camera calibration, allowing for the identification of homologous points between consecutive photographs. Subsequently, the software generated a sparse point cloud, which was later densified by automatically matching points in overlapping images using the Structure from Motion (SfM) technique. Following this, digital models and a georeferenced orthomosaic were produced, with geometric and radiometric correction of the images. WebODM also performed spatial adjustment of the images based on the Control Points (CPs) inserted during processing, contributing to increased positional accuracy of the generated cartographic products. As a result, products such as orthomosaic, DEM, dense point cloud and technical report containing information on accuracy, spatial resolution and processing parameters were obtained (Vacca, 2020; Patel et al., 2024 WebODM, 2024).

The System for Motion (SfM) approach has been widely adopted in photogrammetry with UAVs due to its robustness in three-dimensional reconstruction from highly overlapping images, allowing the generation of dense point clouds and high-resolution terrain models (Westoby et al., 2012; Vacca, 2020; Patel et al., 2024). This technique is based on the automatic identification of common features in multiple images obtained from different perspectives, making it possible to simultaneously estimate the scene geometry and the camera position during image acquisition. In environmental and cartographic applications, SfM offers advantages related to low operational cost, high spatial resolution of the generated products, and flexibility in data acquisition in hard-to-reach areas. Furthermore, the integration between UAVs and SfM has significantly contributed to the development of faster and more detailed topographic and environmental surveys, favoring analyses of relief, land use and land cover, environmental monitoring, and three-dimensional modeling of the Earth's surface.

Quality control of cartographic products

The evaluation of the geometric quality of the orthomosaic and the DEM was performed based on the verification points (VPs) positioned by the GNSS/RTK survey, which were not used in the model generation or adjustment process, thus ensuring their statistical independence. For the calculation of the Positional Accuracy Standard of Digital Cartographic Products (PAP-PCD), in both the planimetric and altimetric components, the procedure proposed in the Technical Specification Standard for Quality Control of Geospatial Data (ET-CQDG) (Brazil,

2016) was used. Initially, the verification points are selected, which must be clearly identifiable on the ground. Subsequently, the errors in each planimetric (ex and ey) and altimetric (ez) component are calculated for the set of points considered, using:

$$ex = Xt - Xr$$
$$ey = Yt - Yr$$
$$eh = Zt - Zr \quad (3)$$

where “t” are the product points to be tested (ARP) and “r” are the reference (control) points, surveyed with GNSS receivers. Subsequently, the horizontal component of the errors (e_{H_i}) is calculated for each point “i” of the sample, by:

$$e_{H_i} = \sqrt{{e_{x_i}}^2 + {e_{y_i}}^2} \quad (4)$$

Next, the Root Mean Square Error (RMSE) of the sample errors is calculated using:

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{n}(e^2{}_{H_i})}{n}} \quad (5)$$

Where, n is the number of samples.

Finally, each value of e_{H_i} is compared with the Maximum Error (ME) for each class (A, B, C, D) contained in the ET-CQDG standard. The product is considered compliant where at least 90% of points have an error lower than the ME. If no value is found, the result will be "non-compliant". The value of RMSE is also compared with the Standard Error (SE) contained in the standard for the identified class. If it is smaller, the result is the class found. If it is larger, the PEC table is used until a smaller value is found or, if none is found, the result will be "non-compliant" (Brazil, 2016).

Results and discussions

Control and Verification Points

The fieldwork lasted approximately three hours, two of which were dedicated to the placement of the control points (PCs) and verification points (PVs), and one to the preparation and execution of the overflights. During the aerial survey, 423 images were captured, distributed across two flights. For the positioning of the PCs and PVs, the BASE Station installed in the mapping area had its geodetic coordinates determined with an accuracy of 0.007 m in E, 0.002 m in N, and 0.070 m in h (geometric altitude) using the IBGE's PPP method. The set of PCs and PVs presented average accuracies of 0.011 m in E, 0.009 m in N, and 0.072 m in h using the GNSS/PPK method, that is, in relation to the BASE station, considering the propagation of variances from the BASE station to the PC and PV points. The geoidal height used in the conversion of geometric altitude to normal altitude (Equation 1) was -9.550 m, and the respective estimated error was 0.070 m. Thus, according to Equation 2, the normal altitude of the BASE Station had an accuracy of 0.100 m (0.072 m from the geometric altitude and 0.070 m from the geoidal height).

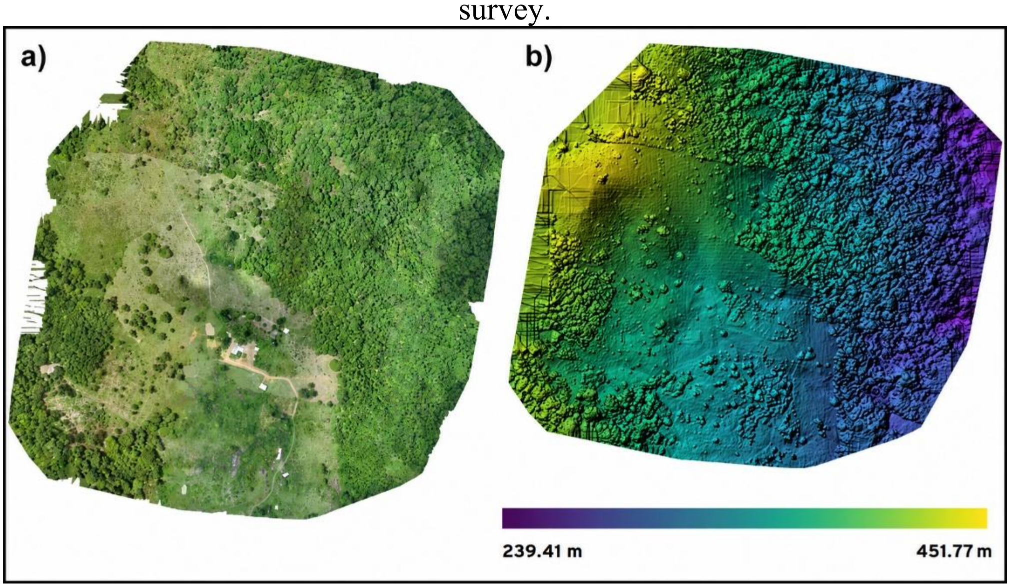
These results are consistent with the literature, in which GNSS/RTK surveys show an accuracy of a few centimeters in cadastral mapping applications (Ferreira et al., 2016; Souza, 2023), confirming the robustness of the method adopted. In addition, the use of PPP-IBGE processing for defining the base station contributes to the geodetic consistency of the data, ensuring compatibility with the Brazilian Geodetic System (SGB).

Orthomosaic and DEM generation

Figure 3 (a and b) shows the orthomosaic and DEM generated in the aerophotogrammetric processing of the aerial survey images. The processing in the WebODM software performed the reconstruction of images with the following characteristics: the total processing time was 2 hours and 32 minutes; of the 277 images captured by the UAV, 274 were processed (98.9%); in the reconstruction of the sparse point grid, 248,579 points were predicted, with 92.8% processed; the reconstruction of the dense point grid generated a total of 38,369,500 points; a total of 11,623 terrain features were detected; the GSD of the processing was 7.0 cm/pixel.

According to Teixeira et al. (2024), the GSD has an inversely proportional relationship to the level of detail of the survey, such that a smaller GSD provides better spatial resolution, i.e., greater detail, this being a critical parameter for the accuracy of the aerial survey. Thus, a GSD of 7.0 cm/pixel (decimetric) is suitable for the proposed purpose of aerial photogrammetry. The DEM in Figure 3 (b) shows an altimetric range of 212.36 m, with variations between 239.41 m (blue tones) and 451.77 m (yellow tones).

Figure 3 – (a) Orthomosaic and (b) Digital Elevation Model (DEM) derived from the aerial survey.



Quality control of orthomosaics and MDEs

Table 1 presents the planimetric and altimetric discrepancies obtained from the seven independent PVs used in the accuracy assessment of the orthomosaic and DEM generated by the aerial survey with UAV. The planimetric discrepancies had a mean of 0.202 m and a standard deviation of 0.024 m, while the altimetric discrepancies had a mean of 0.078 m and a standard deviation of 0.152 m. The maximum values observed were 0.219 m in planimetry and 0.264 m in altimetry, with amplitudes of 0.061 m and 0.417 m, respectively. The RMSEs were 0.203 m for the planimetric component and 0.160 m for the altimetric component.

In general, the RMSE values indicate geometric consistency of the generated products, with performance compatible with decimetric resolution surveys.

However, partially contradicting what was expected by photogrammetric and geodetic theory (Westoby et al., 2012; James; Robson, 2014), the results showed a planimetric RMSE higher than the altimetric RMSE. This result may be associated with the identification stage of the geometric centers of the PV targets in the images captured by the UAV, probably due to the low contrast of the cross-shaped plaster targets in relation to the terrain. However, the GSD of 7.0 cm/pixel indicates that the planimetric RMSE (0.203 m) was between 2 and 3 pixels, in accordance with results reported in the literature (Kulikovska et al., 2026; Janicki et al., 2026; Souza, 2023; Zimmerman et al., 2020). Therefore, to improve planimetric accuracy, it is recommended to use standardized high-contrast targets and a flight altitude that provides a lower GSD value.

Table 1 – Assessment of the accuracy of the orthomosaic and DEM through the discrepancies of the coordinates and altitudes at the Verification Points (VPs).

Statistics	Planimetric discrepancy (m)	Altimetric discrepancy (m)
Mean	0.149	0.082
Standard Deviation	0.029	0.167
Minimum	0.107	−0.173
Maximum	0.189	0.307
Range	0.082	0.480
RMSE	0.152	0.175

The positional accuracy assessment of the cartographic products, carried out based on the PAP-PCD criteria of the ET-CQDG standard (BRAZIL, 2016), indicated satisfactory performance for both the planimetric and altimetric components.

For the planimetric component, the RMSE value of 0.203 m made it impossible to classify it as Class A for the 1:1000 scale, since the value exceeds the Standard Error (SE) established for that class. However, when considering the 1:2000 scale, the product simultaneously met the Maximum Error (ME) and SE criteria, being classified as Class A at that scale. For the altimetric component, the RMSE value of 0.160 m was compatible with Class A for the 1:1000 scale, fully meeting the PAP-PCD criteria, with 100% of the points within the ME limit and RMSE lower than the SE. These results demonstrate that the cartographic products exhibit accuracy compatible with detailed-scale applications, such as those required in the CAR (Rural Environmental Registry). Compatible results have been reported in the literature, reinforcing the reliability of products generated from surveys with UAVs and geodetic methods (Bassanelli et al., 2026; Costa et al., 2023; Teixeira et al., 2024).

Land use and occupation, topography, and slope

Figure 3 presents the land use and land cover maps, contour lines, and slope maps, derived from the orthomosaic and DEM of the rural property. In the land use and land cover map (Figure 3.a), the yellow area occupied by pasture and the green areas accompanied by considerable fragments of native vegetation are highlighted. To a lesser extent, artificial dams

ISSN 1679-9860

(small blue areas), buildings (represented by orange squares with hatching), a spring (light blue circle), and a watercourse identified as Ribeirão da Laje (dark blue line) appear. A road (reddish-brown line) cuts through the property in a south-north direction, connecting the buildings. Furthermore, the contour lines in Figure 3(b) and the slope map in Figure 3(c) show that a large part of the terrain has slopes of less than 25°, with restricted areas showing higher slopes, suggesting little topographic limitation for productive activities.

Figure 3 – (a) Land use and occupation map; (b) Contour lines; and (c) Slopes derived from the orthomosaic and DEM of the rural property, respectively

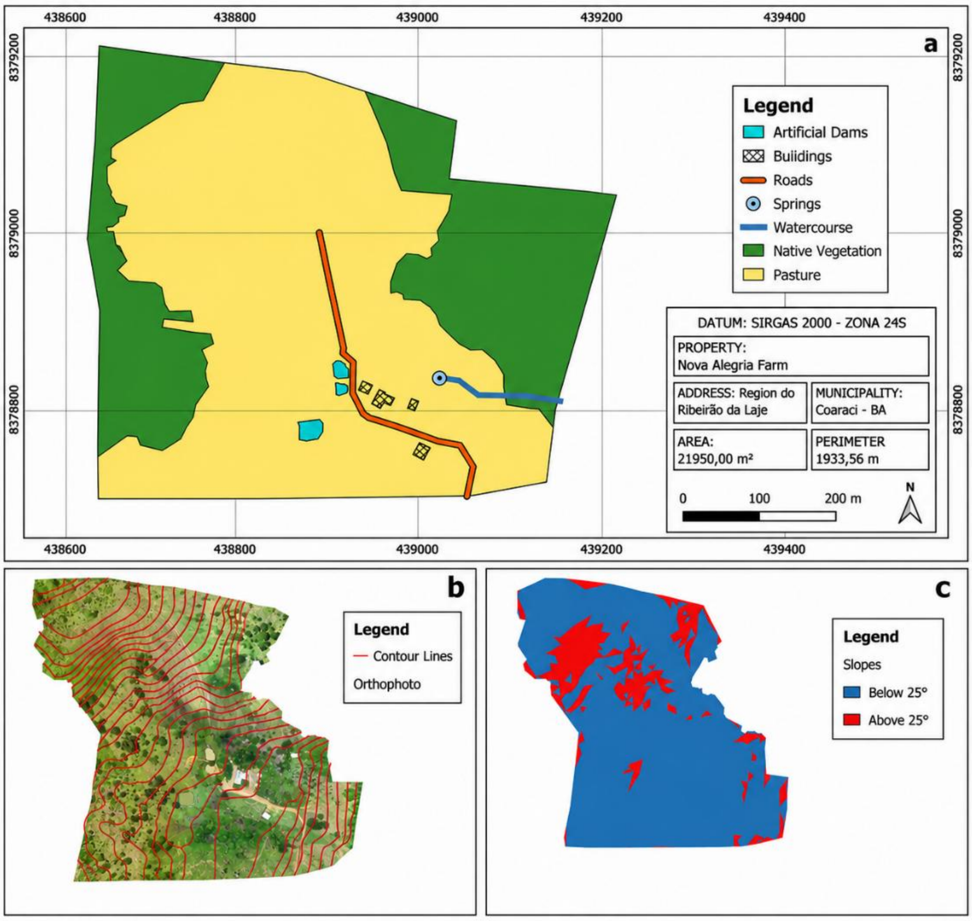


Table 2 presents the land use and land cover classes in the mapped area. The predominant class is Pasture, occupying 13,918 ha (63.41%), followed by Native Vegetation with 7,400 ha (33.71%). The other classes have less representation, including Watercourses with 0.438 ha (1.99%), Artificial dams with 0.075 ha (0.34%), Roads with 0.060 ha (0.27%), Buildings with 0.053 ha (0.24%), and Springs with 0.006 ha (0.02%), indicating that the area is predominantly used for agricultural purposes, with a significant portion still covered by natural vegetation.

Table 2 – Land use and occupation classes of rural properties.

Class	Area (ha)	Percentage (%)
Native Vegetation	7.400	33.71
Pasture	13.918	63.41
Building	0.053	0.24
Spring	0.006	0.02
Watercourse	0.438	1.99
Road	0.060	0.27
Artificial Dams	0.075	0.34

The integrated analysis of land use and occupation maps, contour lines, and slopes (Figure 3) reveals that the areas with the lowest slopes are located further south on the rural property, near the property's headquarters and natural resources, such as the spring and watercourse; and the steepest slopes are in the northern portion, near the top of the hill. This large variation in altitude occurs because the rural property is located within a watershed whose relief shows mountainous and steep characteristics (Rocha et al., 2017).

This land use and occupation pattern was also observed by Menezes and Dias (2019), who, when analyzing CAR data in the municipality of Jataí (GO), identified the coexistence between productive areas and remnants of native vegetation, highlighting the influence of legal requirements for maintaining RL on the spatial configuration of rural properties. In addition, recent studies indicate that this distribution is directly associated with both environmental legislation and the physical limitations of the terrain, especially relief and water availability, which condition anthropic occupation (Valente; Viera, 2025). Similar results were identified by Costa et al. (2023), who found greater preservation of environmental features in areas with greater topographic complexity, associating this condition with the operational limitations of agricultural use and greater susceptibility to environmental degradation. This behavior reinforces the direct relationship between slope, land use and environmental conservation, especially in properties located in more complex geomorphological contexts.

It is worth noting that the contour and slope maps were generated only in the production areas, because, considering only the slope criterion, these would be the areas that could be classified as protected - native vegetation areas and RL are already protected by law. Furthermore, since tree canopies influence the altimetric determinations of the terrain using UAV images, manual filtering was performed by removing the contour lines representing medium-sized trees. Thus, the need for manual filtering of contour lines due to vegetation interference highlights a significant limitation of UAV photogrammetry, related to the difficulty of representing the real topographic surface in areas with tree cover.

This behavior was also discussed by Zimmerman et al. (2020), who highlight the influence of vegetation on altimetric accuracy and relief reconstruction, since the models generated often represent the surface of the canopies and not the terrain. Thus, although UAVs provide high spatial detail, their application in areas with dense vegetation cover requires complementary filtering procedures or integration with other techniques to ensure greater geomorphological fidelity.

In this context, studies based on geotechnologies applied to the CAR demonstrate that inaccuracies in slope modeling can result in errors in the delimitation of APP, compromising the effectiveness of the environmental registry (Garcez; Bono, 2023). Thus, the use of products derived from UAVs, with higher spatial resolution, tends to reduce these uncertainties when compared to methods based on medium-resolution orbital images.

CAR environmental units

Table 3 presents the distribution of the mapped environmental unit classes, totaling an area of 21,950 hectares, corresponding to slightly more than 1 fiscal module, which characterizes the property as a consolidated rural area, as defined by Federal Law No. 12,651/2012 (BRAZIL, 2012). The Production class occupies the largest portion, with 13,159 ha (59.94%), indicating a predominance of productive use. Next, Legal Reserve covers 4,390 ha (20.00%), fulfilling its environmental conservation function, while Native Vegetation occupies 3,190 ha (14.53%), representing remnants of the original cover. The Permanent Preservation Areas (APPs) associated with the spring and watercourse were delimited according to legal parameters (BRAZIL, 2012): the spring APP, with a fixed radius of 50 meters, totaled 0.773 ha (3.53%); The riparian buffer zone was defined with a 15-meter strip,

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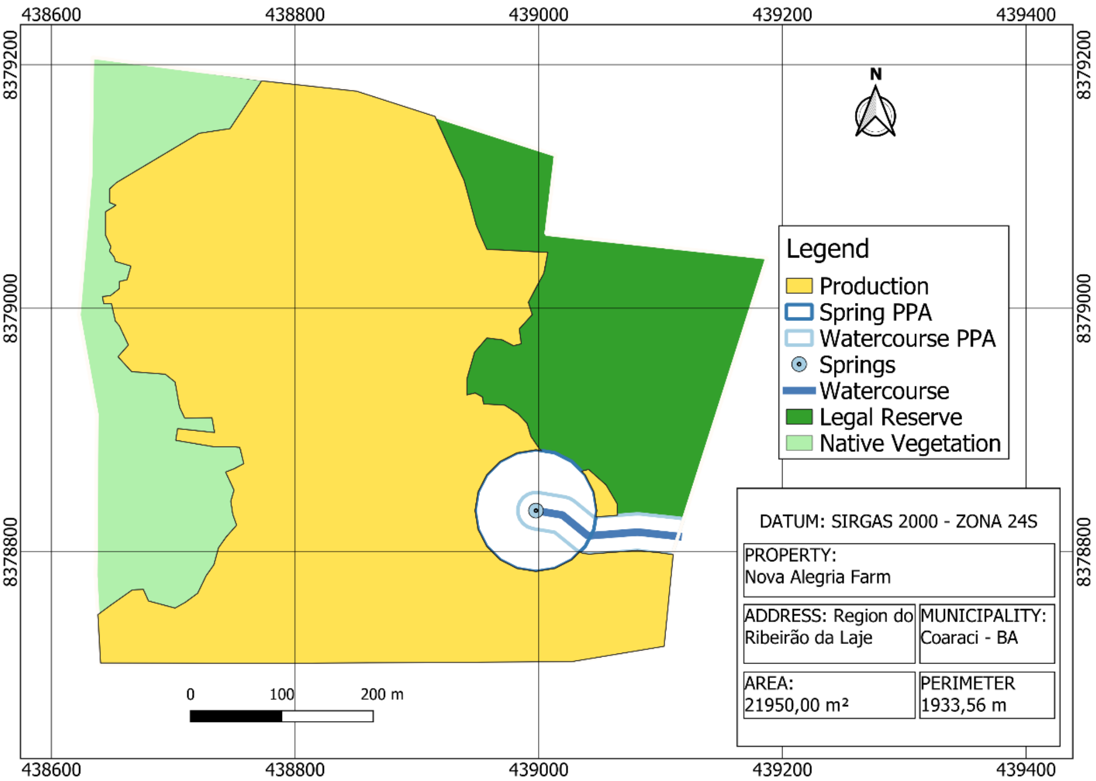
Jataí-GO | n 55 | maio-agos/2026
on-line GEO AMBIENTE
ISSN 1679-9860

as foreseen for properties between 2 and 4 fiscal modules, and corresponded to 0.438 ha (2.00%), being the smallest percentage class of the area. The map of environmental units is presented in Figure 4, where the area in yellow is highlighted as a production area, the dark green area as RL, and the light green area as native vegetation, in addition to the blue lines as riparian buffer zones for watercourses and springs.

Table 3 – Classes of environmental units according to the RER of the rural property.

Class	Area (ha)	Percentage (%)
Legal Reserve	4.390	20.00
Production	13.159	59.94
Spring PPA	0.773	3.53
Watercourse PPA	0.438	2.00
Native Vegetation	3.190	14.53
Total	21.950	100.00

Figure 4 – Map of environmental units according to the CAR of the rural property.



However, it is important to note that the CF establishes criteria for delimiting riparian buffer zones on hilltops, mountains and mountain ranges with a minimum height of 100 meters and an average slope greater than 25°, from the contour line corresponding to two-thirds of the total elevation, considering as a base plains, adjacent water bodies or saddle points (Brazil, 2012). Thus, the slope map in Figure 3(c) was classified into two ranges: below and above 25°, where it can be observed that slopes below 25° predominate in pasture areas with less vegetation cover. However, the study area has high topographic complexity, which made it difficult to determine the minimum height of 100 meters for defining hilltops – the study area is located in a geomorphological unit classified as a sea of hills, typical of the Atlantic Plateau, composed of rounded and strongly dissected elevations (Resende et al., 2022). Therefore, the elaboration of the environmental unit map considered only the other categories of APP, legally defined and spatially identifiable.

Therefore, defining environmental areas that involve the topography of the terrain is technically complex, requiring a clear geomorphological reference. Guimarães and Moreira (2018) criticize the applicability of the fixed altimetric criteria foreseen by the legislation, observing that their adoption may imply the virtual extinction of APPs (Permanent Preservation Areas) in regions with dissected relief, such as the Zona da Mata region of Minas Gerais, a region morphologically similar to the area studied.

Proposal for Standardization of mapping with ARP for CAR

The results of this study contribute to solving the gap in delimiting and validating the boundaries of environmental areas for the CAR (Rural Environmental Registry), by presenting a methodology for integrating aerial photogrammetry with UAV, GNSS/RTK positioning, and normative evaluation through PAP-PCD. The results of the case study demonstrate that the cartographic products meet the established criteria for topographic maps at the detailed scale. The incorporation of this methodological approach can contribute to greater technical rigor, standardization, and comparability of results, fundamental aspects for applications aimed at land and environmental regularization.

Thus, it is proposed that environmental mapping for the CAR be structured from a standardized methodology based on the integration between: i) aerial photogrammetry with UAV; ii) geodetic control by GNSS/RTK; iii) photogrammetric processing with orthomosaic and Digital Elevation Model (DEM) generation; and iv) positional quality control based on PAP-PCD. This approach would allow establishing objective criteria for validating the geometric quality of the products used in the environmental registry. From this perspective, it is recommended that future technical regulations concerning the CAR (Rural Environmental Registry) include, at a minimum:

- Definition of minimum spatial resolution (GSD) standards for cartographic products.
- Requirement for geodetic control in the field using high-precision GNSS.
- Standardized criteria for the distribution of Control Points (CPs) and Verification Points (VPs).
- Mandatory evaluation of positional accuracy based on PAP-PCD.
- Definition of the minimum cartographic scales suitable for each type of environmental application.
- Standardization of photogrammetric processing procedures and generation of derived products.
- Establishment of traceability protocols and metadata for the surveys carried out.

Additionally, the adoption of normative standards for positional quality would significantly contribute to increasing the legal security of declared environmental information, reducing land conflicts and territorial inconsistencies in SICAR. This aspect is particularly relevant considering that the precise delimitation of protected areas has direct implications for environmental regularization, inspection, environmental compensation, the carbon market, and territorial planning.

Another relevant aspect refers to the possibility of periodically updating environmental registries through new aerial surveys with UAVs. Unlike static cartographic bases or medium-resolution orbital images, the high temporal resolution of this technology allows monitoring changes in land use and land cover, expanding the potential of the CAR as a dynamic instrument for environmental monitoring.

Therefore, the results obtained in this study demonstrate that the integration between UAVs, GNSS/RTK, and normative assessment based on PAP-PCD constitutes a technically robust alternative to support the standardization of environmental mapping applied to the CAR. This proposal contributes to filling an important methodological gap that still exists in the

Brazilian environmental registry, promoting greater technical rigor, cartographic reliability, and effectiveness in the territorial and environmental management of rural properties.

Final Considerations

- This case study demonstrated that the use of UAVs, associated with GNSS/RTK positioning and assessment based on PAP-PCD, constitutes a robust and technically reliable approach for mapping rural properties for the CAR (Rural Environmental Registry). The generation of orthomosaics and DEMs enabled the obtaining of high spatial resolution cartographic products, allowing the detailed identification of relevant environmental features, such as native vegetation areas, RL (Legal Reserve), watercourses, springs, production areas, and slope variations, essential elements for the proper delimitation of environmental units required by law.
- In comparative terms, the methodology adopted showed superior performance to methods based on medium-resolution orbital images presented in the literature, especially with regard to the precise delimitation of small environmental features. The high spatial resolution of the orthomosaics (GSD), associated with geodetic control in the field, contributed to the reduction of uncertainties in the identification of legally protected areas, increasing the quality and reliability of the data entered in the environmental registry. The classification of cartographic products in Class A of the PAP-PCD criteria indicates that the products have adequate geometric consistency for detailed-scale applications, reinforcing their reliability for use in the CAR (Rural Environmental Registry).
- However, some limitations should be considered. The application of the methodology requires initial investment in equipment, technical training, and computational infrastructure. Additionally, surveying extensive areas may require multiple missions, increasing costs and execution time. Future research should explore the incorporation of UAV models with direct georeferencing by PPK and RTK, multispectral sensors, automated classification techniques, and systematic sampling strategies, aiming to improve the accuracy, operational efficiency, and scalability of this methodology in different environmental and territorial contexts.
- Finally, it is noteworthy that this work contributes not only to the technical evaluation

of the application of UAVs in the CAR, but also to methodological advancement by integrating aerial photogrammetry, high-precision geodetic control, and normative evaluation based on PAP-PCD. This approach represents a significant step towards standardizing procedures for the positional validation of rural boundaries, filling a gap that still exists within the Brazilian environmental registry.

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Publisher: Universidade Federal de Jataí. Instituto de Geografia. Programa de Pós-graduação em Geografia. Publicação no Portal de Periódicos UFJ. As ideias expressadas neste artigo são de responsabilidade de seus autores, não representando, necessariamente, a opinião dos editores ou da universidade.

Contribuições dos autores: Filipe de Oliveira Santana: Coleta, elaboração, escrita, organização, análise dos dados, discussão e revisão; Marcelo Soares Teles Santos: Coleta, elaboração, escrita, organização, análise dos dados, discussão, revisão e orientação; Anderson Targino da Silva Ferreira: Escrita, organização, análise dos dados, revisão e tradução; Daniel Ramos dos Santos: Coleta e organização dos dados.

Financiamento: A presente pesquisa contou com apoio institucional da Universidade Federal do Sul da Bahia (UFSB), por meio da disponibilização de infraestrutura computacional para o processamento e análise dos dados. Os autores declaram que não receberam bolsas de pesquisa ou financiamento específico para a realização deste estudo.

Conflito de interesse: Os autores declaram que não possuem interesses financeiros ou não financeiros relevantes relacionados a este trabalho.