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Geoinformação e Sensoriamento Remoto em Geografia

Resources of Geographical Information Systems and open source database as a support to environmental surveillance for monitoring and detection of illegal deforestation

Recursos de Sistemas de Informações Geográficas e banco de dados de código aberto como um suporte à fiscalização ambiental para monitoramento e detecção de desmatamentos ilegais

Recursos de Sistemas de Información Geográfica y base de datos de código abierto como apoyo a la vigilancia ambiental para el monitoreo y detección de la deforestación ilegal

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ABSTRACT

The use of remote sensing images and freely available geographic information system tools for spatial analysis has enabled the development of successful actions by environmental inspection agencies. In this sense, the images made freely available by the Norwegian International Climate and Forest Initiative (NICFI) constitute an important database that enables the comparative analysis of environmental interventions in monthly periods. The objectives of this research considered the use of freely available geoprocessing resources and techniques, the application of supervised classification methods to the images, and the evaluation of the accuracy of the classification procedure, which allowed the validation of the methodology. An important conclusion of this research indicates the possibility of using open data, such as those made available on the Planet platform (free for tropical regions through NICFI), as well as the growing availability of open-access software, providing satisfactory results in increasingly diverse environmental analyses.

Keywords: Free orbital imagery; Thematic classification; Thematic accuracy; Geoprocessing; Open-source software

RESUMO

A utilização de imagens de sensoriamento remoto e de ferramentas gratuitas de sistemas de informações geográficas para análises espaciais têm proporcionado o desenvolvimento de ações exitosas pelos órgãos de fiscalização ambiental. Nesse sentido, as imagens disponibilizadas gratuitamente pela Norwegian International Climate and Forest Initiative (NICFI) constituem um importante banco de dados que viabiliza a análise comparativa de intervenções ambientais em períodos mensais. Os objetivos da presente pesquisa consideraram o emprego de recursos e técnicas de geoprocessamento disponibilizadas de forma gratuita, a aplicação de métodos de classificação supervisionada nas imagens, além da avaliação da acurácia do procedimento de classificação que permitiu a validação da metodologia. Uma importante conclusão da presente pesquisa indica a possibilidade de usar dados abertos, tais como os disponibilizados na plataforma da Planet (gratuitos para regiões tropicais através da NICFI), bem como a crescente disponibilização de softwares de livre acesso, proporcionando resultados satisfatórios em análises ambientais cada vez mais diversificadas.

Palavras-chave: Imagens orbitais gratuitas; Classificação temática; Acurácia temática; Geoprocessamento; Programas de código aberto

RESUMEN

El uso de imágenes satelitales y herramientas gratuitas de sistemas de información geográfica para el análisis espacial ha permitido el desarrollo de acciones exitosas por parte de las agencias de supervisión ambiental. En este sentido, las imágenes disponibles de modo gratuito por la Norwegian International Climate and Forest Initiative (NICFI) constituyen una importante base de datos que permite el análisis comparativo de intervenciones ambientales en períodos mensuales. Los objetivos de esta investigación consideraron el uso de los recursos y de las técnicas de geoprocesamiento disponibles gratuitamente, la aplicación de métodos de clasificación supervisada a las imágenes y la evaluación de la exactitud del procedimiento de clasificación, lo que permitió la validación de la metodología. Una conclusión importante de esta investigación apunta la posibilidad de utilizar datos libres, como los puestos a disposición en la plataforma Planet (gratuitos a las regiones tropicales a través de NICFI), así como la creciente disponibilidad de software de acceso abierto, proporcionando resultados satisfactorios en análisis ambientales cada vez más diversos.

Palabras-clave: Imágenes satelitales libres; Clasificación temática; Exactitud temática; Geoprocesamiento; Programas de código abierto

1 INTRODUCTION

According to Ribeiro and Walter (2008) the Cerrado is the second largest biome in the Brazilian territory, surpassed only by the Amazon Forest. It covers extensive areas, increasing its vulnerability to deforestation, as well as to fires, favored by its typical phytophysiognomy consisting predominantly of shrubs and small sparse trees. As a result, some important strategies have been progressively employed by environmental inspection agencies to prevent environmental irregularities. Applications using remote sensing resources have been highlighted in identifying the suppression of native vegetation and forest fires, enabling preventive and repressive actions with great effectiveness, such as, for example, presented by Oliveira *et al*., (2017), Silva & Camelo (2024), Hong *et al*., (2025), Long *et al*., (2025) and Wang *et al*., (2025).

The research developed by Fernandes (2019), in the study area of the Metropolitan Region of Belo Horizonte - MG, applied artificial neural network techniques in conjunction with geographic information system resources to produce thematic fire prediction maps monthly. The results submitted to Person's p test for thematic validation produced satisfactory statistical indices.

In turn, the monitoring of deforested areas based on remote sensing resources still requires additional actions, as it is a type of intervention in natural environments with dynamic characteristics that make it difficult for the immediate response of environmental inspection agencies. Some of these difficulties are due to the extent of the affected vegetative areas (demanding better spatial resolution images), the speed of vegetative suppression actions (demanding better temporal resolution of the remote sensor), the leaf senescence of the vegetation, difficult access to places of unauthorized interventions, among others. In view of these aspects, environmental inspections still frequently resort to field reconnaissance, either to quantify the suppression of vegetation or to estimate the woody yield resulting from the environment infraction.

Given this context, there is clearly a significant demand for the improvement of techniques and availability of tools for analyzing spatial data that can optimize the use of scarce human resources and the few logistical means available to deal with this important environmental issue. Thus, the use of remote sensing images made available, free of charge, by the Norway International Climate and Forestry Initiative (NICFI, 2025) through the Planet Explorer and Basemap Viewer platforms, becomes an important alternative to subsidize the development of new research. Thus, the main objective of this work is to demonstrate the effectiveness of tools embedded in Geographical Information Systems in association with open source databases as an important support to environmental surveillance for monitoring and detection of illegal deforestation. The importance of studies like the one conducted in this research is somewhat self-explanatory, given the current level of high degradation that is increasingly spreading across all natural environments on the planet. Paradoxically, this degrading environmental situation contrasts with the increasingly consistent evidence, not only through science but mainly through common sense in society, that the need to preserve environmental resources is truly urgent, as otherwise it could jeopardize the very existence of humanity, as well as the future of the planet's biodiversity.

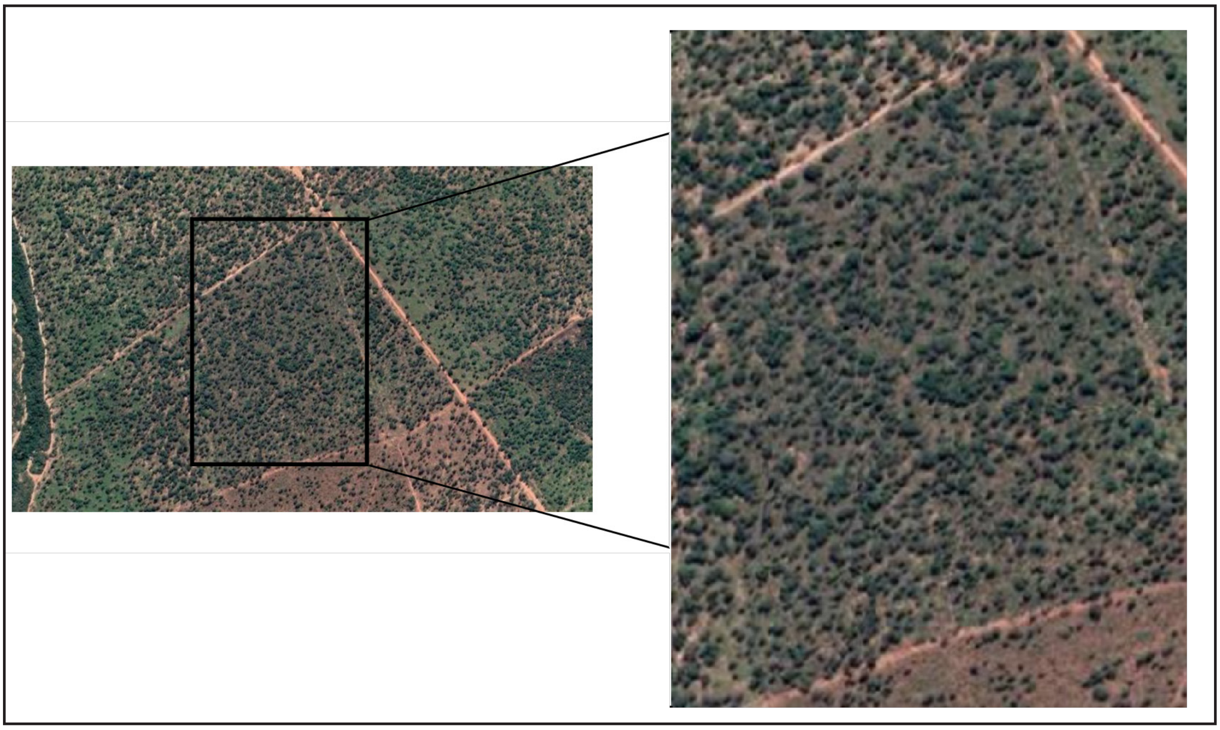
2 MATERIALS AND METHODS

2.1 Study Area

The deforestation polygon analyzed in this study is in the western part of the State of Minas Gerais (Brazil), where typical vegetation of the Cerrado biome predominates. The total area delimited in the study has about 51 hectares, presenting three different land cover classes: vegetation, deforestation and exposed soil.

The suppression of vegetation found in this case study occurred without authorization from the competent environmental agency, therefore the intervention in the natural environment resulted in the application of administrative penalties by the Military Police for the Environment of the State of Minas Gerais. However, in compliance with Law nº 13.709, of August 14, 2018 (General Law for the Protection of Personal Data – LGPD, Brasil, 2018), both the name of the municipality and the specific information on the location of the property cannot be disclosed. Thus, the location of the environmental violation will be generically called "Study Area", as shown in Figure 1.

Figure 1 – Study Area, located in the Cerrado biome, with the presence of trees distributed in a random pattern, without a continuous canopy



Source: Adapted from Google Earth (2025)

The polygon delimited in this study is a savanna formation who is the main phytophysiognomy is the Cerrado Strictu Sensu, characterized by the presence of arboreal and shrubby-herbaceous strata randomly distributed in different densities, without the formation of a continuous canopy.

One of the Infraction Notices referring to the illegal deforestation of this case study was drawn up by the Military Police for the Environment on July 1, 2021, describing the cutting of 76 trees sparsely distributed in the area without removing the vegetation material from the site. During the inspection, the characteristics of the trees felled were evaluated in order to determine the stage of the vegetation development (Figure 2).

Figure 2 – Visual characterization of individual suppressed trees

(a) (b) (c)

Source: Command of Military Police for the Environment of Minas Gerais state (2025)

2.2 Methods

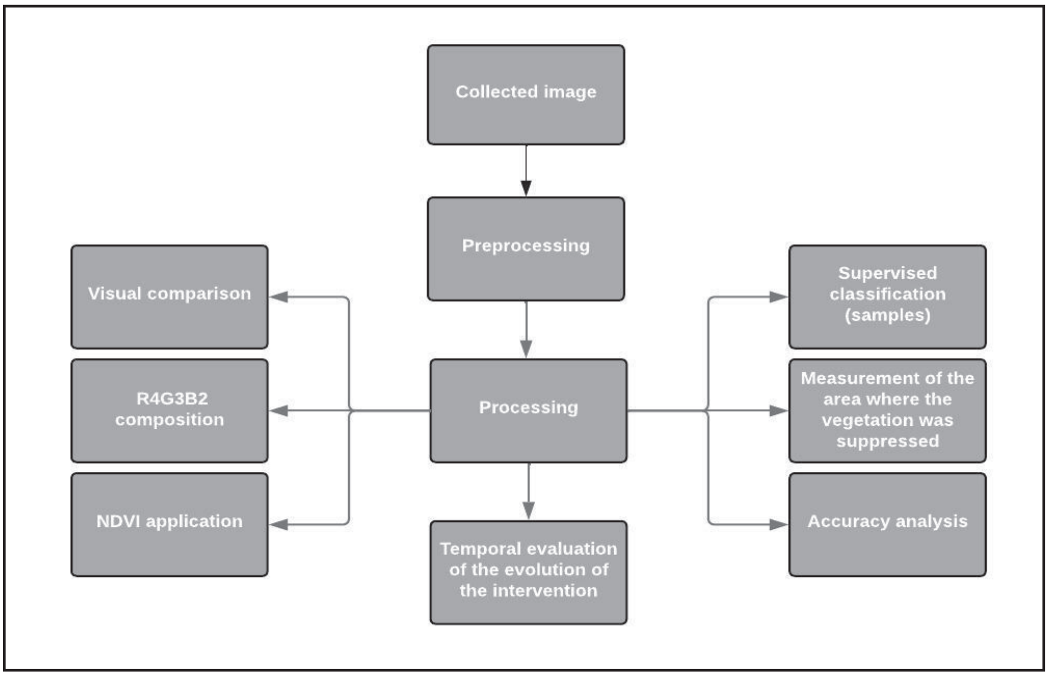
2.2.1 DATA AQUISITION

Three remote sensing orbital images were obtained at different times in the Cerrado biome study area. Each multispectral image is composed of four bands numbered as 1, 2, 3 and 4, corresponding respectively to blue, green, red and near infrared (NIR) spectra. The images cover data from May 28, June 30 and July 31, 2021, obtained through the "Planet Explorer" and "Basemap Viewer" (NICFI, 2025) platforms for monitoring changes in tropical forests, available free of charge through a prior registration on the platform. Technical specifications of NICFI data: scan cover area for global tropical regions, spatial resolution: 4.77 m, spectral resolution for visual analysis in three bands: R (red), G (green), B (blue) and for multispectral analysis in four bands R (red), G (green), B (blue), NIR (near infrared), temporal resolution: coverage from December 2015 to August 2020 on a biennial basis and monitoring on a monthly basis from September 2020.

2.2.2 Methodological Procedures

The three main stages of the methodology adopted in the study consist of pre-processing, processing and temporal evaluation of the unauthorized intervention, according to the flowchart in Figure 3.

Figure 3 – Flowchart of methodological procedures



Source: The authors (2025)

In the pre-processing stage the data were previously subjected to radiometric calibration, conversion of the digital pixel values to normalized surface reflectance through atmospheric correction and geometric orthorectification procedures, the scenes available on the platform with the lowest cloud cover percentage in the monthly period were selected. Through computational procedures available in QGIS (QGIS, 2021), the selected images were clipped to the exact perimeter of the area where vegetation suppression occurred.

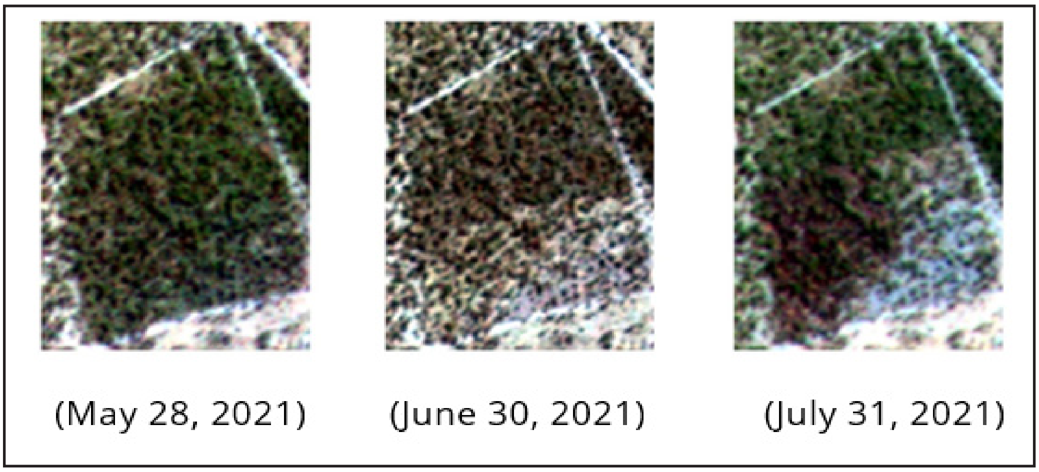
In the processing stage, the images were analyzed in three different ways: visually, the dynamics of the intervention evolution was investigated using the RGB432 false color composition of the bands, which provides a good enhancement of forested areas. Through the Normalized Difference Vegetation Index (NDVI) it was highlighted the vigor of the vegetation. In this case NDVI rendering has been changed to false color single band style, with a five-slice spectral color gradient. Then, the supervised classification of the images was performed using the Dzetsaka plugin (Karasiak, 2016) based on the Gaussian Mixture Model (GMM) classifier. In this process, 30 training samples were collected in each image so that ten training samples for each land cover class were acquired in order to enable the recognition of vegetation, deforestation and exposed soil areas.

To assess the thematic accuracy of the land cover classification map, the AcATaMa plugin (Llano, 2024) was used, applying the statistical method of sampling stratified by classes and selecting 292 randomly distributed sample points, which were analyzed by visual interpretation comparing an RGB image color composition with the map resulted from classification. This procedure made it possible to obtain the confusion matrix, the global accuracy and the Kappa index. Finally, the results obtained were analyzed to obtain a critical view of the temporal evolution of the unauthorized environmental intervention.

2.2.2.1 Visual Comparisson

As already explained in the data acquisition stage the three images for this study were collected at different periods, covering the same deforestation polygon. Through visual analysis relying on the interpretation of experienced environmental analysts, it was verified that the suppression of tree individuals occurred in a selective and superficial way, a technique known as clear cutting where the immediate removal of the roots close to the ground does not occur. This type of intervention has been a recurrent practice used by environmental offenders to make it difficult to recognize suppressed vegetation and prevent the measurement of the respective woody yield. As will be better emphasized in the discussion phase of the study results, the visual comparison of the images (Figure 4) in the analysis of the interventions allowed a better understanding of the evolution of the deforestation under study, allowing defining a more adequate strategy for the use of the classification technique.

Figure 4 – Visual comparison of the multitemporal images



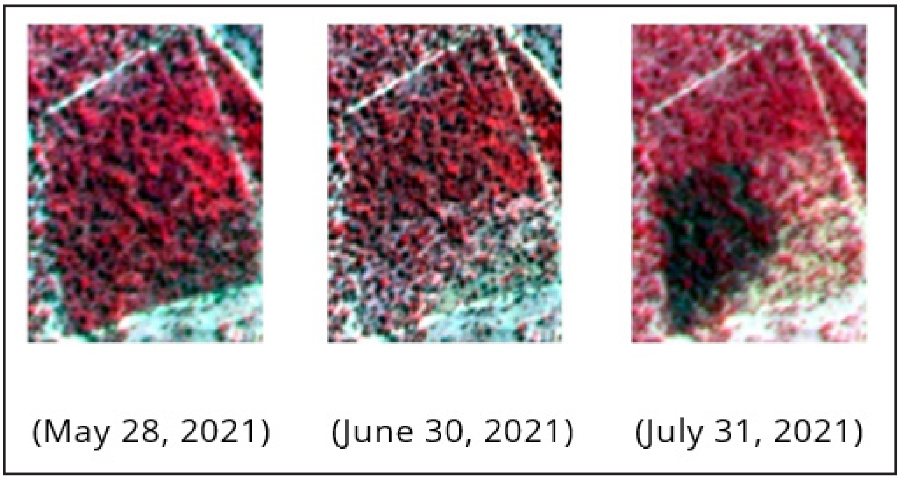
Source: The authors (2025)

For the identification and quantification of damage and valuations related to land use change, the supervised classification procedure of images was performed with the Dzetsaka plugin (Karasiak, 2016), installed in the QGIS program (QGIS, 2021). Previously, a vector layer was created containing 10 small contour polygons defining the training samples for each of the existing land cover classes.

2.2.2.2 RGB432 color composition

For a more accurate visualization of the different land cover features, a false color composition of the images was performed (Figure 5), adjusting the bands for the RGB channels: band 4 (NIR spectrum) associated to R channel, band 3 (red spectrum) associated to G channel and band 2 (green spectrum) associated to B channel.

Figure 5 – Color composition of image bands



Source: The authors (2025)

As shown in Figure 5 and as will be better emphasized in the discussion phase of the study results, this type of false color composition highlights the vegetation and treetops with shades of red, so that it can be identified in the last image collected on July 31, 2021, through the highlight given by a shade of dark color, the possible realization of burning in the study area.

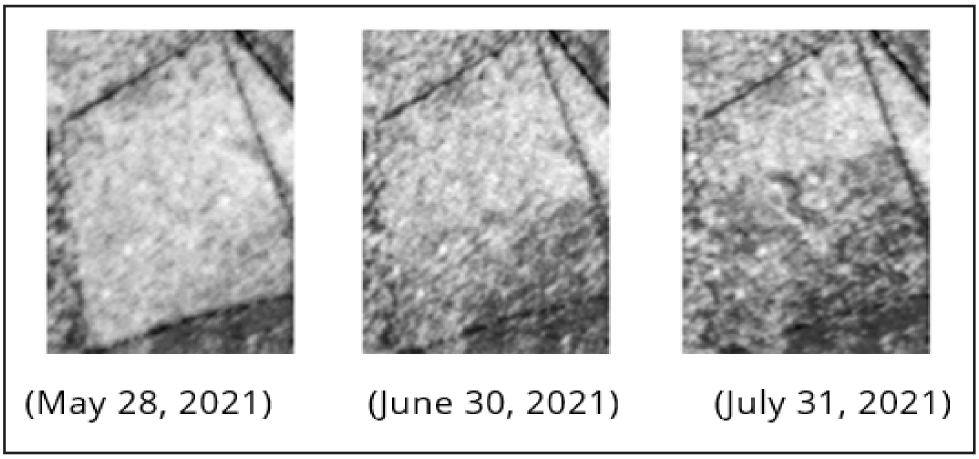
2.2.2.3 NDVI composition

The NDVI is a spectral index that highlights the spectral response of vegetation. It is calculated by the difference between the near infrared spectrum band and the red spectrum band divided by the sum of both bands. This index is widely used to demonstrate the differences between vegetation stages (under water stress, the stage of the life cycle, in addition to other vegetation strata) and other elements such as water bodies and exposed soil. Its value varies from -1 to 1, in such a way that the higher the value, the better the spectral response and, therefore, the greater the photosynthetic activity of the vegetation. NDVI applications are discussed in many scientific studies such as Pereira and Tavares Júnior (2017), Moraes *et al*., (2018), Cambraia Filho, Brites and Souza Bias (2020), the latter using images from Remotely Piloted Aircrafts (RPAs). Although there are many vegetation indices, NDVI is one of the most consolidated in general studies and has been the most used for investigations similar to that carried out in this research. Thus, the NDVI data were calculated from the infrared and red spectrum bands, as described in Equation 1:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$ Equation (1)

As will be better emphasized in the discussion phase of the study results and to demonstrate the suppression of vegetation in this area of the Cerrado biome highlighting the consequent increase in soil exposure, NDVI data were analyzed, as shown in Figure 6.

Figure 6 – NDVI data derived from remote sensing images

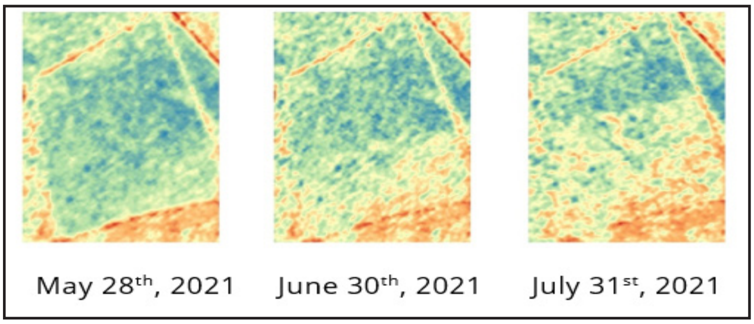


Source: The authors (2025)

2.2.2.4 False color single band enhancement

As will be better emphasized in the discussion phase of the study results and for a better visualization of the vegetation spectral response, the NDVI data derived from the images were sliced into five classes at equal intervals, as shown in Figure 7. Relying on the interpretation of experienced environmental analysts this representation favored the recognition of the vegetation based on the photosynthetic activity that is reflected in the response in the near infrared spectrum as well as highlighting areas of exposed soil.

Figure 7 – Images in false color single band composition

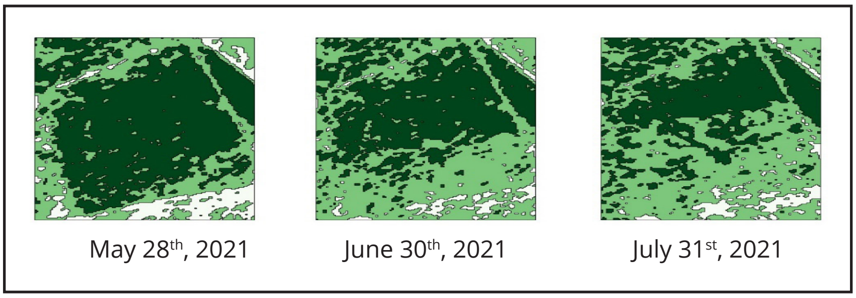


Source: The authors (2025)

2.2.2.5 Supervised classification

The supervised classification of all images was performed based on the Dzetsaka plugin, developed by Kasariak (2016), which uses the Gaussian Mixture Model (GMM) algorithm. As will be better emphasized in the discussion phase of the study results the classification results demonstrated a significant reduction in native vegetation represented in dark green and an increase in deforestation represented in light green, as shown in Figure 8.

Figure 8 – Temporal images showing the reduction of native vegetation and the progression of deforestation.



Souce: The authors (2025)

2.2.2.6 Assessment of thematic accuracy

In the present work, only Free Open-Source Software (FOSS) were used, which are computational resources of special interest for the scientific community, as discussed in Calamito (2017) and OSGeo (2019). The programs are integrated into

Geographic Information Systems environment, enabling vector and raster data processing, as well as the incorporation and development of programming codes in commercial or free languages.

An example of a FOSS application is the AcATaMa plugin version 24.10 (Llano, 2024), which is used in this research and integrated into the QGIS computational environment (QGIS, 2021). This application allows a random sampling design or proportional to the areas of the classes, where the user provides the sample size obtained according to the statistical theory of independent sampling, using the formulation presented in See *et al*., (2017) and Ariza-López (2002), according to Equation 2. Finally, by comparing the samples obtained from the classification map with reference data representative of terrestrial truth, it is possible to construct the confusion matrix and generate the global accuracy index.

$$n = \frac{{Z_{\alpha/2}}^{2} \,.\, p\,.q}{E^{2}} \qquad \text{Equation (2)}$$

where:

p: success probability; q: error probability (1-p); $Z_{\alpha/2:}$ critical value corresponding to the desired confidence level; E: error limit.

After obtaining the sample size, its spatial distribution and the data to compose the error matrix, the Kappa statistic is applied, which allows a comparative evaluation of the quality of maps obtained through remote sensing (Landis & Koch, 1977). The error matrix used for thematic accuracy analysis was built according to the model presented in Table 1, where the columns represent the reference data and the rows represent the classification map data. From this same error matrix, statistics are obtained for the Kappa index (Equation 3), global accuracy (Equation 4), producer accuracy (Equation 5) and user accuracy (Equation 6).

Table 1 – Error matrix model (4 x 4) used to assess the thematic accuracy

Classes	A	B	C	D	Sum of Rows
A	n11	n12	n13	n1k	n1+
B	n21	n22	n23	n2k	n2+
C	n31	n32	n33	n3k	n3+
D	n41	n42	n43	n4k	nK+
Sum of Columns	n+1	n+2	n+3	n+K	n

Source: Adapted from Congalton and Green (2009) and Santos et al., (2010)

– Kappa Index: $$\frac{\sum_{i=1}^{k} n_{ii} - \sum_{i=1}^{K} n_{i+} + n_{+i}}{n^2 - \sum_{1=1}^{K} n_i + n_{+1}}$$ Equation (3)

– Global Accuracy: $$\frac{\sum_{i=1}^{k} n_{ij}}{n}$$ Equation (4)

– Producer Accuracy: $$\frac{n_{ij}}{n_{+j}}$$ Equation (5)

– User Accuracy: $$\frac{n_{ii}}{n_{i+}}$$ Equation (6)

The quality of the classification, associated with the Kappa statistic values, can be evaluated according to Fleiss, Cohen and Everitt (1969), Congalton and Green (2019) based on Landis and Koch (1977) and Monserud and Leemans (1992) and demonstrated by Foody (2020) according to Table 2.

Table 2 – Accuracy levels of a classification, according to the Kappa index value

<table>
<tr><th></th><th></th><th>Congalton e Green (2019)</th><th>Fleiss, Cohen e Everit (1969)</th><th>Monserud e Leemans (1992)</th></tr>
<tr><td rowspan="7">Kappa</td><td>1,0</td><td>Almost Perfect</td><td rowspan="2">Excellent</td><td>Excellent</td></tr>
<tr><td>0,8</td><td>Substantial</td><td>Very Good</td></tr>
<tr><td rowspan="2">0,6</td><td rowspan="2">Moderate</td><td rowspan="2">Good Enough</td><td>Good</td></tr>
<tr><td>Sufficient</td></tr>
<tr><td>0,4</td><td>Sufficient</td><td rowspan="3">Poor</td><td>Poor</td></tr>
<tr><td>0,2</td><td>Light</td><td>Very Poor</td></tr>
<tr><td>0,0</td><td>Poor</td><td>None</td></tr>
</table>

Source: Adapted (FOODY, 2020)

3 RESULTS

3.1 Measurement of deforested areas

The area results obtained for the three different evaluated coverage classes are shown in Table 3.

Table 3 – Measurement of deforested areas (hectares)

Class	05.28.21	06.30.21	07.31.21
Vegetation	29.25	22.20	19.86
Deforestation	16.74	26.21	27.92
Exposed Soil	5.08	2.66	3.28
Total	51.07	51.07	51.07

Source: The authors (2025)

3.2 Thematic quality

Equation 2 was used to define the most appropriate sample size for assessing the thematic quality using the AcATaMa plugin, assuming the values for the variables p: 0,95; q: 0,05; $Z_{\alpha/2}$: 1,96; e E: 0,025.

Thus, a total of 292 sample points was reached and the division of points according to each class was adjusted according to the percentage of the corresponding area, as shown in Table 4.

Table 4 – Defined points for thematic quality assessment

Image Date	Defined Class	Area (ha)	Area (%)	Number of Points
28.05.21	Vegetation	29.25	57.28	167
	Deforestation	16.74	32.78	96
	Exposed Soil	5.08	9.94	29
30.06.21	Vegetation	22.20	43.47	127
	Deforestation	26.21	51.32	150
	Exposed Soil	2.66	5.21	15
31.07.21	Vegetation	19.86	38.89	114
	Deforestation	27.92	54.68	160
	Exposed Soil	3.28	6.43	19

Source: The authors (2025)

Finally, confusion matrices were constructed for each of the three classified images, according to the results presented in Tables 5, 6 and 7.

Table 5 – Confusion matrix - Image classification - 28.05.2021

Class	Vegetation	Deforestation	Exposed Soil	Total
Vegetation	160	7	0	167
Deforestation	9	84	3	96
Exposed Soil	0	2	27	29
Total	169	93	30	292

Source: The authors (2025)

Table 6 – Confusion matrix - Image classification - 30.06.2021

Class	Vegetation	Deforestation	Exposed Soil	Total
Vegetation	117	10	0	127
Deforestation	10	127	13	150
Exposed Soil	0	5	10	15
Total	127	142	23	292

Source: The authors (2025)

Table 7 – Confusion matrix - Image classification - 31.07.2021

Class	Vegetation	Deforestation	Exposed Soil	Total
Vegetation	23	2	1	26
Deforestation	4	124	7	135
Exposed Soil	0	13	118	131
Total	27	139	126	292

Source: The authors (2025)

For each of the three classified images, the global performance and the Kappa Index were calculated, obtained from Equation 3. The accuracy results obtained were very satisfactory and demonstrated a good performance of the methodology used in the work, as shown in Table 8.

Table 8 – General classification statistics

Classified Image	Global Accuracy	Kappa Index
05.28.21	92.82%	87.02%
06.30.21	86.97%	76.64%
07.31.21	90.94%	84.01%

Source: The authors (2025)

Producer and user accuracies, defined in Equations 5 and 6, were also calculated and are shown in Table 9.

Table 9 – Producer and user accuracy for image classification maps

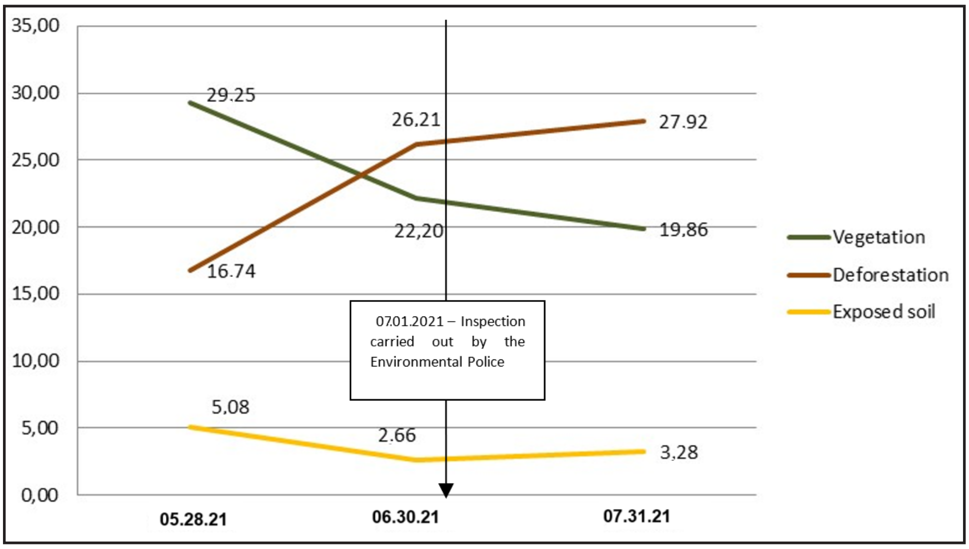
Image	Accuracy	Vegetation	Deforestation	Exposed Soil
05.28.21	Producer	94.67%	90.32%	90.0%
	User	95.80%	87.5%	93.10%
06.30.21	Producer	92.12%	89.43%	43.48%
	User	92.12%	84.67%	66.67%
07.31.21	Producer	85.18%	89.21%	93.65%
	User	88.46%	91.85%	90.08%

Source: The authors (2025)

3.3 Temporal evaluation of deforestation

The processing of remote sensing orbital images made it possible to verify that deforestation in the Study Area advanced significantly in the period from May 28 to June 30, reaching a percentage of 56.57%, equivalent to 26.21 hectares of the total deforested area. In the same interval, the clear cutting of tree individuals, a practice used by environmental offenders to carry out suppression, represented a reduction of existing native vegetation from 29.25 to 22.20 hectares. On July 1, 2021, there was an inspection carried out by the Environmental Policing at the site of deforestation, and the felling of 76 trees from the native vegetation of the Cerrado was verified. However, from the result of image processing, it was possible to verify that, after that date, there was a probable interruption of environmental interventions, since there was a decrease in the deforestation rate, as shown in Figure 9.

Figure 9 – Temporal assessment of deforestation in the study area



Source: The authors (2025)

As shown in Figure 6 (see item 2.3.2.3), there was fire in a portion of the study area which, in practice, may represent an alternative method of environmental intervention without direct suppression of vegetation. For the purposes of supervised classification, this change was included in the deforestation class.

4 CONCLUSIONS

The use of orbital images for evaluating environmental interventions has been an important strategy for optimizing the plans and responses in the work of environmental inspection agencies. In the present case study, it was verified that the spatial and temporal resolution of the data are decisive for these types of analyzes involving environmental violations, because the shorter the interval of availability of the images, the more effective the response against environmental violators. In this sense, the images made available free of charge by the Norwegian International Climate and Forest Initiative (NICFI, 2025), even though restricted to tropical forests with a monthly temporality, can become an important tool for monitoring and supervising deforestation due to their quality in terms of spatial and temporal resolutions.

For proper validation of the processes and to guarantee the reliability of the information processed from the images, it is essential to apply thematic quality assessment procedures so that the classification quality statistics reach satisfactory results. This was proved in the quality results obtained for estimating the Kappa index. In these validation phases, other quality estimation indices can be applied, such as Pearson's coefficient, data scatter analysis, in addition to others available. The tests can also be compared with images of better spatial resolution and compatible temporal resolution, as is the case of UAVs (Unmanned Aerial Vehicles) images, in order to consolidate the methodology used here.

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