RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

Integrated Application of TGI and NDMI to Identify Chemical Deforestation in the Pantanal, Brazil

Aplicação Integrada de TGI e NDMI para Identificação de Desmatamento Químico no Pantanal, Brasil

Jean Carlos Ferreira[*], André Pereira Dias[**], Joberth Firmino Gambati[***]

[*] Secretaria de Estado de Meio Ambiente do Estado de Mato Grosso – SEMA/MT, jeancarfloresta7@gmail.com
[**] Universidade do Estado de Mato Grosso – UNEMAT, andrefloresta@gmail.com
[***] Secretaria de Estado de Meio Ambiente do Estado de Mato Grosso – SEMA/MT, joberth.gambati@gmail.com

https://doi.org/10.5380/raega.v63i2.99972

Abstract

This study presents an innovative approach to detect and monitor chemical deforestation in the Brazilian Pantanal, presenting alarming impacts of aerial herbicide spraying on native vegetation. With the integration of the Triangular Greenness Index (TGI) and the Normalized Difference Moisture (NDMI) spectral indices applied to Sentinel-2A images, we identified characteristic patterns of chemical degradation in 158,776 hectares of wetlands and native vegetation formations in the Pantanal of Barão de Melgaço, Mato Grosso, that occurred between 2021 and 2023. The methodology developed demostrated high precision (89% accuracy) to discriminate between pesticide damage and other natural or anthropogenic disturbances, revealing specific spectral signatures and spatial patterns typical for aerial application. The results provided a crucial scientific evidence that support environmental inspection actions, culminating in the embargo of the affected areas and the application of fines and environmental recovery commitments. In addition to demonstrate the effectiveness of TGI-NDMI integration for environmental monitoring, this study warns on a new degradation frontier of tropical humid ecosystems, highlighting the urgency of specific public policies to regulate aerial spraying and protect these sensitive ecosystems. The approach developed presents itself as a strategic tool for environmental monitoring, allowing for the rapid detection and accurate assessment of large-scale damage, with potential application in other tropical biomes threatened by similar chemical deforestation practices.

Keywords:
Agrochemicals, Environmental degradation, Environmental monitoring, Spectral indices.

Resumo

Este estudo apresenta uma abordagem inovadora para detecção e monitoramento de desmatamento químico no Pantanal brasileiro, revelando impactos alarmantes da pulverização aérea de herbicidas sobre a vegetação nativa. Através da integração dos índices espectrais Índice Triangular de Verdor (TGI) e de Umidade por Diferença Normalizada (NDMI) aplicados a imagens Sentinel-2A, identificamos padrões característicos de degradação química em 158 776 hectares de

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

áreas úmidas e formações vegetais nativas no Pantanal de Barão de Melgaço, Mato Grosso, ocorridos entre 2021 e 2023. A metodologia desenvolvida demonstrou alta precisão (89% de acurácia) na discriminação entre danos por agrotóxicos e outros distúrbios naturais ou antrópicos, revelando assinaturas espectrais específicas e padrões espaciais típicos de aplicação aérea. Os resultados forneceram evidências científicas cruciais que embasaram ações de fiscalização ambiental, culminando no embargo das áreas afetadas e aplicação em multas e compromissos de recuperação ambiental. Além de comprovar a eficácia da integração TGI-NDMI para monitoramento ambiental, o estudo alerta para uma nova fronteira de degradação em ecossistemas úmidos tropicais, destacando a urgência de políticas públicas específicas para regulamentação da pulverização aérea e proteção desses ecossistemas sensíveis. A abordagem desenvolvida se apresenta como ferramenta estratégica para fiscalização ambiental, permitindo a rápida detecção e valoração precisa de danos em larga escala, com potencial aplicação em outros biomas tropicais ameaçados por práticas similares de desmatamento químico.

Palavras-chave:
Agrotóxicos, Degradação ambiental, Fiscalização ambiental, Índices espectrais.

I. INTRODUCTION

Advances in the Geotechnologies and remote sensing transformed environmental monitoring, enabling rapid detection of vegetation disturbances and changes in land use, resulting in planning more effective environmental control actions (Penha et al., 2023; Assis et al., 2019). These tools are essential for monitoring in countries with large territories, such as Brazil, reducing the dependence of on-site inspections and increasing the effectiveness to combat environmental crimes (Paranhos et al., 2021). Faster monitoring actions result in a significant increase in the seizure of illegal machinery and in holding offenders accountable, contributing to the decapitalization of these illicit activities in the State (Mato Grosso, 2024).

Nevertheless, as monitoring technologies evolve, illegal practices also become more sophisticated. Alternative methods to clear-cutting, such as the gradual use of fire to reduce tree cover, also lead to deforestation driven by successive anthropogenic disturbances (Lapola et al., 2023).

In recent years, chemical deforestation, characterized by aerial spraying of herbicides to induce progressive forest mortality, has emerged as a growing threat to tropical ecosystems. This method avoids abrupt changes in land cover, mimicking natural processes of vegetative decline and making it difficult to identify by traditional monitoring systems. According to Armentaras (2024), the resulting gradual degradation delays satellite detection, allowing the illegal conversion of forests to other uses, such as pasture, compromising the effectiveness of monitoring systems and hindering environmental oversight.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

As the world's largest consumer of pesticides (FAO, 2023), Brazil is facing a dual regulatory crisis: the easing of environmental laws - evidenced by the historic record of new pesticide registrations in 2022, including substances banned in other countries (Hess et al., 2023) - and the escalation of illegal trade with these products. In Mato Grosso, the epicenter of this problem, the recent approval of Bill 1833/2025, which reduces the buffer zones for spraying near communities and water sources, coincides with the alarming statistic that 65% of smuggled pesticides seized in the country between 2012-2022 were intercepted in this State, although it represents only 4.5% of federal operations in the period (Ferreira et al., 2025). This combination of illegal use of unregistered or smuggled products and irregular application in violation of environmental protection standards exponentially increases ecological risks, compromising both the biodiversity of the Pantanal and the health of the region's traditional populations.

Cases of chemical deforestation have been documented in different regions (Freitas, 2021; Gonzalez, 2022; Nicas; Milhorance, 2024; Brown, 2024), including in Indigenous Lands and protected areas (Montenegro; Colce, 2023). A recent case, with wide national and international repercussions (MPMT, 2024) revealed the practice of large-scale chemical deforestation in the Pantanal of Barão de Melgaço (MT). The Pantanal, one of the largest humid ecosystems on Earth and recognized as a Natural Heritage of Humanity, is highly vulnerable to chemical contaminants, which reinforces the need for monitoring with robust methodologies to preserve its ecological integrity.

In this context, spectral indices such as the TGI (Triangular Greenness Index) and the NDMI (Normalized Difference Moisture Index) emerge as promising tools to characterize this type of forest disturbance. The TGI detects early biochemical changes associated with plant degradation, such as chlorophyll reduction, in addition to capturing structural and biophysical variations in vegetation, without the need for near infrared, and is less susceptible to saturation than conventional indices (Huete et al., 2002; Hunt et al., 2011). This index has proven effective to distinguish between healthy and stressed vegetation (Garza et al., 2020; Lemes et al., 2022), but despite its widespread use in agriculture, there are few studies on its application in forests, highlighting the works of Polat (2020) and Polat et al. (2024). The NDMI is sensitive to the moisture content of vegetation (Gao, 1996), allowing the differentiation of healthy vegetation from those affected by environmental disturbances (Lastovicka et al., 2020; Strashok et al., 2022). Its combination with other indices improves the detection of degradation, especially in environments with sparse vegetation cover (Schultz et al., 2018).

This study integrates multitemporal analyses of the TGI and NDMI spectral indices with geospatial processing techniques to improve the detection of forest degradation. It seeks to overcome the limitations of

198
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

conventional methods by applying an innovative approach to monitor tropical humid ecosystems, focusing on identifying and characterizing native vegetation affected by chemical deforestation.

The main objective is to develop and validate a methodology capable of: (i) quantify with high accuracy the spatial extent of herbicide-induced damage; (ii) reconstruct the chronology of degradation events from spectral signatures; (iii) discriminate robustly the impacts caused by herbicides in relation to other disturbance agents, such as fires and seasonal variations; and (iv) provide qualified technical support to strengthen mechanisms for environmental inspection, monitoring, and accountability.

The methodology was applied in the Pantanal Barão de Melgaço (Mato Grosso State), a region known for recent records of aerial herbicide spraying on native vegetation. In order to fill a critical gap in current degradation detection and warning systems, this study offers an evidence-based tool for the accurate diagnosis of this specific type of anthropogenic disturbance, contributing directly to biodiversity conservation and environmental governance in highly vulnerable ecosystems.

Study area

The study area is located in 11 contiguous rural properties, intended for extensive livestock farming, with a total area of 277,325 hectares, located in the Pantanal Barão de Melgaço, a sub-region of the Pantanal biome (Silva; Abdon, 1998). This sub-region presents a spatial heterogeneity of soils that, associated with the types of flooding and seasonal water variations, generates great diversity of microhabitats.

Altitudes range from 100 to 150 m and the slope is negligible, according to a study by Beirigo (2008). The vegetation in the study area is composed of wooded savanna, grassy-woody savanna and park savanna, lowland semi-deciduous and alluvial seasonal forest, with emergent canopy, according to the Brazilian Vegetation Classification (IBGE, 2012). The rural properties covered by the study, obtained from the National Rural Environmental Registry System (SICAR), are located between São Lourenço and Piquiri rivers, on the border with Mato Grosso do Sul State. They are located around the Perigara and Baía dos Guatós Indigenous Lands and close to two conservation units, the Encontro das Águas State Park and the largest Private Natural Heritage Reserve in Brazil, the SESC Pantanal National Park (Figure 1 – Location map of the study area in the Upper Rio Paraguay Basin. Limits of the sub-regions from the Pantanal biome, adapted from Silva & Abdon (1998), obtained from https://forest-gis.com/shapefiles/ Pantanal_SubR_Estimated.zip).

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

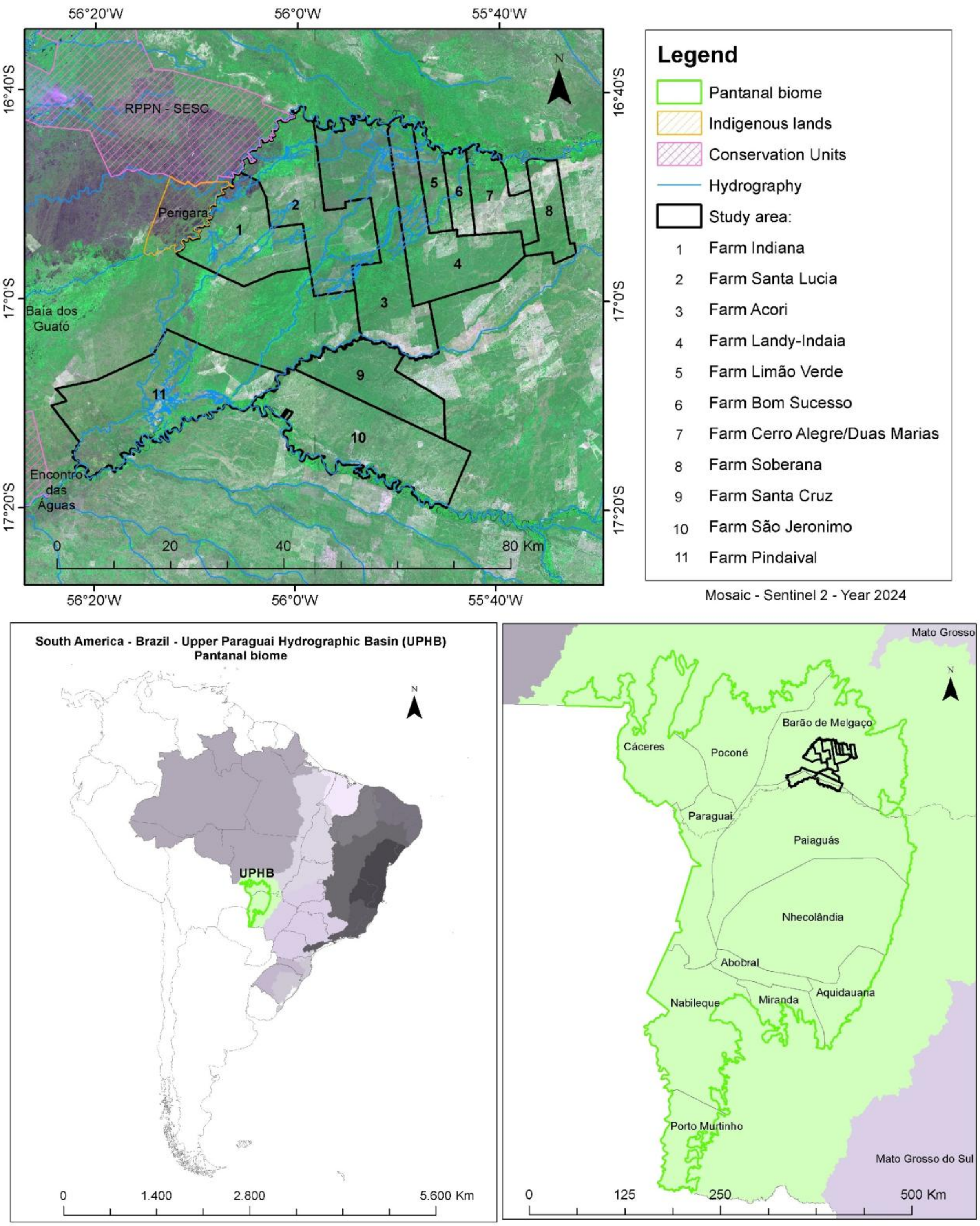

Figure 1 – Location map of the study area in the Upper Rio Paraguay Basin. Limits of the sub-regions from the Pantanal biome, adapted from Silva & Abdon (1998), obtained from https://forest-gis.com/shapefiles/ Pantanal_SubR_Estimated.zip.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

II. Materials and Methods

Initially, ground and aerial inspections were carried out in March 2023, during the flood period in the Pantanal, to verify and record the natural areas affected and non-affected by herbicides, covering different vegetation formations, such as forests, savannas, native fields, in addition to exotic grass plantations, wet and dry areas, including regions with use restrictions, such as Permanent Preservation Areas (APP) and Legal Reserve Areas (ARL).

After confirming the damage in areas affected by herbicides, we conducted a temporal analysis from 2019 onwards to characterize the dynamics of changes in native vegetation and land use over the years and to compare the scenarios at different times, using images from the Sentinel-2 satellites and the PlanetScope constellation. Deforestation alerts derived from daily images of Planet satellites were used to identify areas with degradation and fire scars. These data provided an initial exploratory basis for estimating the extent of the impacts, determining the period of occurrence to support the choice of images used in the study and assessing the progression of the degradation process in the region.

The temporal analysis made it possible to map affected areas and understand the dynamics of change over time, but it did not provide detailed information on the vegetation's physiological and biophysical responses to chemical stress. Although initial approaches effectively identified the damage, a more refined analysis was conducted to characterize and quantify the magnitude of the impacts of herbicide spraying on native vegetation. To fill this gap, we used the TGI and NDMI indices. According to Hunt et al. (2013), the TGI is sensitive to verify changes in chlorophyll concentration in leaves at the canopy scale, but relatively insensitive to the leaf area index, ensuring greater robustness in different vegetation conditions (Jelínek et al., 2020). The application of the NDMI allows to detecting variations in vegetation moisture content, degradation or mortality, as explained by Delgado-Moreno & Gao (2021).

To optimize the processing flow, vegetation indices were generated via the Copernicus Browser, a platform that provides access to the full Sentinel-2 time series and offers a wide range of pre-configured spectral indices, along with the option to implement custom scripts for advanced orbital image processing (ESA, 2024a).

The vegetation indices were applied to Sentinel-2 satellite images covering all scenes available from 2019 to 2023 with less than 20% cloud cover. The images used are at the L2A processing level, characterized as Analysis Ready Data (ARD), and have already been subjected to the Sen2Cor algorithm, responsible for the atmospheric correction. This processing minimizes atmospheric interferences, such as the presence of water

RA'EGA O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

vapor and aerosols, ensuring a higher accuracy in spectral values (ESA, 2024) and eliminating the need for additional pre-processing.

Sentinel-2 imagery proved its' effectivity for this type of monitoring, combining free access, 10-meter spatial resolution and high revisit frequency. This combination offers an advantageous balance between spatial detail, temporal coverage and operational feasibility, essential characteristics for continuous and multitemporal monitoring of vegetation dynamics.

The NDMI was processed directly on the Copernicus Browser platform, which provides a pre-configured layer for calculating this index. The NDMI is defined as:

$$NDMI = \frac{(\mathrm{NIR} - \mathrm{SWIR})}{(\mathrm{NIR} + \mathrm{SWIR})} \tag{1}$$

where NIR represents the reflectance in the near-infrared band (B8A in Sentinel-2) and SWIR the reflectance in the short-wave infrared band (B11 in Sentinel-2).

The TGI, in turn, was applied through a customized script on the same platform, using the visible spectrum bands of Sentinel-2 (Blue (B02), Green (B03) and Red (B04)), as proposed by Hunt et al. (2011):

$$TGI = -0.5 \times [190 \times (Red - Green) - 120 \times (Red - Blue)] \tag{2}$$

where the colors Blue, Green and Red represent the reflectance of bands B02, B03 and B04, respectively, and the coefficients 190 and 120 correspond to the reflectance differences between the bands.

A multispectral approach was adopted to integrate the TGI and NDMI indices for analyzing vegetation dynamics, land-use changes over time, and the progression of environmental disturbances. These indices were subjected to a supervised classification using the Support Vector Machine (SVM) algorithm, with spectral classes defined based on specific thresholds: healthy vegetation (high TGI and moderate NDMI), degraded vegetation (low TGI and NDMI), exposed soil (very low or negative TGI and NDMI) and water bodies (high NDMI and low TGI). Spectral thresholds were adjusted to maximize class separability, followed by applying the classifier to images from the dry season (July) between 2019 and 2023, thereby minimizing seasonal interference and cloud cover. A majority filter (3x3) was used to reduce noise and small isolated regions.

The degraded vegetation class was isolated as the first thematic product for detailed analysis, serving as a basis for directing visual interpretation in RGB compositions (bands 4-8-3). To reduce the occurrence of false positives in the detection of degraded areas, most regions previously converted to other uses, such as

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

established pastures and areas with bare soil, were excluded, based on the land cover and use map from MapBiomas (Collection 9, 2023).

This step consists of an integrated analysis from the results of the spectral classification and the visual interpretation of the Sentinel-2A images, aiming to refine the identification of areas impacted by aerial spraying of herbicides. Recurrent spatial patterns were mapped, such as linear bands of plant mortality, polygons with regular geometric shapes, and contours consistent with flight paths, indicating planned application of chemical products on native vegetation. The combination of this spectral and spatial evidence allowed the precise delimitation of the affected areas, later classified as "Chemical Deforestation". This approach also contributed to the preliminary validation of the observed degradation patterns, increasing the reliability of the detection and reducing the possibility of confusion with other types of disturbance.

However, pasture areas that still contained elements of native tree vegetation or a significant presence of exotic species with substantial biomass were retained in the delimitation, as they exhibited spectral characteristics consistent with the degradation patterns under investigation. This decision aimed to preserve the representativeness of degradation processes in mixed vegetation mosaics, common in agricultural frontier regions, without compromising the accuracy in identifying the effects of chemical spraying.

The confirmation of herbicide degradation required three main criteria: (1) simultaneous decline in TGI and NDMI values in native vegetation, (2) characteristic spatial patterns of aerial chemical spraying, and (3) temporal correlation with records of complaints or inspections. Additionally, areas with deforestation alerts based on daily images (Planet) or historical data of active fires in near real time (NRT) from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS), obtained from the platform Fire Information for Resource Management System (NASA FIRMS, 2024).

The temporal analysis was detailed assessing trends in spectral indices, with an emphasis on the detection of points with an abrupt change. NDVI was incorporated as a reference to differentiate natural seasonal variations from anomalous events. This step allowed the association of critical degradation periods with records of pesticide application, reinforcing a causal inference. To ensure accuracy, degraded areas were manually vectorized in QGIS 3.28 (2021–2023), based on spectral signatures, spatial patterns, and field data, including georeferenced photographs of the affected sites.

Since the Rural Environmental Registry (CAR) was not yet validated by the environmental agency, the delimitation of the APPs (Areas of Permanent Protection) from the properties was carried out in a GIS environment, with the interpretation of historical series of satellite images, supported by field observations

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

considering the streams, lakes, and areas flooded for more than three months, following the dimensions provided by the environmental legislation. The overlapping of degradation polygons with those of APPs allowed the quantification of Degraded APPs, highlighting the impacts of pesticide spraying in these protected areas.

Validation of the "Chemical Deforestation" class was based on evidence collected during field inspections conducted by technical teams from SEMA/MT, which enabled on-site confirmation of the affected areas. During these inspections, georeferenced aerial photographs and detailed records with precise coordinates of the impacted regions were produced, enabling the direct identification of characteristic degradation patterns caused by aerial spraying, such as linear bands of dead vegetation and the absence of mechanical disturbance indicators.

In addition, PlanetScope images with a spatial resolution of 3 meters were used to complement the analysis, providing greater precision in visually verifying the spectral patterns identified in the classification. The combination of field records, photographic evidence and high-resolution images made it possible to assess the reliability of the supervised classification, ensuring that the spectral patterns detected were compatible with the impacts observed in the field.

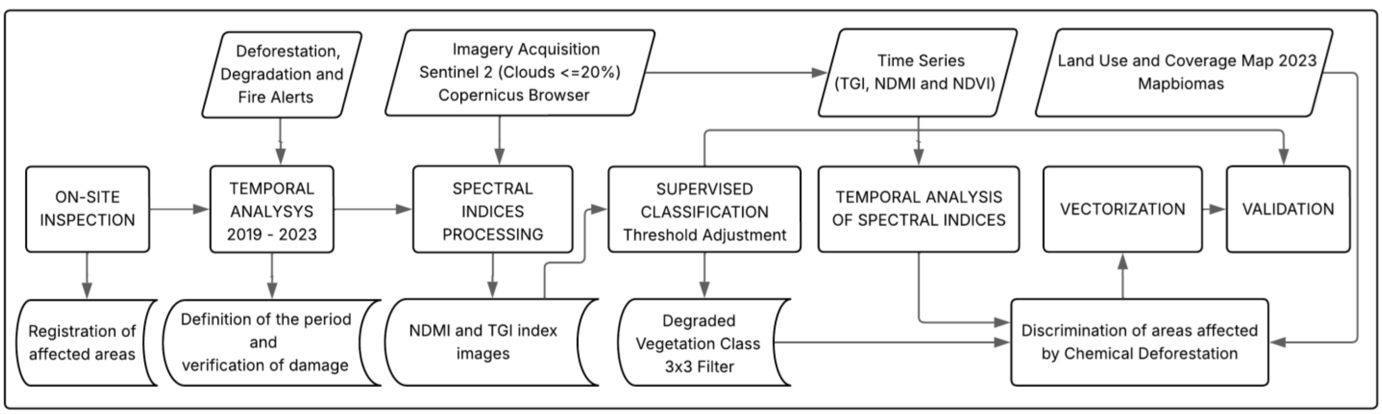

Figure 2 – Steps of the procedure for identifying native forest areas affected by chemical agents.

To validate the data obtained from the vegetation indices, a confusion matrix was generated to calculate overall accuracy, along with detailed assessments of producer and user accuracy. To this end, 100 sampling points were randomly distributed across the study area, considering two classes: "Chemical Deforestation" and "No Chemical Deforestation". This approach strengthens the robustness of the validation by integrating empirical data, spectral analysis and high-resolution images, especially in areas that are difficult to access, such as the flooded areas of the Pantanal.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

III. RESULTS AND DISCUSSION

Inspections in the study areas revealed an anomalous pattern of defoliation in several tree species, indicating a severe and unnatural impact on native vegetation. Leaf loss was abrupt and concentrated in specific areas, in contrast to adjacent regions, where the trees had an intact and healthy canopy. This difference cannot be attributed to climatic or soil variations, as water availability was abundant at the time of the inspection, and the forest formations in the region appeared green and healthy (Figure 3).

Figure 3 – Observation images of tree species mortality in the study area, with the presence of grass not affected by the pesticide, in 2023. Lat. S 16°52'9''S and Long. W.Gr.55°49'40''; Lat. S 17°08'29'' and Long. W.Gr.56°09'39''; Lat. S 16°51'37''S and Long. W.Gr.55°54'59''; Lat. S 16°57'13'' and Long. W.Gr.55°56'1''; Lat. S 16°56'2''S and Long. W.Gr.55°57'59''; Lat. S 16°54'32''S e Long. W.Gr.55°47'13''. Images by the author.

The areas impacted by herbicides were flooded at the time of the field inspection and presented organized patterns of degradation, with well-defined boundaries and high tree mortality. A striking contrast was consistently observed between the significant mortality of dicotyledonous species and the sustained vigor of grasses—including both native forages and exotic species—which showed no visible signs of stress. This selective mortality pattern is compatible with the targeted application of specific herbicides, corroborating evidence collected in the field.

During the inspection, forage seed bags and packages containing over 25 types of pesticides were found on the properties, with a predominance of herbicides selective for broadleaf plants. Among these, compounds based on synthetic auxins stand out, such as 2,4-D (2,4-dichlorophenoxyacetic acid, picloram), widely recognized

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

for its action on dicotyledons, where it causes disordered growth, structural collapse and cell death, resulting in widespread mortality of tree species. This compound, notoriously used as one of the main ingredients of "Agent Orange" during the Vietnam War, is associated with severe and persistent ecotoxic effects. In addition, some of the products found have prolonged residual action, hindering the regeneration of woody vegetation over time, while others inhibit the regrowth of affected trees (based on triclopyr), significantly prolonging the effects of environmental degradation.

Data obtained from the Mato Grosso State Agricultural Defense Institute (INDEA/MT) reinforce the scale of pesticide use in the region. Between 2021 and 2023, 215,587 liters and 1,353 kilograms of herbicides were recorded, with invoices and aerial application records confirming the extensive use of these compounds. The presence of improperly discarded packaging, mixed with regular waste and in locations close to water bodies, in violation to environmental standards, increases the risk of water contamination and ecotoxicological impacts (SEMA-MT, 2023). It is worth noting that the systematic application of selective herbicides targeting the elimination of tree and shrub species deviates from the traditional practices of extensive livestock farming in the Pantanal, which has historically relied on native pastures and low-impact management (Junk; Nunes Da Cunha, 2012).

The time series of spectral indices (NDVI, NDMI and TGI), represented in Figure Figure *4*, shows the trajectory of native vegetation in the study area between 2015 and 2024, highlighting degradation and recovery events. The analysis of the series reveals that, during the reference period between 2015 and 2019, the native vegetation in the study area remained in intact ecological conditions. The values of the NDVI, NDMI and TGI indices remained high, reflecting the health of the vegetation. The behavior of the spectral indices in the sample area observed in the reference period, between 2016 and August 2020, follows the typical seasonal pattern of the Pantanal, with reductions from the values of the indices between the months of July and October, dry season, but still maintaining relatively high minimum levels, with the NDVI rarely below 0.7. The oscillation in TGI reflects the predominance of deciduous species, which lose leaves in the dry season, and the NDMI, around 0.2 to 0.3, indicates a relatively stable canopy moisture, with an expected reduction during the dry months. This pattern confirms the integrity of the vegetation in the pre-disturbance period.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

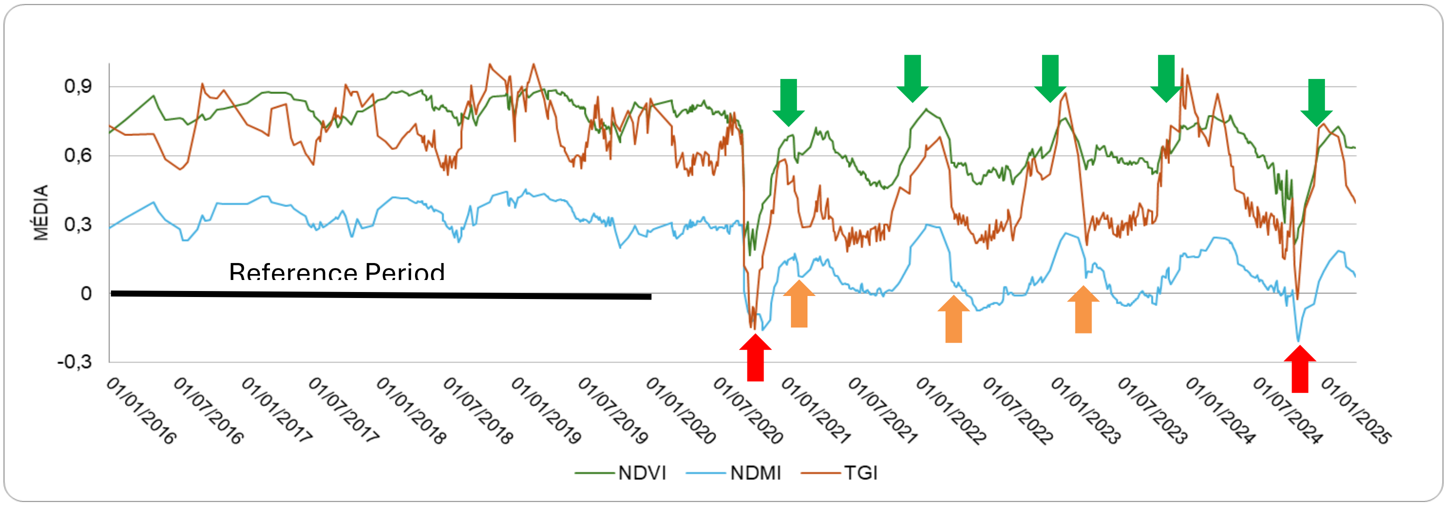

Figure 4 – Time series of NDVI, NDMI and TGI indices for the area located at Farm Landy-Indaiá, delimited by the polygon with vertices at: Lat. S 16°53'0.75''S and Long. W.Gr. 55°48'23.91''; Lat. S 16°53'2.92''and Long. W.Gr.55°46'52.56''; Lat. S 16°53'23.26 92''and Long. W.Gr.55°46'49.38''; Lat. S 16°53'18.35''and Long. W.Gr.55°48'21.53''. Source: prepared by the author.

Starting in August 2020, as indicated by the first red arrow, a sharp drop in all three indices was observed, linked to a large fire that affected the region between August 16 and November 2, 2020. This fire caused the death of many plant species, consumed dry biomass, and increased soil exposure, resulting in a pronounced spectral collapse with NDVI, NDMI, and TGI reaching minimum values, marking the onset of severe native vegetation degradation. With the onset of rains following the fire, the vegetation begins to regrow and naturally regenerate, marked by the appearance of new leaves. This recovery is reflected in the gradual increase of the NDVI, TGI, and NDMI indices until the end of January 2021, as indicated by the first green arrow.

Between February 10th and 20th, 2021, a drop was observed in the three spectral indices analyzed, occurring before the beginning of the typical dry season in the Pantanal, with less abrupt reductions than those caused by fires, but significant, indicated by the first orange arrow in the time series.

Due to the partial resilience of the vegetation, new herbicide applications were carried out in 2022 and 2023, which presented patterns similar to those of 2021, intensifying the degradation process and causing new drops in the indices, always preceding the dry season and coinciding with records of aerial spraying, suggesting a consistent pattern of chemical degradation. Therefore, this cannot be attributed solely to climatic seasonality, which typically influences vegetation between July and October. The decline is associated with leaf loss and the mortality of emerging trees, particularly in areas with a high density of large native vegetation. To a lesser extent, this effect is also observed in areas dominated by exotic grasses with scattered trees and shrubs.

The TGI showed areas with severe stress and loss of photosynthetic activity, while the NDMI indicated strong water stress. The fluctuations in the TGI over time suggest floristic changes, with a predominance of

RA'EGA O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

invasive grasses and uneven regeneration of native species. The response of the NDVI and NDMI indices reinforces the presence of prolonged vegetation stress.

At the end of the time series, a new abrupt drop in the indices was recorded in September and October 2024, consistent with a new forest fire indicated by the second red arrow. This event occurs over already degraded vegetation, severely impacted by the 2020 fire and successive applications of pesticides, resulting in lower accumulated biomass, significant presence of dry material and, consequently, greater fire severity.

This scenario reveals a positive feedback loop, in which vegetation degradation increases the fuel load and intensifies subsequent fires. The repetition of this cycle compromises the resilience of the ecosystem, substantially increasing the susceptibility of trees to mortality, leading to the opening of the canopy, the accumulation of dead biomass and the acceleration of the drying process of combustible material, as already observed by Cochrane et al. (1999).

The multivariate approach demonstrated high sensitivity to detect spectral signatures typical for chemical degradation of vegetation, even in complex environmental contexts such as the wet ecosystems of the Pantanal. The combination of TGI and NDMI indices allowed the identification of specific spectral patterns related to herbicide application, characterized by the simultaneous decline of both indices. This signature is clearly distinct from variations associated with natural or seasonal processes.

Notably, the methodology also proved effective in flooded areas, where paradoxical signatures were observed, such as high NDMI values (indicating water saturation) alongside severely reduced TGI values, signaling a marked loss of chlorophyll. This specific combination represents robust evidence of the action of herbicides in advanced stages of degradation, reinforcing the applicability and accuracy of the method in environments with high hydrological complexity.

Figures Figure *5*, Figure *6* andFigure *7* show the affected areas in three different compositions: (i) true color image on the left, (ii) chlorophyll index (TGI) in the center and (iii) moisture index (NDMI) on the right. This representation aims to facilitate visual interpretation and allows a direct comparative analysis between the real appearance of the scene (true colors), the leaf chlorophyll (TGI) and vegetation moisture (NDMI) indicators, helping to identify degraded areas or areas under water stress. The TGI values were categorized into four levels: black (0), indicating no or minimal vegetation; red (0.25), representing vegetation under severe stress or degradation; yellow (0.5), corresponding to vegetation under moderate stress; and green (>0.75), associated with healthy vegetation with high chlorophyll levels. For NDMI, the Copernicus Browser standardization was adopted, classifying the values as: red (NDMI ≤ -0.8), indicating exposed soil or extremely degraded vegetation;

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

orange (-0.8 < NDMI ≤ -0.24), representing vegetation under strong water stress; yellow/green (-0.24 < NDMI ≤ -0.032), corresponding to moderately stressed vegetation; cyan (-0.032 < NDMI ≤ 0.032), associated with moderate humidity; and dark blue (NDMI ≥ 0.8), indicating very healthy vegetation without water stress.

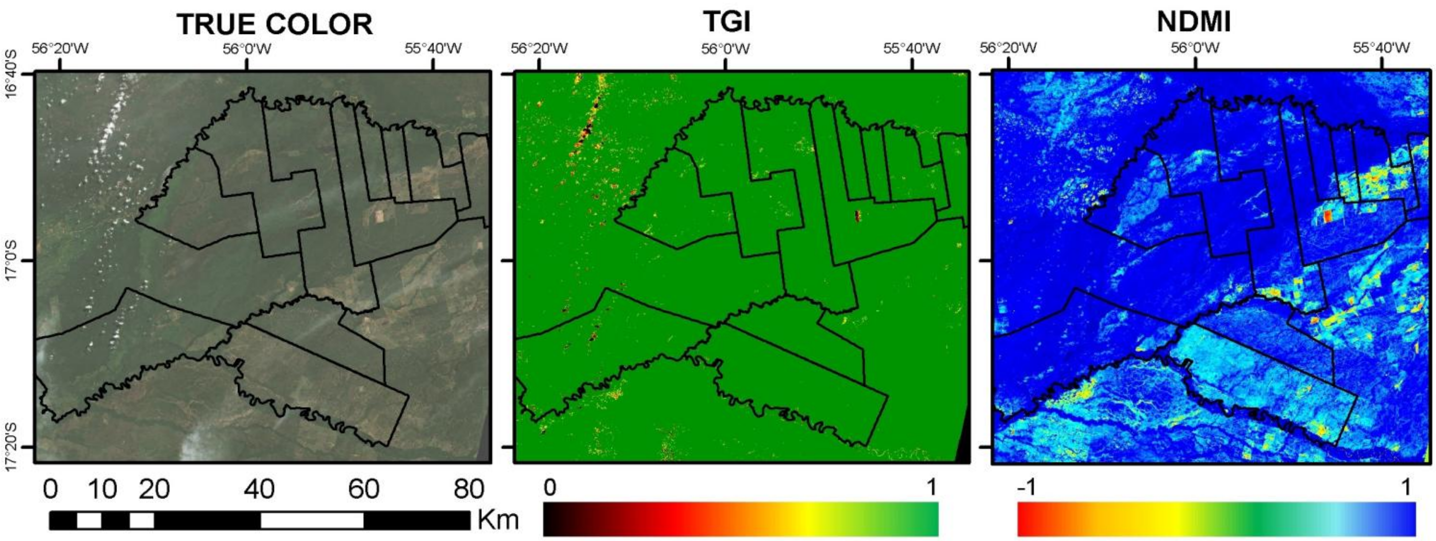

Figure 5 – Scene 2019-04-27-23_59_Sentinel-2_L2A, from 04/27/2019 – Rainy Season. The vegetation presents high integrity, with dense and healthy forests and Cerrado. The TGI displays a predominance of dark green, indicating high chlorophyll vigor, and the NDMI shows high values (dark blue), signaling the absence of water stress. It is noteworthy that the southern part (Farm São Jerônimo), with Park Savanna, presents lower humidity even before the occurrence of disturbances. Source: prepared by the author.

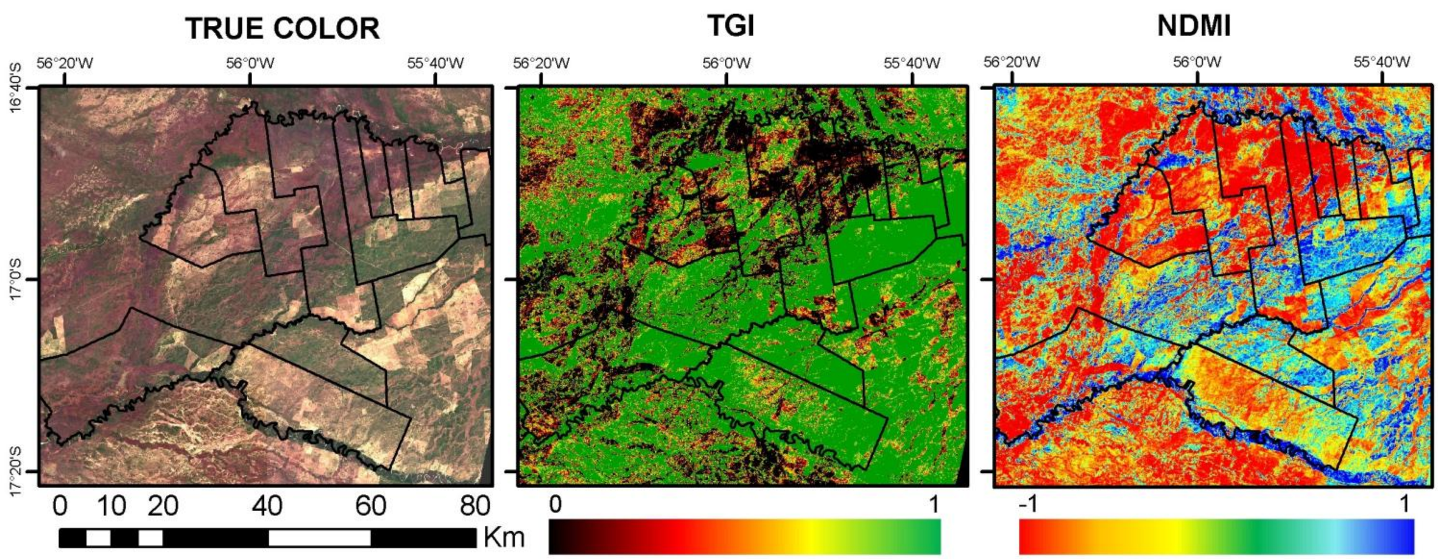

Figure 6 – Scene 2020-11-02-23_59_Sentinel-2_L2A, from 11/02/2020 – Dry Season. The True Color image shows extensive degradation caused by fires, with large areas in dark brown. The TGI highlights burned regions in red and black, with low photosynthetic activity. The NDMI reinforces the impact, with spots in shades of yellow to red, indicating strong water stress and severely affected vegetation. Source: prepared by the author.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

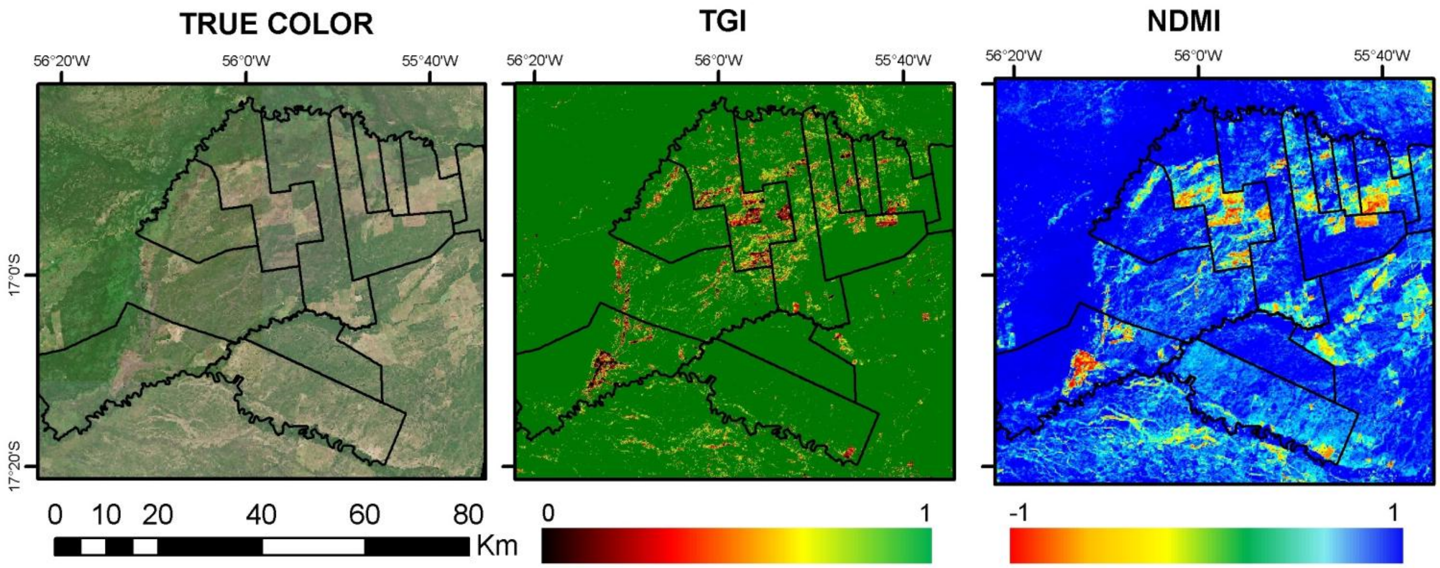

Figure 7 – Scene 2021-04-21-23_59_Sentinel-2, from 04/21/2021 – Rainy Season. Unlike previous years, the vegetation shows clear signs of degradation by pesticides, with large areas in gray and light brown. The TGI shows low values (red and black), indicating strong stress and reduced photosynthetic activity, and the NDMI reveals moisture loss with shades of cyan to red. Source: prepared by the author.

Images in figures Figure *8* and Figure *9* show in detail the result of the "Chemical Deforestation" class obtained from the supervised classification integrating the TGI and NDMI indices.

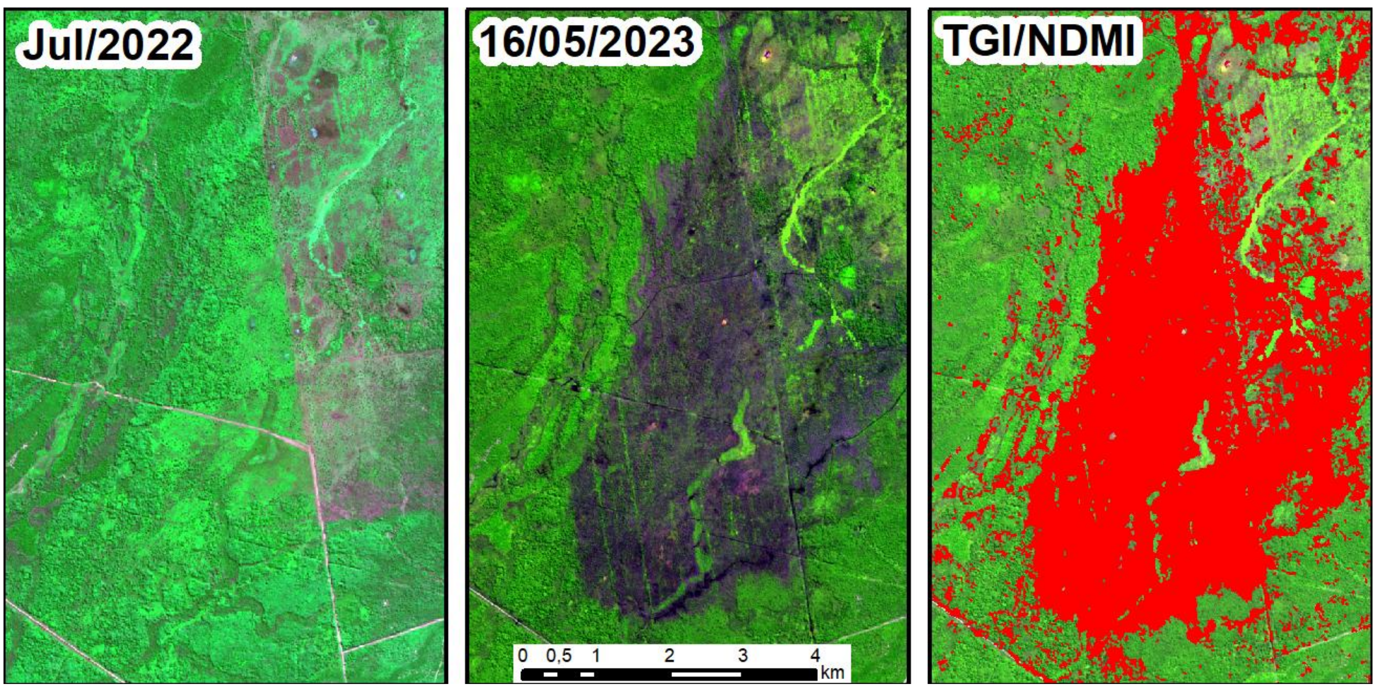

Figure 8 – Detection of forest degradation. Sentinel-2_L2A image from July 2022 (left), from 05/16/2023 (center) and result of TGI and NDMI integration on 05/16/2023 (right). Central coordinate: Long. W.Gr. 55°49'58"and Lat. S 16°54'2.07". Source: prepared by the author.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

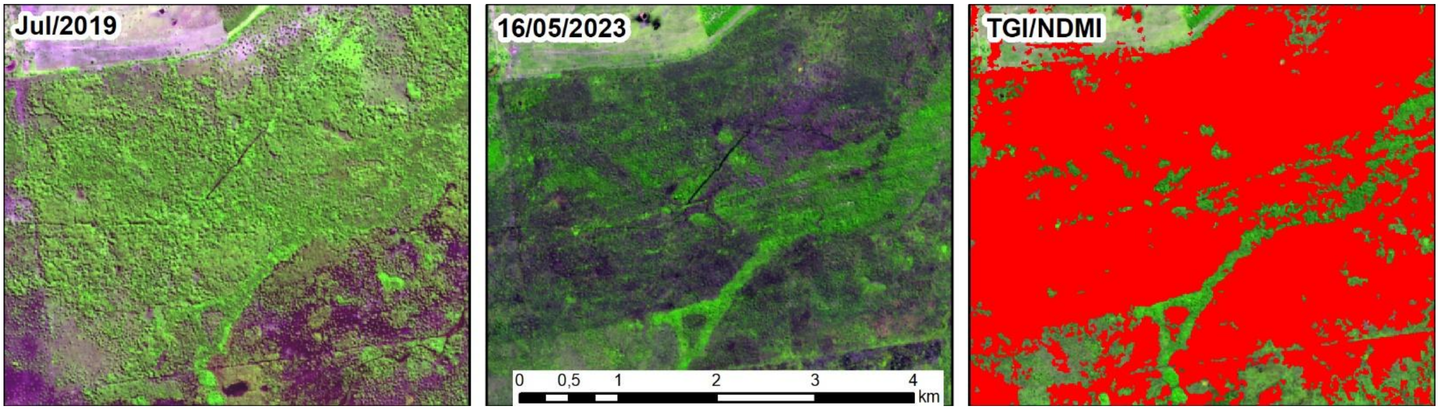

Figure 9 – Forest Degradation Detection. Sentinel-2_L2A image from July 2019 (left), from 05/16/2023 (center) and result of TGI and NDMI integration in the scene from 05/16/2023 (right). The detection of degradation stands out, including vegetation in a humid area in the SE of the image. Central coordinate: Long. W.Gr. 55°54'13.37"and Lat. S 16°49'29.02"S. Source: Prepared by the author.

The approach adopted allows to distinguish accurately between the different agents of forest degradation, and to assess not only the extent, but also the intensity and frequency of impacts on native vegetation. The methodological difference lies in the articulation of multiple analysis dimensions (spectral, temporal and spatial) combined with the application of rigorous filters to minimize interference of natural or anthropogenic origin not related to the use of pesticides.

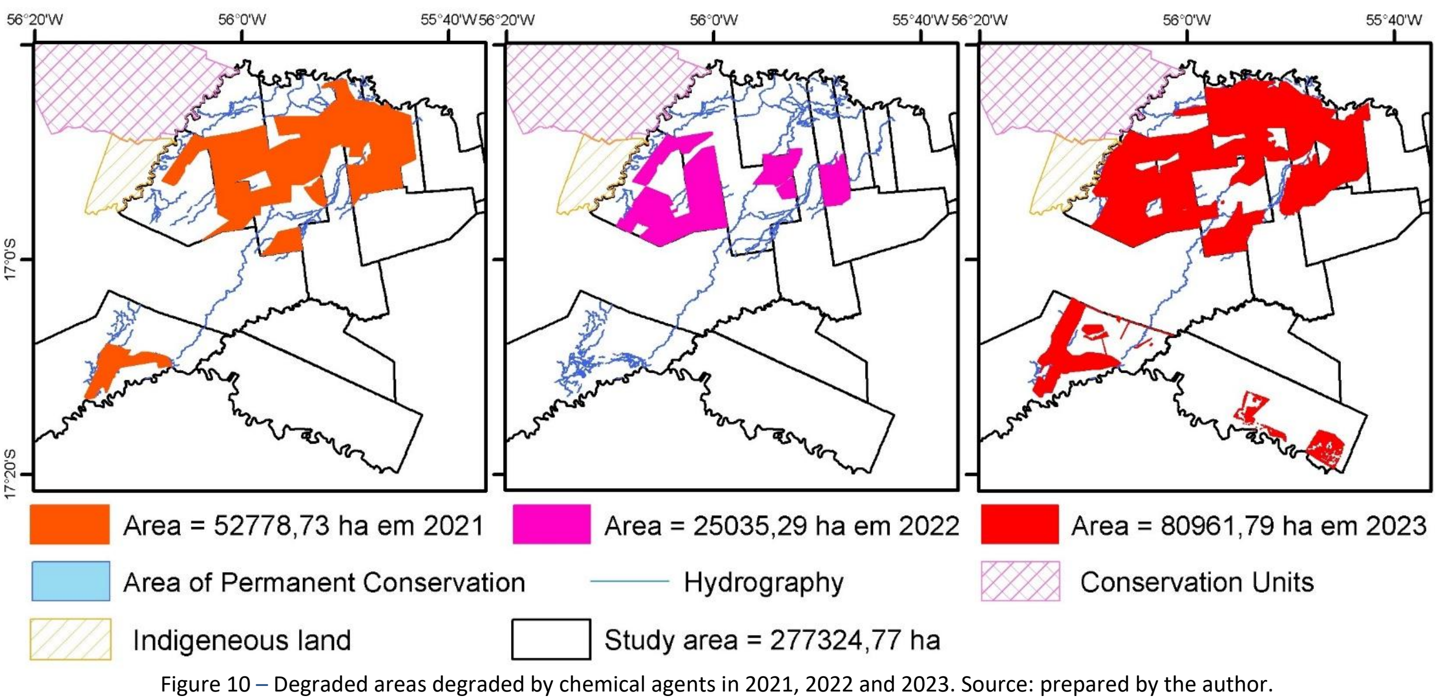

Figure 10 – Degraded areas degraded by chemical agents in 2021, 2022 and 2023. Source: prepared by the author.

This methodology strengthens the ability to detect spectral signatures specifically associated with chemical degradation, making the results more reliable and enabling the precise delimitation of areas specifically affected by herbicide spraying, quantified in 52,779 hectares detected in 2021, 25,035 hectares in

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

2022 and 80,962 hectares in 2023, totaling 158,776 hectares impacted over the analyzed period (Figure 10). Of this total, 5,223 hectares correspond to degraded APPs, which accentuates the severity of the environmental damage detected.

These data not only highlight the extent of the environmental impact, but also play a crucial role in guiding public policies and control measures. The information obtained was essential to support technically the inspection actions, offering strategic support for carrying out on-site operations.

The aerial spraying of herbicides over native vegetation, which was carried out repeatedly over a period of three years, resulted in severe impacts on the biodiversity, the effects of which are difficult to fully measure. In addition to the destruction of plant formations in stages of natural regeneration, including in regions with restrictions on use, there were signs of water pollution and adverse effects on wildlife. These findings highlight the urgent need to implement effective measures to monitor and control the use of herbicides, especially in ecologically sensitive regions.

The data obtained by supervised classification, resulting from the integration of the TGI and NDMI indices, were corroborated by a validation process that combined field inspections with georeferenced aerial photos, complemented by high spatial resolution images.

Table 1 – Confusion matrix and accuracy metrics of supervised classification.

Validation table		Referência de campo			
		Chemical Deforestation	Without chemical deforestation	Total	User accuracy
ThematicMap	Chemical deforestation	19	11	30	0.63
	Without chemical deforestation	6	64	70	0.91
	Total	25	75	100	
	Producer accuracy	0.69	0.89		**0.8483**

Source: the authors.

The overall 0.85 accuracy demonstrates the effectiveness of the model to detect areas affected by chemical deforestation, especially when capturing spectral signatures typical for herbicide application, such as the simultaneous decrease in TGI and NDMI. The "Chemical Deforestation" class obtained moderate accuracies, but showed strong spatial coherence with the patterns documented during the surveys, such as selective mortality of species, the linear arrangement of affected vegetation and the presence of chemicals. On the other hand, the high accuracy of the "No Chemical Deforestation" class helped to minimize false positives, increasing the reliability of the mapping. These results reinforce the potential of the approach for operational applications to monitor chemical degradation, even in complex and seasonally flooded ecosystems.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

The results demonstrate the effectiveness of the model to detect spectral patterns associated with pesticide application, especially when integrated with field validations. The ability to distinguish specific changes caused by herbicides from other environmental disturbances reflects the robustness of the adopted approach, even in face of the spectral complexity from degraded areas. Although there is a partial overlap between classes, as expected in natural environments with high heterogeneity, the classification demonstrated a satisfactory performance, especially due to the incorporation of refined spectral criteria and the temporal and spatial interpretation of the detected anomalies.

The dynamics of natural regeneration after chemical degradation events, characterized by gradual increases in TGI and NDMI values, illustrates the complexity of the scenario analyzed. This regeneration includes the replacement of tree species by herbaceous species, regrowth under the canopy, and the advance of exotic grasses, which can soften the spectral signals of recent degradation, making the boundaries of the affected areas less evident. Furthermore, in regions with a predominance of native grasses, subject to seasonal variations and intensive grazing, soil exposure and structural reconfiguration of vegetation contribute to spectral signatures similar to those of chemical degradation.

This challenge is exemplified in the southern portion of the study area, in the section known as Farm São Jeronimo, where a sector of Park Savannah, with high soil exposure (30–45%) and extensive pasture use, exhibited moderate NDMI values that remained consistently lower than those of the native vegetation in the rest of the study area throughout the analyzed period (2019–2023). Although these values could initially indicate degradation, the temporal analysis revealed stability in the spectral behavior and the absence of spatial patterns characteristic of aerial spraying, allowing the exclusion of this area as a false positive. This type of integrated analysis contributed directly to the accuracy achieved, demonstrating the methodology's ability to deal with the subtleties of the natural environment and reduce classification errors.

The results of this study provide crucial technical evidence that support integrated environmental monitoring actions between SEMA and partner agencies, culminating in the embargo of degraded areas and the application of environmental fines totaling R$2.9 billion, in addition to the imposition of environmental recovery measures estimated at R$2.3 billion. These values represent a milestone in penalties for chemical deforestation in Brazil, highlighting the effectiveness of remote sensing as a strategic tool for detecting, quantifying, and proving large-scale environmental crimes.

The ability to generate georeferenced, temporally consistent, and legally robust information strengthens the effectiveness of control agencies by enabling faster accountability for offenders and contributing to the

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

consolidation of public policies to combat chemical degradation of native vegetation. Furthermore, the findings underscore the role of geotechnologies as essential technical and scientific support for promoting environmental justice and conserving sensitive biomes such as the Pantanal.

IV. Conclusions

The results of this study demonstrated the effectiveness of the approach based on the Triangular Greenness Index (TGI) and Normalized Difference Moisture Index (NDMI) spectral indices in detecting impacts related to chemical deforestation on native vegetation, especially in wetlands of the Pantanal. The sensitivity of these indices proved to be adequate for identifying spectral signatures compatible with chemical degradation processes, highlighting their potential as an operational tool for monitoring and early diagnosis of plant stress induced by pesticides.

However, limited spectral separation capacity was observed between chemical degradation and other disturbance types, such as fires, particularly in areas with naturally sparse vegetation. This necessitates analyzing spatial patterns in degraded areas to enable more precise discrimination among different degradation agents. Therefore, it is recommended to improve the method, incorporating additional spectral and spatial metrics, as well as the adoption of object-oriented classification techniques (Object-Based Image Analysis – OBIA), which allow the integration of spectral, geometric and contextual attributes from the mapped features.

The application of supervised machine learning algorithms, especially Random Forest, can contribute significantly to increase the accuracy, robustness and degree of automation from the classification process, especially in heterogeneous environments such as the Pantanal. Additionally, it is suggested to integrate data from active and passive sensors — such as hyperspectral sensors, LiDAR and synthetic aperture radar (SAR) — aiming to capture more specific structural and biophysical characteristics of vegetation affected by chemical agents, such as canopy height, leaf density and floristic composition.

It is also recommended to use time series–based models, such as BFAST (Breaks For Additive Season and Trend), to detect inflection points and analyze trend and seasonality components, thereby refining the detection of anomalous changes associated with chemical degradation.

The adoption of continuous monitoring strategies, associated with the dynamic adjustment of spectral thresholds according to the different successional stages of vegetation, shows promise to increase the sensitivity and accuracy to detect impacts over time, especially in areas subject to recurring disturbances.

The overlap between water stress, intensive use of herbicides and recurrent fires establishes a scenario of high ecological vulnerability, compromising the regeneration capacity and resilience of the Pantanal's humid

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

ecosystems. Even so, the proposed methodology demonstrated a high application potential, with consistent results even in hydrologically complex environments. Its replicable nature and ability to identify specific patterns of chemical degradation make this approach a strategic ally for environmental monitoring.

With the suggested improvements, the approach tends to consolidate itself as a robust tool for the continuous monitoring of anthropogenic impacts, contributing effectively to the control of chemical deforestation and the conservation of ecologically sensitive biomes.

V. References

ARMENTERAS, D. La amenaza silenciosa de la deforestación química en los países amazónicos: un nuevo desafío para la conservación y la legislación ambiental. Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales, v. 48, n. 189, p. 967–969, 2024.

ASSIS, L. F. et al. TerraBrasilis: a spatial data analytics infrastructure for large-scale thematic mapping. ISPRS International Journal of Geo-Information, v. 8, n. 11, p. 513, 2019. Disponível em: https://doi.org/10.3390/ijgi8110513. Acesso em: 9 jun. 2025.

ASSEMBLEIA LEGISLATIVA DO ESTADO DE MATO GROSSO (ALMT). Deputados aprovam projeto que trata da aplicação de agrotóxicos em MT. 2025. Disponível em: https://www.al.mt.gov.br/midia/texto/deputados-aprovam-projeto-que-trata-da-aplicacao-de-agrotoxicos-em-mt/visualizar. Acesso em: 27 mar. 2025.

BEIRIGO, R. M. Sistema pedológico Planosolo-Plintossolo no Pantanal de Barão de Melgaço-MT. 2008. 86 f. Dissertação (Mestrado em Solos e Nutrição de Plantas) – Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, 2008. DOI: 10.11606/D.11.2008.tde-11022009-090704.

BROWN, S. Report exposes meatpackers' role in recent chemical deforestation in Brazil. Mongabay – Conservation News, 2024. Disponível em: https://news.mongabay.com/2024/09/report-exposes-meatpackers-role-in-recent-chemical-deforestation-in-brazil/. Acesso em: 20 mar. 2025.

COCHRANE, M. A. et al. Positive feedbacks in the fire dynamic of closed canopy tropical forests. Science, v. 284, n. 5421, p. 1832–1835, 1999.

DELGADO-MORENO, D.; GAO, Y. Forest degradation estimation through trend analysis of annual time series NDVI, NDMI and NDFI (2010–2020) using Landsat images. In: INTERNATIONAL CONFERENCE ON GEOSPATIAL INFORMATION SCIENCES, 2021, Cham. Anais [...]. Cham: Springer International Publishing, 2021. p. 149–159.

EUROPEAN SPACE AGENCY (ESA). Sentinel-2 Level-2A: Top of Canopy (TOC). Copernicus Data Space Ecosystem, 2024. Disponível em: https://documentation.dataspace.copernicus.eu/Data/SentinelMissions/Sentinel2.html#sentinel-2-level-2a-top-of-canopy-toc. Acesso em: 3 fev. 2025.

EUROPEAN SPACE AGENCY (ESA). Copernicus Browser: User Documentation. Copernicus Data Space Ecosystem, 2024a. Disponível em: https://documentation.dataspace.copernicus.eu/Applications/Browser.html. Acesso em: 3 fev. 2025.

FAO – FOOD AND AGRICULTURE ORGANIZATION. Pesticides Use and Trade, 1990–2021. FAOSTAT Analytical Briefs, 2023.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

FERREIRA, A. M. D. S. D.; LIMA, R. B.; COSTA NETO, S. V. O crescimento agrícola e comércio ilegal de agrotóxicos no Brasil. Observatório de la Economía Latinoamericana, v. 23, n. 2, e8894, 2025.

FREITAS, H. Fazendeiros jogam agrotóxico sobre Amazônia para acelerar desmatamento. Repórter Brasil, 2021. Disponível em: https://reporterbrasil.org.br. Acesso em: 18 mar. 2025.

GAO, B. C. NDWI – A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sensing of Environment, v. 58, n. 3, p. 257–266, 1996.

GARZA, B. N. et al. Quantifying citrus tree health using true color UAV image. Remote Sensing, v. 12, 170, 2020. DOI: 10.3390/rs12010170.

GONZALES, J. Chemical defoliants sprayed on Amazon rainforest to facilitate deforestation in Brazil. 2022.

HESS, S. C. et al. Agrotóxicos no Brasil: cenários de políticas sinistras. Revista da ANPEGE, v. 20, n. 42, 2024.

HUETE, A. et al. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment, v. 83, p. 195–213, 2002. DOI: 10.1016/S0034-4257(02)00096-2.

HUNT JR, E. R. et al. Remote sensing leaf chlorophyll content using a visible band index. Agronomy Journal, v. 103, n. 4, p. 1090–1099, 2011.

HUNT JR, E. R. et al. A visible band index for remote sensing leaf chlorophyll content at the canopy scale. International Journal of Applied Earth Observation and Geoinformation, v. 21, p. 103–112, 2013.

IBGE – INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. Manual técnico da vegetação brasileira. 2. ed. rev. e ampl. Rio de Janeiro: IBGE, 2012.

JELÍNEK, Z. et al. Winter wheat, winter rape and poppy crop growth evaluation with the help of remote and proximal sensing measurements. Agronomy Research, v. 18, n. 3, p. 2049–2059, 2020. DOI: https://doi.org/10.15159/AR.20.176.

JUNK, W. J.; NUNES DA CUNHA, C. Pasture clearing from invasive woody plants in the Pantanal: a tool for sustainable management or environmental destruction? Wetlands Ecology and Management, v. 20, p. 111–122, 2012.

LASTOVICKA, J. et al. Sentinel-2 data in an evaluation of the impact of the disturbances on forest vegetation. Remote Sensing, v. 12, 1914, 2020. DOI: 10.3390/rs12121914.

LAPOLA, D. M. et al. The drivers and impacts of Amazon forest degradation. Science, v. 379, n. 6630, eabp8622, 2023.

LEMES, E. M. et al. Triangular greenness index to evaluate the effects of dicamba in soybean. AgriEngineering, v. 4, n. 3, p. 758–769, 2022.

MAPBIOMAS. Coleção 9 da série anual de Mapas de Cobertura e Uso da Terra do Brasil. 2025. Disponível em: https://plataforma.brasil.mapbiomas.org/. Acesso em: 18 fev. 2025.

MONTENEGRO, M.; COLCE, J. (Orgs.). Atlas dos agrotóxicos: fatos e dados sobre agrotóxicos na agricultura. Rio de Janeiro: Fundação Heinrich Böll, 2023. 68 p. ISBN 978-65-87665-17-7. Disponível em: https://br.boell.org/sites/default/files/2023-12/atlasdo-agrotoxico-2023.pdf. Acesso em: 14 nov. 2024.

MATO GROSSO. Secretaria de Estado de Meio Ambiente. Parceria SEMA-REM/MT: apreensão de maquinários flagrados em desmate ilegal interrompe ciclo de crimes ambientais. 2024. Disponível em:

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972

https://rem.sema.mt.gov.br/imprensa/parceria-sema-rem-mt-apreensao-de-maquinarios-flagrados-em-desmate-ilegal-interrompe-ciclo-de-crimes-ambientais/. Acesso em: 25 mar. 2025.

MINISTÉRIO PÚBLICO DO ESTADO DE MATO GROSSO (MPMT). Desmatamento químico em MT repercute na imprensa internacional. 2024. Disponível em: https://www.mpmt.mp.br/conteudo/58/149273/desmatamento-quimico-em-mt-repercute-na-imprensa-internacional. Acesso em: 27 mar. 2025.

NASA FIRMS. Fire Information for Resource Management System (FIRMS), 2024. Disponível em: https://firms.modaps.eosdis.nasa.gov. Acesso em: 18 jan. 2025.

NICAS, J.; MILHORANCE, F. La nueva amenaza para los bosques brasileños: los productos químicos. The New York Times, 2024. Acesso em: 25 mar. 2025.

PARANHOS, A. C. et al. Geotecnologias para aplicações ambientais. Criciúma: Uniedusul, 2021. p. 394.

PENHA, A. R. et al. Análise de dados Harmonized Landsat Sentinel para mapeamento de uso e cobertura da terra em área de expansão agrícola no Cerrado. Boletim de Geografia, v. 41, p. 38–56, e64865, 2 abr. 2023.

POLAT, N. An investigation of Triangular Greenness Index performance in vegetation detection. Intercontinental Geoinformation Days, v. 1, p. 166–168, 2020.

POLAT, N.; MEMDUHOĞLU, A.; KAYA, Y. Triangular Greenness Index Analysis for Monitoring Fungal Disease in Pine Trees: A UAV-based Approach. Bartın Orman Fakültesi Dergisi, v. 26, n. 2, p. 1-15, 2024. DOI: https://doi.org/10.24011/barofd.1352729.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.63, n.2, p. 195 – 217, 8/2025
https://doi.org/10.5380/raega.v63i2.99972