Environ Monit Assess (2022) 194: 201
https://doi.org/10.1007/s10661-021-09651-5

Application of remote sensing to analyze the loss of natural vegetation in the Jalapão Mosaic (Brazil) before and after the creation of protected area (1970–2018)

Fabrícia Cristina Santos · Rita Marcia da Silva Pinto Vieira · Alexandre Augusto Barbosa · Yara da Cruz Ferreira · Silvia Palotti Polizel · Marcelo Francisco Sestini · Jean Pierre Henry Balbaud Ometto

Received: 14 May 2021 / Accepted: 12 November 2021 / Published online: 19 February 2022

Abstract This study aims to map the changes in land use and land cover between 1970 and 2018, analyzing the influence of the protected area s (PAs) in the Cerrado biome, specifically in the area of the Jalapão Mosaic. Images from the Landsat 1-MSS, 5-TM, and 8-OLI satellites were used and processed in SPRING and ArcGIS software. The analyses were based on three approaches: (1) the boundary of the Jalapão Mosaic, (2) the PAs, and (3) a comparison between the PAs and their surroundings. The Jalapão Mosaic results demonstrated that 26% (≅8410 km^2) of the area was burned, and 15.5% (4971 km^2) was anthropized in at least one of the analyzed periods. Among the PAs, the Serra Geral do Tocantins Ecological Station (Integral Protection) presented the largest burned area (43.7%≅3095 km^2); however, there was no significant increase in the anthropized areas due to fire. Meanwhile, the anthropized areas in the Rio Preto and Serra da Tabatinga Environmental Protection Areas (Sustainable Use) increased by 27.5% and by 75%, respectively, due to agricultural expansion. By analyzing the two groups of PAs and their surroundings, it was observed that the loss of natural vegetation was restrained and fires were less intense in the Integral Protection Units; in the Sustainable Use Units, there was a significant increase in the anthropized areas. Furthermore, over 70% of the anthropized areas occurred in the surrounding areas, thus showing the importance of creating PAs.

Keywords Linear spectral mixing model (LSMM) · Land cover change · Deforestation · Cerrado biome · Protected area

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10661-021-09651-5.

F. C. Santos (✉) · R. M. da Silva Pinto Vieira · A. A. Barbosa · Y. da Cruz Ferreira · S. P. Polizel · M. F. Sestini · J. P. H. B. Ometto
Instituto Nacional de Pesquisas Espaciais–INPE, Caixa Postal 515, Sao Jose dos Campos, SP 12245-970, Brazil
e-mail: fabriciacs96@gmail.com

R. M. da Silva Pinto Vieira
e-mail: rita.marcia@inpe.br; ritamsp@gmail.com

A. A. Barbosa
e-mail: alexandre.barbosa@inpe.br

Y. da Cruz Ferreira
e-mail: yara.ferreira@inpe.br

S. P. Polizel
e-mail: sppolizel@gmail.com

M. F. Sestini
e-mail: marcelofsestini@gmail.com

J. P. H. B. Ometto
e-mail: jean.ometto@inpe.br

Introduction

The Cerrado is the second largest biome in South America, accounting for 22% of the Brazilian territory and nearly 2 million km^2. In addition to its wide extension in the country, the region has many springs that contribute to the formation of important hydrographic basins in South America (MMA, 2018a; WWF, 2019). The biome is considered the richest biodiversity savanna in the world due to its considerable amount of flora and fauna species (Klink & Machado, 2005; MMA, 2018a; Sawyer et al., 2017). The biome is, therefore, considered one of the world's biodiversity hotspots, characterized by a high index of endemism and high threat degree to its species (Klink & Machado, 2005; Myers et al., 2000); nevertheless, high percentage of natural vegetation loss is observed in the past 20 years.

Between 2000 and 2018, the agricultural area in the biome increased 16.4% (MAPBIOMAS, 2021). Between 2000 and 2001, soybean comprised 75,300 km^2, and from 2018 to 2019, reached 182,000 km^2 in the Cerrado states (Rudorff et al., 2020). According to the TerraClass Project (MMA, 2015a) mapping for 2013, the anthropic use corresponded to 43.4% of the total biome area, with the main uses being planted pasture (29.5%), annual agriculture (8.5%), and perennial agriculture (3.1%). Furthermore, the MAPBIOMAS Project mapping for 2018 indicated a 44% of anthropized area in the biome (MAPBIOMAS, 2021).

Another activity threatening the Cerrado is anthropic fires. As some authors claim that controlled and well-planned burnings help the ecosystem functionality and biodiversity, a policy that considers fire as part of the biome's dynamics is necessary (Durigan & Ratter, 2016; Hoffmann, 2013; Schmidt et al., 2016). Klink and Machado (2005) state that although the Cerrado is adapted to burning, uncontrolled and frequent use of this technique can lead to loss of nutrients, soil compaction, and erosion.

Among the regions intensely affected by deforestation and fires in the Cerrado is Brazil's newest agricultural frontier, formed by the states of Maranhão, Tocantins, Piauí, and Bahia, called MATOPIBA. The region was officially delimited by Decree No. 8447 of May 2015 and encompasses 73 million hectares (BRASIL, 2015; Miranda et al., 2014). However, some articles point that the area already was used as an agricultural region in the mid-1980s, when it was financially benefited by the Japanese-Brazilian Cooperation Program for the Development of Cerrados (PRODECER) (Pires, 2000; Pessoa & Inocêncio, 2014; Santos, 2016; Salvador & Brito, 2018).

According to the Satellite Monitoring of Deforestation in Brazilian Biomes (MMA, 2009, 2011a, b, 2015b), between 2002 and 2008, the states in MATOPIBA were among the five that most deforested the Cerrado. During the years 2008–2009, 2009–2010, and 2010–2011 mappings showed that these states contributed most to the biome's deforestation. The region is also under pressure by agricultural expansion, especially soybeans, as well as pastures, coal, and mining (Malleson et al., 2018). Agricultural expansion in MATOPIBA occurred mainly over areas of native vegetation, while in other Cerrado areas, it happened over areas of pasture (Rudorff et al., 2015). Contrastingly, in the crop seasons of 2013–2014 and 2018–2019 for MATOPIBA, 80.8% of the soybean expansion occurred in areas without deforestation (Rudorff et al., 2020).

In the MATOPIBA, fire management is used to open new agricultural areas, as it is the fastest and cheapest tool that farmers have to expand croplands, besides being used in a controlled way at harvest time and for weed control (Resende et al., 2017; Silva et al., 2020). According to Silva et al. (2020), 58% of the Cerrado biome's burned areas occurred within MATOPIBA between 2001 and 2018, with 50% of the areas corresponding to the Tocantins microregions. The Jalapão microregion was the most affected, on a data history of the past 18 years, 332% of its area burned (Silva et al., 2020).

Studies indicate that in Cerrado areas where natural vegetation has already been converted to other uses, the remnant of natural vegetation is located in protected areas (Alencar et al., 2020). One of the largest areas of forest remnants in the Cerrado is the Jalapão region, which has two categories of protected areas: (1) Integral Protection, whose main objective is nature protection, and (2) Sustainable Use, which purpose is to reconcile nature conservation and the sustainable use of available resources (ICMBIO, 2013; Klink & Machado, 2005; MMA, 2018b, c; Schmidt et al., 2011). In September 2016, through Ordinance No. 434 (BRASIL, 2016), the PAs in the Jalapão region were converted into a Mosaic in order to ensure the conservation of the region's fauna, flora, and traditional customs through integrated and participatory management, while still meeting the particular needs of each PA category (BRASIL, 2016; MMA, 2018b).

Despite the importance of Jalapão protection, due to its environmental richness, the agricultural expansion is a big threat to the natural systems in this region (Cristo et al., 2016; Gamba & Collicchio, 2018). The agricultural potential of the region, summed to the financial aid from the national and foreign governments for soybean production (in particular on the periods of 1960 and 1985–1995) and the strong financial support, on the 2000s, from a regional state government (Bahia) for the mechanization and expansion of agriculture, directly framed the anthropic use of Jalapão Mosaic's area (Cristo et al., 2016; Espíndola & Cunha, 2015; ICMBIO, 2013; Menke et al., 2009; Pessoa & Inocêncio, 2014; Pires, 2000; Santos, 2016). Moreover, fires are generally misused for managing agricultural areas aiming on stimulating pasture regrowth for cattle grazing and stimulate the flowering of "capim-dourado" (golden grass) used in handicrafts (Schmidt et al., 2011, 2016). Resende et al. (2017) stressed the important of the management plan in MATOPIBA's Pas. Lower percentage of burned area was observed in the Serra das Confusões National Park compared to the Araguaia National Park, where a management plan was ever established.

Due to the broad coverage, updating, and data frequency, remote sensing is used in several environmental studies, such as the detection of environmental damage, land use and land cover mapping, identification and monitoring of deforestation, and occurrence of fires (Ortiz & Freitas, 2005; Vaeza et al., 2010). In this sense, linear spatial spectral mixture model and band ratio techniques were used by Barbosa et al. (2009) to identify the pressure caused by logging in the Jamari National Forest in Rondônia and on two other national forests. Ferraz Neto et al. (2011) used the linear spatial spectral mixture model and band ratio technique to map the deforestation resulting from the removal of timber for charcoal. The authors concluded that the Environmental Protection Area (EPA) establishment in 1997 reverted the deforestation in 1990 and 1994, maintaining the region's preservation in subsequent mappings. Resende et al. (2017) used the linear spatial spectral mixture model and image segmentation in mapping MATOPIBA, determining that 96% of the fires occurred in savanna, woody savanna, and grass areas. In addition, they observed that fires occurred more frequently in drier years and on properties that use fire for land management. The PAs disclosed high burned area percentages, with those in the Jalapão Mosaic having 20% of their areas burned in the analyzed years. Gamba and Collichio (2018) analyzed soybean expansion in the Cerrado, in MATOPIBA, emphasizing the Jalapão Mosaic. They found that of the seventeen municipalities that encompass or are close to the PAs in the Jalapão Mosaic, only three do not produce soybean. Although created to conserve and preserve the environment, the authors concluded that the Jalapão Mosaic has been under intense pressure from the agribusiness developed in MATOPIBA.

Considering the importance of MATOPIBA region in the context of the national discussion to cope agricultural production and environmental conservation, this work focused on two central objectives: first, to identify and understand the main drivers of land use cover change for the Jalapão PAs based on land use and land cover change maps for the period between 1970 and 2018 and secondly, to evaluate the influence of the creation of PAs on the containment of deforestation and fire control, and the preservation of forest remnants.

Study Area

The study region is the Jalapão Mosaic, which encompasses eight PAs (four of them being Integral Protection and four being Sustainable Use), as well as non-protected areas (BRASIL, 2016; MMA, 2018d). Together, they account for an area of approximately 32,000 km^2 spread over seventeen municipalities in the states that make up the MATOPIBA (Fig. 1).

The dry season in the region occurs between May and September, and the rainy season between October and April, with July being the driest month (ICMBIO, 2011; SEPLAN, 2003, 2017). The average annual rainfall of the region is between 1500 and 1600 mm, 95% of which occurs during the rainy season; the average temperature is 25 °C (ICMBIO, 2011; SEPLAN, 2012, 2017).

The region's vegetation consists mainly of campo limpo, campo sujo, cerrado sensu stricto, riparian, and gallery forests, besides presenting tablelands and veredas in its landscape (Cristo et al., 2016; SEPLAN, 2017; Veloso, 2019). The predominant soils are Neosol and Latosol (ICMBIO, 2013; SEPLAN, 2017). Neosol is a poorly developed soil, formed by mineral or organic material with low levels of natural fertility, low available water capacity, and high susceptibility to erosion (Lumbreras et al., 2015; EMBRAPA, 2018a). Latosol is a soil formed by mineral material with suitable physical conditions for crop root development and low susceptibility to erosion; however, it is also characterized by low natural fertility (Lumbreras et al., 2015; EMBRAPA, 2018a).

The Jalapão Mosaic has the largest cluster of PAs in the Cerrado (Table 1), and its management is shared by the Chico Mendes Institute for Biodiversity

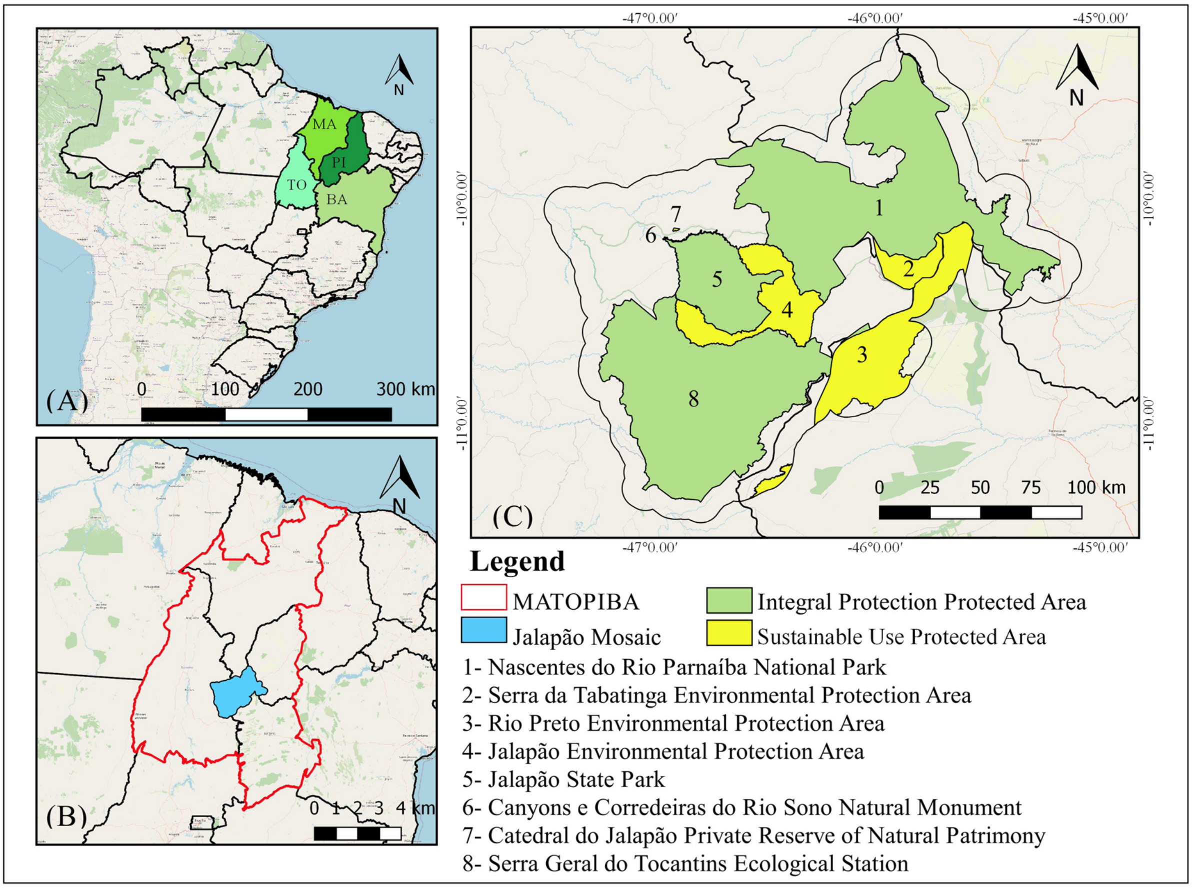


Fig. 1 Location of the study area and groups of PAs: **A** states constituting the MATOPIBA region, **B** boundary of MATOPIBA and Jalapão Mosaic, and **C** protected area belonging to the Jalapão Mosaic

Table 1 Protected area in the Jalapão Mosaic by group and date of creation

Protected area	Area (km^2)	Group	Year of creation
Rio Preto Environmental Protection Area	2199	Sustainable Use	2005
Jalapão Environmental Protection Area	1349	Sustainable Use	2000
Serra da Tabatinga Environmental Protection Area	418	Sustainable Use	1990, with a reduction in 2002
Serra Geral do Tocantins Ecological Station	7071	Integral Protection	2001
Canyons e Corredeiras do Rio Sono Natural Monument	15	Integral Protection	2012
Jalapão State Park	1590	Integral Protection	2001
Nascentes do Rio Parnaíba National Park	7312	Integral Protection	2002
Catedral do Jalapão Private Reserve of Natural Patrimony	3	Sustainable Use	2010

Conservation, the Institute of Environment and Water Resources of Bahia, the São Félix do Tocantins Municipal Environment Secretariat, and a privately managed PA (Borges et al., 2016; ICMBIO, 2013; Veloso, 2016).

Materials and methods

Datasets

Mapping was based on 36 images from the Landsat 1-MSS, Landsat 5-TM, and Landsat 8-OLI satellite, corresponding to the period from 1970 to 2018 (see Table S1 Supplementary Material). Images of the dry period were selected with minimal cloud cover, and mosaics were prepared for six decadal periods of analyzes (1970s, 1980s, 1990s, 2000s, and 2010s, including a mosaic for 2018). The images were chosen and acquired through the US Geological Survey website (https://store.usgs.gov/). All images were made available with standard terrain correction, radiometric and geometric corrections, and orthorectified (USGS, 2019).

The data on fires focuses and scars were acquired from the BdQueimadas Project of the Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (INPE) for the last three mapped periods (2000, 2010, and 2018), since they began to be reported and made available in 1998 (https://queimadas.dgi.inpe.br/queimadas/portal). In relation to water bodies, this data corresponds to a mask generated from the database derived from the MAPBIOMAS Project—collection 3.1, available at https://mapbiomas.org/.

All data processing was performed using the free-access SPRING software developed by INPE, versions 4.2 and 5.5.1, and ArcGIS 10.2.2 software.

Image processing

Initially, the Linear Spectral Mixture Model (LSMM) was applied to the Landsat images, considering the Blue (band 3), Red (band 4), and Green (band 5) channels, to estimate the proportion of soil, vegetation, and shade (or water). From this stage, it was generated three fraction images: (1) the soil-fraction that highlights areas with high reflectance values such as bare soil and clear-cuts and also areas smaller such as log landings and logging roads of selective logging activities, (2) the vegetation-fraction that highlights the forest cover conditions and allow differentiating between forest and non-forest areas, and (3) the shade-fraction image that highlights areas with low reflectance values such as water, shade, and burned areas and, consequently, allow forest degradation caused by fires to be identified (Shimabukuro & Smith, 1991; Shimabukuro et al., 2019). The fraction images reduce the size of the input data that will be used, for example, in image classification, in addition to highlighting targets of interest (Ferreira et al., 2003). Thus, LSMM is written according to Eq. 1:

$$\gamma_i = \sum \left(a_i j_x j_l\right) + \varepsilon_i \quad (1)$$

where Υ_i denotes average spectral reflectance in the spectral band i; aij denotes spectral response of the j component of the mixture in the spectral band i; xj denotes proportion of the component j at a pixel; εi denotes error in the spectral band i; $i=1$, n (number of spectral bands used); $j=1$, and m (number of considered components).

In order to derive a greater image to highlight the difference between forested and deforested areas, the arithmetic operation of band ratio was applied to the soil-fraction and vegetation-fraction images, calculated by the following equation (INPE - DPI, 2019a):

$$\text{Band Ratio} = \text{Gain} \times (A/B) + \text{Off} - \text{set} \quad (2)$$

with the gain value is set at 90, A is the soil-fraction, B is the vegetation-fraction, and the offset value is set at 50, according to studies of Barbosa et al. (2009) and Ferraz Neto et al. (2011).

The fraction images were segmented, dividing the image into regions or segments composed of sets of pixels with spectral similarities (Bins et al., 1993; INPE - DPI, 2019b). The number of polygons generated, the image processing time, and the number of segmented classes depend on the similarity and area values that will be defined by the user taking into account the characteristics of the image (Jensen, 2005).

After the segmentation process, the segmented fraction images were classified using the ISOSEG unsupervised classification method (Bins et al., 1993), in which several unknown pixels are divided into classes from image value groupings (Ganem et al., 2020). The groupings were defined by considering the classes of natural vegetation, anthropized area, burned area, water, and not observed, following the interpretation key described in Table 2.

The burned area polygons were extracted from the BdQueimadas project database, being the raw data derived from satellite images, polygonized, classified, and converted to raster. The classes referring to cloud and cloud shadow were mapped using the Spatial Language for Algebraic Geoprocessing – LEGAL (Câmara, 1995) (Supplementary Material – Scripts S2). We also included to the mapping the information regarding water bodies provided by MAPBIOMAS. This class of the mapping was obtained by the following conditional:

Con((”layer” >= 0) and (”MAPBIOMAS datum” == 26)
|(”MAPBIOMAS datum” == 33)
|(”MAPBIOMAS datum” == 31)), 33,
Con((”layer” >= 0), ”layer”)}

with the numbers corresponding to the MAPBIOMAS classes, being 26 the “Water” class, 33 the “River, Lake and Ocean” one, and 31 the class “Aquaculture.”

All classes obtained by automatic classification were checked by visual interpretation and, when necessary, the polygons were adjusted or deleted.

In the final mosaic, a pixel cleanup was applied to eliminate areas with less than ten pixels, and the mosaics were reprojected to the Albers/SAD 69 projection. In addition, the zero-valued pixels were changed to “No Data,” preventing these from being overlaid on top of the classified pixels. For this step, we used the following conditional:

$$SetNull(''layer'' == 0, ''layer'')$$

Mapping validation

The Kappa Index was calculated to assess mapping reliability using Eq. 3 (Cohen, 1960; Landis & Koch, 1977). The calculation was made using the “Interrater Reliability” analysis contained in the “Real Statistics” tool of the Excel software.

$$k = \frac{Pa - _{Ps}}{1 - _{Ps}} \quad (3)$$

where p_a is the observational probability of agreement, p_s is the hypothetical expected probability of agreement, and the value 1 is used to standardize the index so that the result is not above 1.

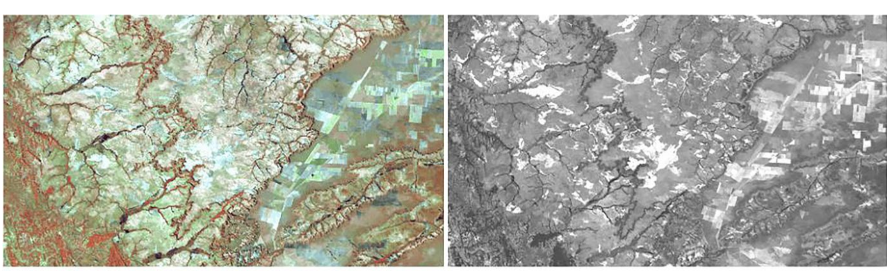
For the construction of the Kappa confusion matrix, information collected in the field campaign in 2018 was used as ground truth. Some of the photos taken during fieldwork, with their respective pattern in the image and class description, can be seen in Table S2 in the Supplementary Material.

Results and discussion

Mapping of the burned and deforested/anthropized areas

The combination of soil-vegetation fraction image showed the best contrast for mapping the classes of interest, with segmentation defined by thresholds 10 and 50, corresponding to the values of similarity and area, respectively. Figure 2 illustrates an original image (Fig. 2A) and a soil-vegetation fraction image (Fig. 2B) highlighting burned and deforested/anthropized areas.

The characteristics of the LSMM images helped to speed up the mapping of the classes of interest in relation to the original image. This happened because the fraction images contained the proportions referring to the soil, vegetation, and shadow components present in the different pixels of the image, in addition to highlighting the features to separate deforested areas from vegetated areas. Additionally, we used



(A) (B)

Fig. 2 Landsat image (**A**) and soil-vegetation fraction image (**B**) separating deforested areas from vegetated areas (areas with higher brightness in the image) field information for a better acquisition of endmembers (pure pixels) and collection of the samples visually. According to Dutra et al. (2019), the complexity of pixel composition of orbital images has been commonly referred to the spectral mixture problem and the better the input data, the more accurate the LSMM results. Figure 3 illustrates the mapping results for the Jalapão Mosaic for the six analyzed periods, and Table 3 presents the areas for each mapped classes.

Burned areas can also be observed in Fig. 3 and Table 3. The 1990s and 2010s showed considerable increases in burned areas; however, the largest occurred in the 1970s when 9.5% of the area of the Jalapão Mosaic was affected by fire. Results indicate that approximately 26% (8410 km^2) of the total area was burned in at least one analyzed period. Figure 4 shows the spatial distribution of all burned areas between 1970 and 2018 (4A), and how often each of these areas was burned during this period (4B).

According to Schmidt et al. (2016), the most common productive, commercial, and subsistence activities in Jalapão (agriculture, livestock, subsistence hunting, and handicrafts) depend on the use of fire. Durigan and Ratter (2016) argue that the lack of consistent policies for fire management and contention, which would be essential to maintain the structure, biodiversity, and ecosystem functionality, threats the Cerrado biome. Figures 3 and 4 show a large burned area in the studied period, although few regions had a recurrence of fire or were converted into anthropized areas, allowing the natural vegetation recovery (Table 4).

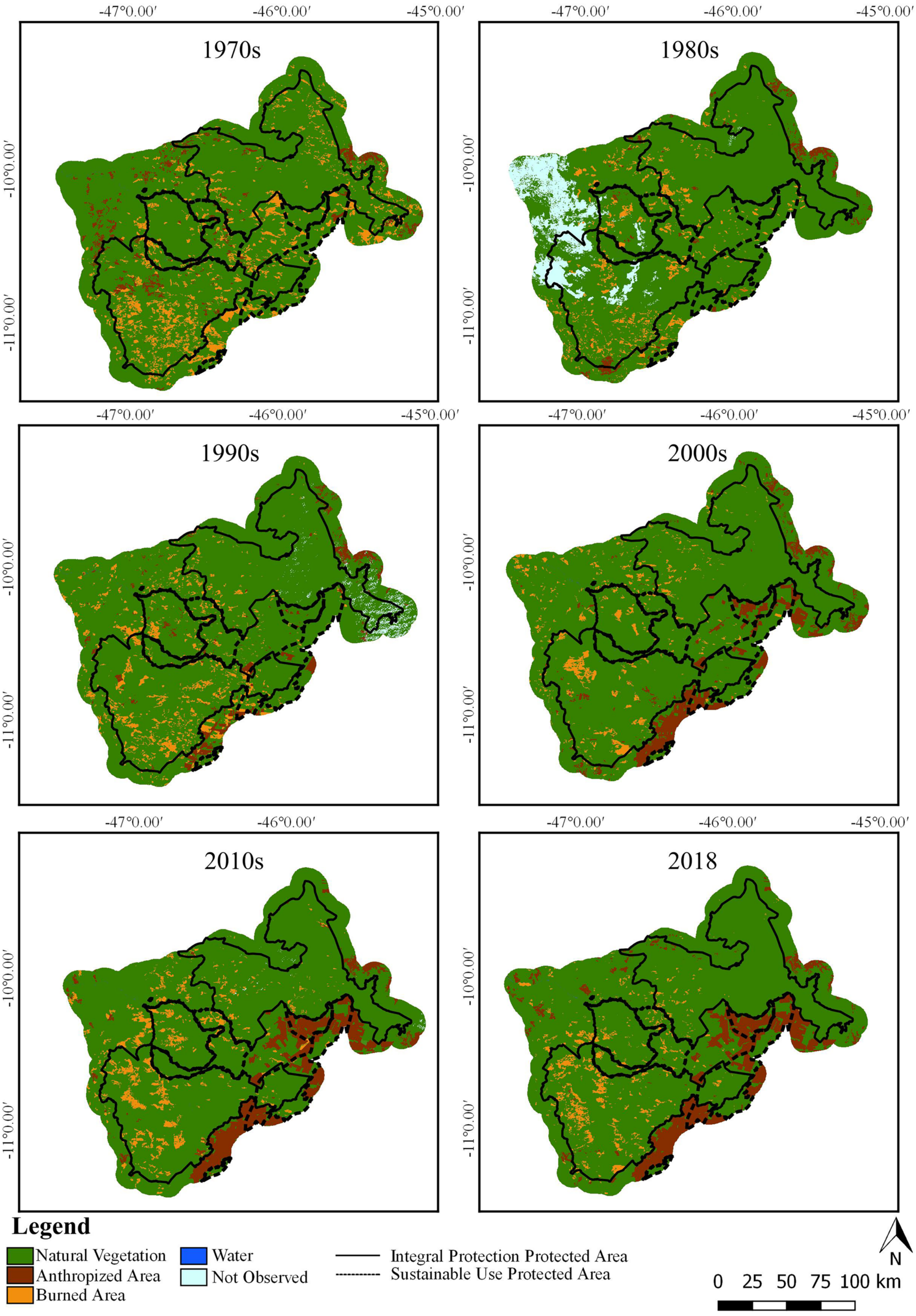
During the initial years of the anthropic conversion of natural areas, these actions accounted for a little over 3% of the Mosaic, decreasing to 1.7% in the second decade. However, in the following periods, these areas experienced exponential growth, reaching 10.2% in 2018 (Table 3). The anthropized areas are concentrated in the eastern and southeastern portions of the Jalapão Mosaic, where agriculture has occupied natural vegetation areas (Fig. 5). These results corroborate those found by Rudorff et al. (2015), who identified that the MATOPIBA states have 4.2% of the anthropized areas with high agricultural suitability; between 2000 and 2014, most of the expansion in the agricultural frontier occurred over areas of native vegetation. The mapping results indicate that 15.5% (4971 km^2) of the total area was anthropized during at least one of the analyzed periods (Fig. 5B).

The increase in anthropized areas in the 1970s may have occurred because this period was marked by large financial incentives such as the institution of subsidized agricultural credit and linked to the technologies of the "Green Revolution," through Law No. 4,829/1965. This law created the National Rural Credit System, the Development Program Midwest (in Portuguese PRODOESTE), which defined for agriculture the objective of supplying urban centers, supplying raw materials for industries and strengthening exports, among others.

In the 1980s, there was a reduction in credit and the governments, with the objective of environmental protection, implemented incentives for small producers, the permanence of the population in the rural area, the offer of basic services, and the rationalization of the use of natural resources in regional development programs (Franco et al., 2016). In addition, the creation of the Nossa Natureza Program, one of the most important ecological preservation programs in Brazil, refined the legislation, changing important laws such as the Forest Code, the National Environmental Policy Law and created the National Environment Fund (Law No. 7,797/89), which resources had priority for projects destined to protected area, aiming at adapting the units to the new regulations and the purpose of their creation (Borges et al., 2009). These actions are probably the main responsible for the reduction of anthropized areas, identified in this study.

From the 1990s onwards, there has been an increase in the agricultural sector, which became the main responsible for the surplus in the Brazilian trade balance. Between 1990 and 2017, the country's agricultural balance increased almost tenfold, reaching in this last year US$ 81.7 billion. The advancement of research and technology plant species, such as soybeans, was developed, capable of adapting to any type of soil and climate in the country, which allowed planting in Cerrado areas that were not suitable until then (EMBRAPA, 2018b). In addition, we observed that 25.5 Mha of the Cerrado biome were converted to agricultural and pasture lands between 1985 and 2019 (MAPBIOMAS, 2021), highlighting the growth of the agricultural sector in the region.

Considering the land-use and land-cover changes (km^2) in the Jalapão Mosaic between 1970 and 2018, it was noted a decrease in natural vegetation and


1970s
1980s
1990s
2000s
2010s
2018
-47°0.00′
-46°0.00′
-45°0.00′
-10°0.00′
-11°0.00′
Legend
Natural Vegetation
Anthropized Area
Burned Area
Water
Not Observed
Integral Protection Protected Area
Sustainable Use Protected Area
N
0 25 50 75 100 km

◂**Fig. 3** Land use and land cover mapping of the Jalapão Mosaic for the period from 1970 to 2018

increase in anthropized areas, especially from the 2000s onward (Fig. 6).

As in the agricultural frontier area, the surroundings of the Jalapão region also show potential for agriculture, suffering pressure from the most common crops (soy, rice, corn, and cotton) (Cristo et al., 2016; ICMBIO, 2013; Menke et al., 2009). Agriculture in MATOPIBA was encouraged by several financial programs such as PRODECER, developed by the Brazilian and Japanese governments in 1985 and 1995 in the states of Bahia, Maranhão, and Tocantins, to expand agricultural areas, especially for soybean cultivation (Pessoa & Inocêncio, 2014; Santos, 2016). From 2000 onwards, the government of Bahia implemented four programs to leverage the agricultural production in the state, directly impacting the west of the state, and consequently, the municipality of Formosa do Rio Preto, one of the municipalities most occupied by anthropized areas in the Jalapão Mosaic (Gamba & Collicchio, 2018; Menke et al., 2009).

Mapping of the Integral Protection PAs

Table 5 presents data related to the quantification of the classes mapped over the analyzed periods concerning changes in land use and land cover specifically in the Integral Protection PAs in the Jalapão Mosaic.

The analysis of Table 5 showed that the Serra Geral do Tocantins Ecological Station was the PA with the largest burned area, with 43.7% (≅3095 km^2) of the total area burned in at least one period, without significant loss of natural vegetation areas. The frequency in which fires occurred may justify the absence of fire conversion in anthropized areas, as there was a high frequency of fire in several areas (Fig. 7). Additionally in 2014, the Serra Geral do Tocantins Ecological Station was selected to implement the Integrated Fire Management Pilot Program. Among the techniques used by the program are early burns carried out at the beginning of the dry season, thus changing the fire regime of the PA, which until then, occurred at the end of the dry season. With the implementation of the new regime, fires were less severe and slower due to the weather conditions of the period (Schmidt et al., 2016).

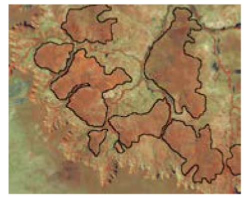
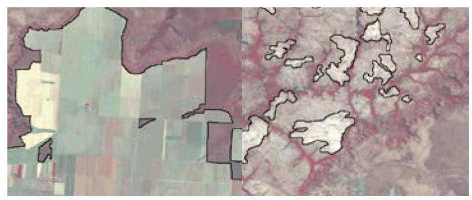
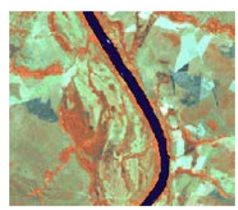
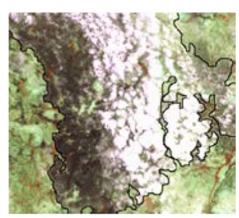
Although there is a negative view of fire in natural areas, it is essential to emphasize that the use of fire is not prohibited in all PAs, and is allowed in three situations according to Art. 38 of Law No: 12.651 of 2012: (I) specific conditions for agropastoral or forestry practices, (II) PAs that have controlled burning in their management plan and only in environments that have the use of fire in their evolution as ecological characteristics, and (III) scientific research of duly approved projects conducted by a recognized research institution. All cases require an authorization from the responsible environmental agencies (BRASIL, 2012). Besides the national legislation, which allows fire in certain situations, in the municipalities within the State of Tocantins in the Jalapão Mosaic, controlled burning is allowed through authorization and compliance with regulations in the months of May, June, and July. However, these authorizations and actions are suspended in case of adverse meteorological conditions (DEFESA CIVIL, 2020; NATURATINS, 2020). The standardization of fire use may contribute to the moderate frequency of burnings and to the non-conversion of these areas into anthropized areas.

The analysis of Table 5 also shows that the Rio do Sono Canyons and Rapids Natural Monument, the Jalapão State Park, and the Nascentes do Rio Parnaíba National Park did not suffer significant loss of natural vegetation as the increase in anthropized areas was not significant and the fires occurred in a controlled way.

Mapping of Sustainable Use PAs

Concerning the dynamics of land cover change in Sustainable Use PAs, the Rio Preto and Serra da Tabatinga EPA presented the most significant negative impacts in the Jalapão Mosaic in the analyzed period (Table 6). In both cases, the anthropized areas were the most prominent in the 2018 mapping, with 27.5% of this class in the Rio Preto EPA located in the municipality of Formosa do Rio Preto in Bahia, and 75% in the Serra da Tabatinga EPA located in the municipality of Mateiros in Tocantins. These PAs are located to the east and southeast of the Jalapão Mosaic and, as mentioned earlier, comprise the largest portion occupied by agriculture. MATOPIBA produced 8.3% (about US$ 8 billion) of Brazil's total agribusiness exports in 2018 (MAPA, 2019), and the municipalities of Formosa do Rio Preto and Mateiros

Table 2 Description of the classes mapped and their interpretation key considering Landsat images.

Classes	Description	Landsat Image Standard
Natural Vegetation	Forest areas	
	Grassland areas	
Anthropized Area	Areas modified by humans, such as pasture, agriculture, urban areas, mining, and exposed soil areas	
Burned	Areas with fire scars and natural and anthropic burned areas	
Water	Water bodies	
Not observed	Cloud and cloud shadow areas	

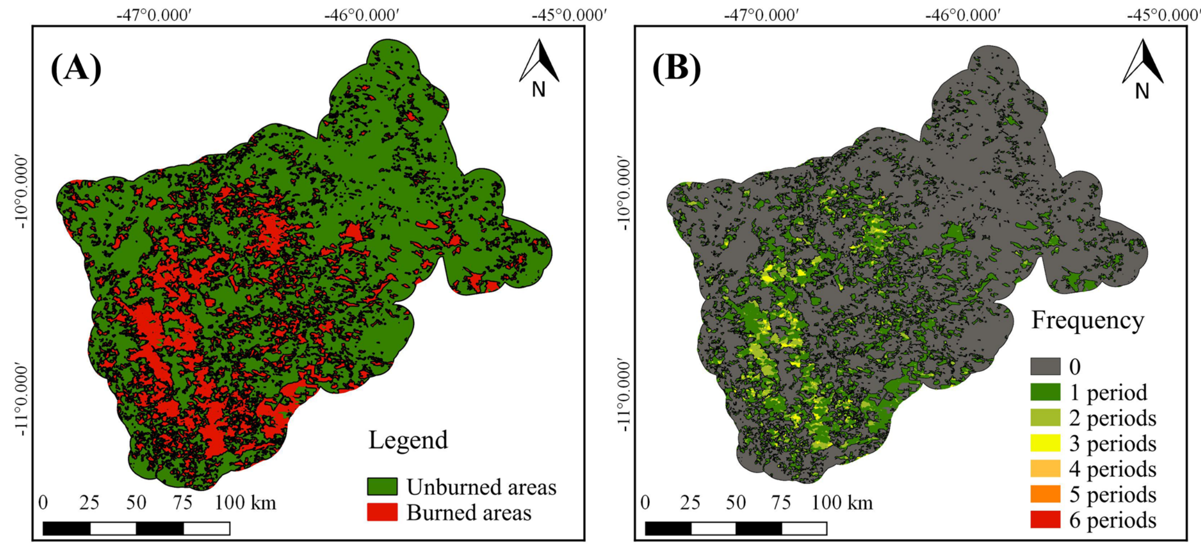


Fig. 4 Distribution of burned and unburned areas (**A**) and the frequency of burned areas (**B**) between 1970 and 2018

produced the most soybeans in their respective states (Gamba & Collicchio, 2018).

According to Article 2 of Law No. 9985 of 2000, EPA are not required to have buffer zones, which follow specific rules and restrictions (BRASIL, 2000); these are used to reduce the negative impacts on the PAs arising from human activities. According to Silva et al. (2017), the absence of buffer zones may contribute to the anthropic pressure on the PAs as the population living near these units has difficulties in distinguishing their area limits. Additionally, the above mentioned PAs do not have a Management Plan in place. According to the MMA (2020), only 466 PAs (19.0%) in Brazil have Management Plans, while 1,980 do not.

The Jalapão EPA obtained positive results; i.e., it maintained the natural vegetation and reduced anthropized areas. Two factors may have contributed to the preservation of the region: (1) It is the only PA of the EPA category in the state of Tocantins that has a management plan (MMA, 2020; Silva et al., 2017). (2) It is the only Sustainable Use CU located between Integral Protection PAs and is more protected than the other PAs in the region.

Dynamics of land use and land cover in the PAs (Integral Protection and Sustainable Use) and the Jalapão Mosaic

Figure 8 displays the distribution of land use and land cover in the Integral Protection and Sustainable Use PAs and in the Jalapão Mosaic area not protected by PAs.

Figure 8 shows that 64.1% (≅18,026 km^2) of the natural vegetation of the Jalapão Mosaic is located in PAs, of which 52.1% are in areas of Integral Protection and 12% in areas of Sustainable Use. Regarding anthropized areas, 70.5% (≅1284 km^2) are outside the Pas, while 22.6% (≅412 km^2) are inside Sustainable Use PAs. A total of 58.5% of

Table 3 Area of the mapped classes for each studied period in km^2

Classes	1970s	1980s	1990s	2000s	2010s	2018
Natural vegetation	28,172.4	27,571.7	29,009.3	28,944.5	27,448.6	27,648.7
Anthropized area	998.4	542.5	927.2	2140.5	3028.6	3291.6
Burned	3064.9	1403.8	1882.8	1140.5	1730.8	1286.0
Water	9.2	9.2	9.0	10.8	8.7	8.9
Not observed	0	2707.9	407.2	0	18,7	0

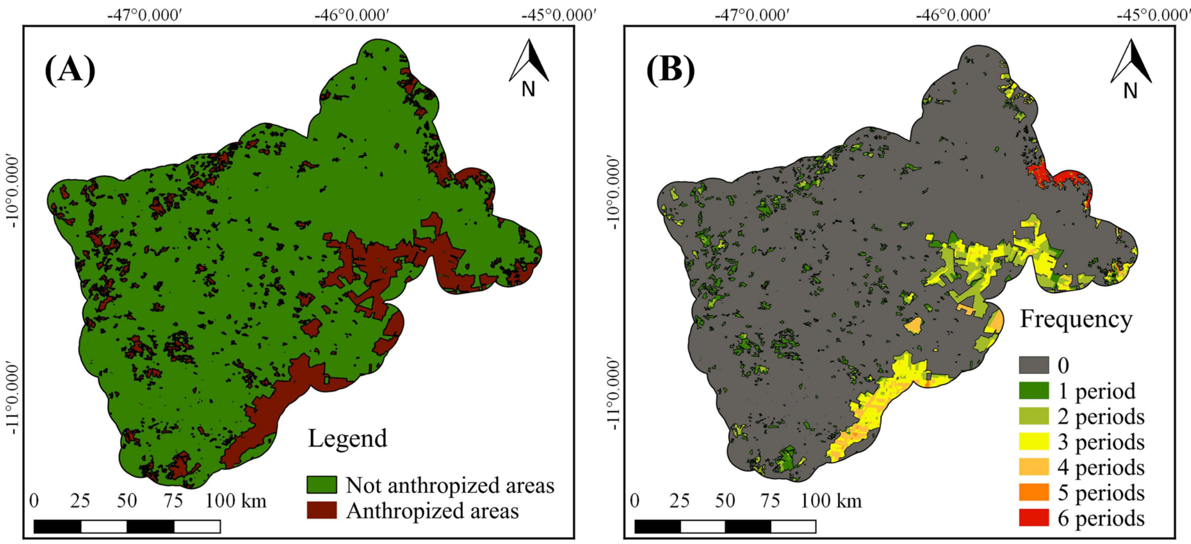


Fig. 5 Anthropized areas (**A**) and frequency of anthropized areas (**B**) between 1970 and 2018

the burned areas (≅1026 km^2) occurred in Integral Protection PAs, and only 10.9% (≅190.75 km^2) were in Sustainable Use PAs. In the case of Integral Protection PAs, the increase in the number of burnt areas may be associated with the integrated fire management plan. Since 2010, integrated fire management has been used in some PAs, of Cerrado, to preventing major forest fires, being found a decrease in Federal protected areas, of 33% when compared to years of critical weather events (El Niño) such as 2010 and 2017, and the reduction reached 40% in 2019 despite political reflexes in the increase of deforestation and fire occurrence (Berlinck & Batista, 2020). In 2014, Schmidt et al. (2016) implemented the integrated fire management in three protected areas of Cerrado: Chapada das Mesas National Park (CMNP), the Jalapão State Park (JSP), and the Serra Geral do Tocantins Ecological Station (SGTES) and used low intensity prescribed fires at the beginning of the dry season as a management strategy. Results show that prescribed burns were of low intensity in the PAs since the fire

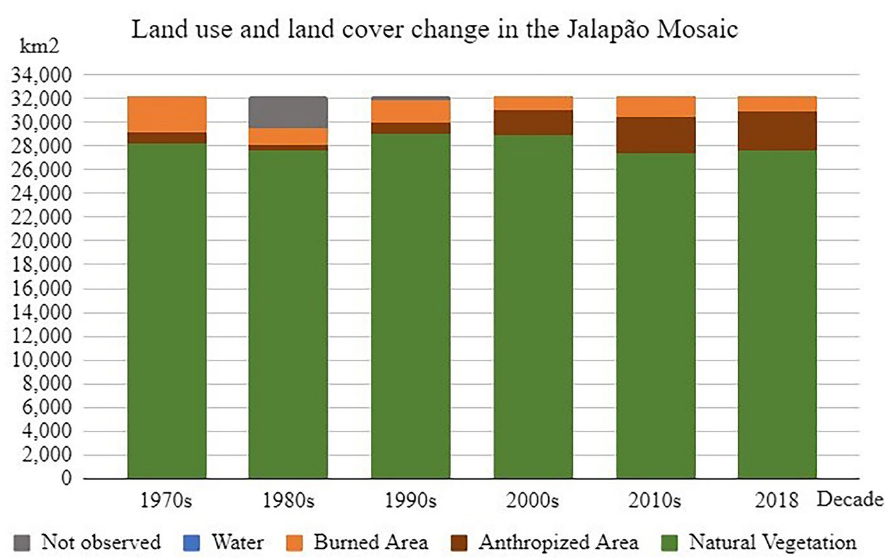


Fig. 6 Land use and land cover change between 1970 and 2018 (km^2)

Table 4 Status of burned areas after the fire event in km^2

Period	Remained burnt	Converted to natural vegetation	Converted to anthropized area	Not observed areas
1970 to 1980	197.6	2777.7	61.2	28.3
1980 to 1990	166.9	1175.9	61.0	0
1990 to 2000	171.7	1526.0	185.1	0
2000 to 2010	113.3	982.9	44.2	0.1
2010 to 2018	235.1	1449.4	46.4	0

was carried out at the beginning of the dry season, in the late afternoon, and early evening with fuel consumption ranging between 46 and 84%.

Integral Protection PAs have greater amounts of natural vegetation and fire events, while the Sustainable Use PAs have larger anthropized areas (see Figures S1 and S2 in the Supplementary Material). In general, the creation of the Integral Protection PAs positively influenced the preservation of natural vegetation and decrease of anthropized areas, while the creation of the Sustainable Use PAs was insufficient to prevent the increase and progress of anthropized areas.

Validation

First, the mapping for 2018 was compared with the points collected during the fieldwork for the same year. The overall accuracy index was 70%, with percentages of 68% for natural vegetation and 88% for burned areas. This map served as the basis for mapping previous years, in addition to the information contained in the MABIOMAS mapping, and in the high-resolution images from Google Earth that were used as secondary evidence.

Regarding the anthropized areas, the accuracy was only 49%. The high error associated with this

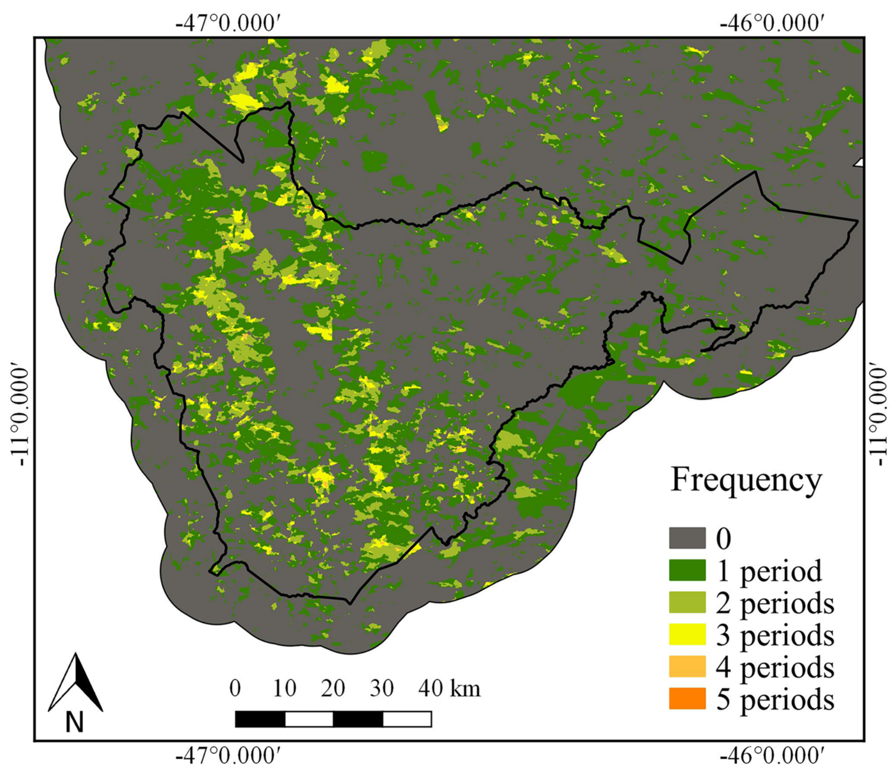


Fig. 7 Frequency of fires in the Serra Geral do Tocantins Ecological Station between 1970 and 2018

Table 5 Land cover change in the Jalapão Mosaic for the Integral Protection protected area from 1970 to 2018

Classes	1970s	1980s	1990s	2000s	2010s	2018
Serra Geral do Tocantins Ecological Station						
Natural vegetation	5849.9	5783.8	6206.4	6511.6	6305.9	6287.8
Anthropized	226.2	58.8	52.2	92.6	9.4	24.6
Burned	994.0	451.5	811.1	465.0	754.7	757.6
Water	0.8	0.7	1.1	1.6	0.7	0.8
Not observed	0	776.0	0	0	0	0
Canyons e Corredeiras do Rio Sono Natural Monument						
Natural vegetation	14.1	14.4	13.9	14.1	13.8	14.2
Anthropized	0	0	0.1	0.1	0	0.1
Burned	0.3	0.5	0.5	0.2	0.6	0.2
Water	0.1	0.1	0.1	0.2	0.1	0.1
Not observed	0	0	0	0	0	0
Jalapão State Park						
Natural vegetation	1512.1	1356.8	1411.3	1496.4	1421.2	1508.8
Anthropized	6.1	21.8	33.2	0.6	0	0
Burned	71.0	132.1	144.8	92.2	168.1	80.4
Water	0.4	0.5	0.4	0.5	0.3	0.5
Not observed	0	78.6	0	0	0	0
Nascentes do Rio Parnaíba National Park						
Natural vegetation	6755.2	7063.1	6995.0	7153.8	7109.1	7173.5
Anthropized	82.0	36.2	36.8	8.1	13.1	50.2
Burned	474.3	207.9	125.5	150.0	182.8	88.1
Water	0	0	0	0	0	0
Not observed	0	4.6	154.6	0	6.8	0

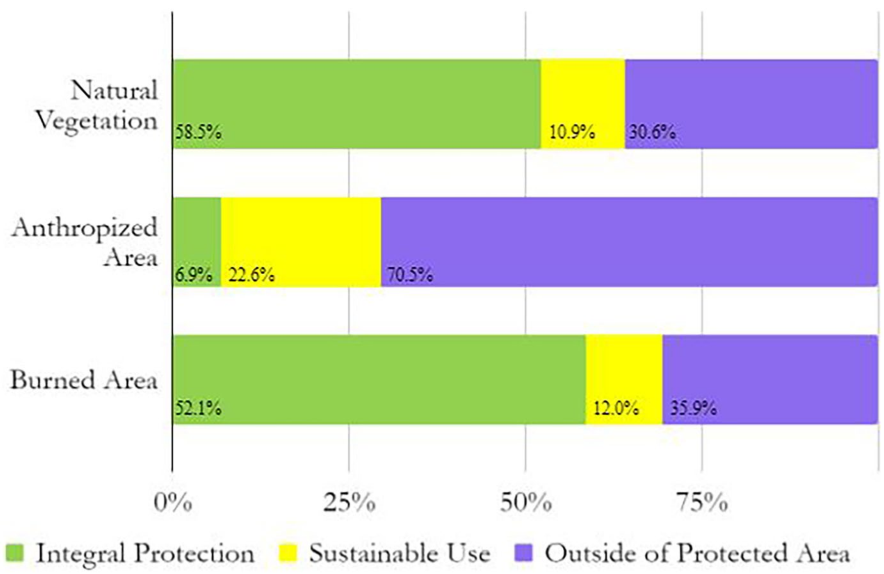


Fig. 8 Comparison between land use and land cover classes for the areas with and without PAs in the Jalapão Mosaic

Table 6 Jalapão Mosaic cover change for Sustainable Use protected area, between 1970 and 2018

Classes	1970s	1980s	1990s	2000s	2010s	2018
Jalapão Environmental Protection Area						
Natural vegetation	1159.8	1239.1	1256.4	1319.6	1238.1	1236.7
Anthropized	40.8	4.1	15.8	0.3	0	1.2
Burned	147.3	96.5	75.5	27.7	109.6	109.8
Water	1.6	1.6	1.8	1.9	1.8	1.8
Not observed	0	8.1	0	0	0	0
Rio Preto Environmental Protection Area						
Natural vegetation	1927.4	2115.8	2008.6	1867.8	1554.9	1571.8
Anthropized	42.0	1.9	79.2	305.6	585.4	605.5
Burned	229.1	79.8	109.3	24.1	57.3	20.3
Water	0	0	0	0	0	0
Not observed	0	0	0.4586	0	0	0
Serra da Tabatinga Environmental Protection Area						
Natural vegetation	380.2	402.0	395.4	253.1	122.4	102.4
Anthropized	0	0	18.9	164.6	293.5	315.4
Burned	37.5	15.8	3.2	0	1.8	0
Water	0	0	0	0	0	0
Not observed	0	0	0.3	0	0	0
Catedral do Jalapão Private Reserve of Natural Patrimony						
Natural vegetation	3.3	3.3	3.2	3.2	3.2	3.2
Anthropized	0	0	0	0	0	0
Burned	0	0	0	0	0	0
Water	0	0	0	0	0	0
Not observed	0	0	0	0	0	0

thematic class probably occurred due to spectral confusion between the anthropized area classes, mainly mining and bare soil with the grassland areas. The grassland vegetation, with predominance of herbaceous stratum, is associated with areas that have been anthropized and widely used for grazing and mining activities in the study area (Vieira et al., 2021). The complexity of discriminating the types of non forest natural formation in the Cerrado is also one of the main factors that compromise the global accuracy of several projects such as MAPBIOMAS that which recorded inclusion and omission errors at classification level II where the accuracy of the mapping is lower, 51.5% and 44% respectively, for the year 2018 (Oliveira et al., 2020). In the TerraClass Cerrado project, the strata corresponding to mining, mosaic of occupations and urban area, and other bare soil had the highest omission rate, 61% and 39%, respectively.

In this work, the number of samples used in the validation (Table 7) was determined based on the points collected in the field. Acquiring a larger set of field points could have improved the quality of the mapping. However, the heterogeneity of the landscape and the distance between the areas of interest was one of the factors that prevented a greater collection.

To improve the accuracy of mappings in the Cerrado, some studies have suggested the use of high-resolution image data such as the classification carried out in 2015

Table 7 Degree of agreement between the field points, collected in 2018, used for training and validation

Map	Field points			
	Natural vegetation	Anthropized area	Burned	Total
Natural vegetation	156	19	6	181
Anthropized area	0	11	0	11
Burned	0	0	27	27
Kappa	0.68	0.49	0.88	0.70

by the Brazilian Biomes High Resolution Mapping Project done by the Brazilian Foundation for Sustainable Development (In Portuguese Fundação Brasileira para o Desenvolvimento Sustentável — FBDS). In this project, land use and land cover mapping was carried out through the supervised classification of RapidEye images, base year 2013, and the validation of the mapping was done with points randomly distributed by RapidEye scenes (100 points for each scene), which were compared in the high-resolution images. All mapped scenes reached a minimum accuracy of 95% (FBDS, 2015).

Vegetation indices such as Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) can also help to improve mappings (Oliveira et al., 2020). NDVI analysis, for example, has been successfully used to delimit areas of bare soil in areas of highly seasonal vegetation such as the Caatinga and Cerrado biomes (Tomasella et al., 2018; Vieira et al., 2021).

Table 7 illustrates the number of convergent and divergent points between the field truth and the 2018 mapping.

Conclusion

Analysis showed that the Jalapão Mosaic has been losing natural vegetation area due to the expansion of anthropized areas, which have increased rapidly since the 1990s. The Serra Geral do Tocantins Ecological Station (Integral Protection protected area) had the highest number of burned areas between 1970 and 2018. However, even with 43.7% of its area burned, at least in a mapped period, this PA remained preserved due to proper fire management. Meanwhile, the Rio Preto and Serra da Tabatinga EP and Sustainable Use Areas were the most deforested, with a significant increase in agriculture beginning in the 1990s.

Monitoring changes in land use and land cover changes in the period from 1970 to 2018 in the PAs inserted in the Jalapão Mosaic were possible due to the temporal frequency and spatial resolution of the Landsat images. The methodology used is widely applied in areas with highly seasonal vegetation such as the Cerrado and Caatinga. The techniques used in this work demonstrate the potential of the application of linear spectral mixing model to highlight vegetated areas and areas without vegetation. Nonetheless, it is necessary to explore the availability of new sensors with higher resolution, as well as environmental data such as indices of vegetation to improve the detail of the physiognomies and converted areas.

It is possible to conclude from this study that the pressure of anthropic uses in the Jalapão Mosaic highlights the need to create more PAs with appropriate Management Plans for each category. It is also necessary to create public policies that prioritize training for teams that work in the PAs and for the local population regarding uses that are and are allowed in each area. The continuous monitoring of the PAs is an acceptable way to evaluate and maintain the effectiveness of the conservation and preservation objectives assigned to these areas. This can be used as an efficient government plan to fight the degradation of Brazilian's natural resources.

Acknowledgements We are grateful for the support and guidance received during this research project from a number of leaders at the ECOMETRICA and the Foundation for Science, Technology and Space Applications (FUNCATE) for the administrative support.

Funding This study had support from the Forests 2020 project, part of the UK Space Agency's International Partnership Programme (IPP), funded by the UK's Global Challenges Research Fund (GCRF). The authors also received the support of FAPESP through the project 17/22269–2.

Data availability The data used in the present study are available on the websites: Landsat images — https://store.usgs.gov/, fire focuses and scars — https://queimadas.dgi.inpe.br/queimadas/portal, and water bodies — https://mapbiomas.org/. The data generated that support the results of the study are available in the article.

References

Alencar, A., Shimbo, J. Z., Lenti, F., Balzani Marques, C., Zimbres, B., Rosa, M., & Barroso, M. (2020). Mapping three decades of changes in the Brazilian savanna native vegetation using Landsat data processed in the Google Earth Engine platform. *Remote Sens 12,* 924–1016.

Barbosa, A. M., Salum, M. R., Almeida, C. A., & Valeriano, D. M. (2009). Identificação multitemporal da exploração seletiva de madeira na Floresta Nacional do Jamari–RO. *XIV Simpósio Brasileiro de Sensoriamento Remoto*, 5625-5632. 5625–5632. http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr@80/2008/11.17.18.35.53/doc/5625-5632.pdf

Berlinck, C. N., & Batista, E. K. (2020). Good fire, bad fire: It depends on who burns. *Flora, 268*, 151610. https://doi.org/10.1016/j.flora.2020.151610

Bins, L. S., Erthal, G. J., Fonseca, L. M. G. (1993). Um método de classificação não supervisionada por regiões. *VI Simpósio Brasileiro de Computação Gráfica e Processamento de Imagens (SIBGRAPI)*, Recife, PE, Brasil, 65–68. http://urlib.net/rep/8JMKD3MGPBW34M/3D8K8KS

Borges, L. A. C., de Rezende, J. L. P., & Pereira, J. A. A. (2009). < b> Evolução da Legislação Ambiental no Brasil. Revista em Agronegócio e Meio Ambiente, 2(3), 447–466. https://doi.org/10.17765/2176-9168.2009v2n3p447-466

Borges, S. L., Eloy, L., Schmidt, I., Barradas, A. C. S., Santos, I. A. (2016). Manejo do fogo em vereda: novas perspectivas a partir dos ecossistemas agrícolas tradicionais no Jalapão. *Revista Ambiente & Sociedade*, 19 (3), 275–300. https://www.redalyc.org/pdf/317/31748020015.pdf

BRASIL. (2000). Lei n° 9.985, de 18 de julho de 2000 - *Institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências*, Brasília, DF, Brasil.https://legislacao.presidencia.gov.br/atos/?tipo=LEI&numero=9985&ano=2000&ato=77ck3aq1kMNpWTfc9

BRASIL. (2012). Lei n° 12.651, de 25 de maio de 2012 - *Dispõe sobre a proteção da vegetação nativa altera as Leis nºs 6.938, de 31 de agosto de 1981, 9.393, de 19 de dezembro de 1996, e 11.428, de 22 de dezembro de 2006; revoga as Leis nºs 4.771, de 15 de setembro de 1965, e 7.754, de 14 de abril de 1989, e a Medida Provisória nº 2.166–67, de 24 de agosto de 2001; e dá outras providências*, Brasília, DF, Brasil. http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm

BRASIL. (2015). Decreto n° 8.447, de 6 de maio de 2015 - *Dispõe sobre o Plano de Desenvolvimento Agropecuária do Matopiba e a criação de seu Comitê Gestor*, Brasília, DF, Brasil. http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2015/decreto/d8447.htm

BRASIL. (2016). Portaria n° 434, de 29 de setembro de 2016 - Reconhece o Mosaico do Jalapão. *Diário Oficial da União*, Brasília, DF, Brasil. https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/24208347/do1-2016-09-30-portaria-n-434-de-29-de-setembro-de-2016-24208306

Câmara, G. (1995). Modelos, Linguagens e Arquiteturas para banco de dados geográficos. Doctoral thesis. Applied Computing, National Institute For Space Research, São José dos Campos, SP, Brasil. https://www.researchgate.net/publication/43653652_Modelos_linguagens_e_arquiteturas_para_bancos_de_dados_geograficos

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Revista Educational and Psychological Measurement, 10*(1), 37–46. https://doi.org/10.1177/001316446002000104

Cristo, S. S., Trentin, R., & Robaina, L. E. S. (2016). Análise do uso e ocupação da terra na Estação Ecológica Serra Geral do Tocantins, estados do Tocantins e Bahia. *Revista Geografia, Ensino & Pesquisa, 20*(3), 182–191. https://doi.org/10.5902/2236499422311

DEFESA CIVIL. (2020). Veja em qual período seu município está inserido. https://defesacivil.to.gov.br/calendario-de-queima-controlada-/veja-em-qual-periodo-seu-municipio-esta-inserido/

Durigan, G., Ratter, J. A. (2016). The need for a consistent fire policy for Cerrado conservation. *Journal of Applied Ecology*, 53, 11–15.https://doi.org/10.1111/1365-2664.12559

Dutra, A. C., Shimabukuro, Y. E., & Arai, E. (2019). Linear spectral mixing model applied in images from PROBA-V sensor: A spatial multiresolution approach. *Raega-O Espaço Geográfico Em Análise, 46*(3), 48–62.

EMBRAPA. (2018a). *Sistema Brasileiro de Classificação de Solos*, 5° edição. https://www.embrapa.br/solos/sibcs/classificacao-de-solos

EMBRAPA. (2018b). Visão 2030: o futuro da agricultura brasileira. – Brasília, DF : EMBRAPA, 212.

Espíndola, C. J., & Cunha, R. C. C. (2015). A dinâmica geoeconômica recente da cadeia produtiva da soja no Brasil e no mundo. *GeoTextos, 11*(1), 217–238. https://doi.org/10.9771/1984-5537geo.v11i1.12692

FBDS. (2015). Sustainable Rural Development. Available in: http://geo.fbds.org.br/Metodologia.pdf. Access in: 26 August 2021.

Ferraz Neto, S., Vieira, R. M. S. P., Viana, D. R., Alvala, R. C. S. (2011). Análise multitemporal do desmatamento na Área de Preservação Ambiental da Chapada do Araripe, PE. *XV Simpósio Brasileiro de Sensoriamento Remoto (SBSR)*, Curitiba, PR, Brasil, 6896–6902. http://urlib.net/rep/3ERPFQRTRW/3A4DC35

Ferreira, M. E., Ferreira, L. G., Sano, E. E., Shimabukuro, Y. (2003). Uso do modelo linear de mistura espectral para o mapeamento sistemático e operacional do bioma cerrado: possibilidades, implicações e procedimentos metodológicos. In: Simpósio Brasileiro de Sensoriamento Remoto, XI., 2003, Belo Horizonte. **Anais...** Belo Horizonte: INPE, 657–664.

Franco, J. L. D. A., Ganem, R., & Barreto, C. (2016). Devastação e conservação no bioma cerrado: duas dinâmicas de fronteira. *Expedições: Teoria da história e historiografia*, 7(2), 56–83.

Gamba, F. B., Collicchio, E. (2018). Cultivo da soja em áreas de entorno do Mosaico das Unidades de Conservação do Jalapão, na região do Matopiba. *Revista Liberato*, 19(32), 179–190. https://doi.org/10.31514/rliberato.2018v19n32.p179

Ganem, K. A., Dutra, A. C., de Oliveira, M. T., de Freitas, R. M., Grecchi, R. C., Vieira, R. M. D. S. P., ... & Shimabukuro, Y. E. (2020). Mapeamento da Vegetação da Caatinga a partir de Dados Ópticos de Observação da Terra–Oportunidades e Desafios. Revista Brasileira de Cartografia, 72, 829–854. https://doi.org/10.14393/rbcv72nespecial50anos-56543

Hoffmann, A. A. (2013). Prevenção, Controle e Monitoramento de incêndios florestais no Cerrado: Sistemas de Alerta e Descentralização das Autorizações de Queima no Estado do Tocantins. 3° Relatório de Consultoria. http://cerradojalapao.mma.gov.br/biblioteca/arquivos

ICMBIO. (2011). Atlas do Corredor Ecológico da Região do Jalapão. https://www.icmbio.gov.br/projetojalapao/pt/downloads/publicacacoes.html

ICMBIO. (2013). Relatório com os subsídios para o Plano Estratégico do Mosaico do Jalapão. Relatório do Projeto Corredor Ecológico- Região do Jalapão. http://icmbio.gov.br/projetojalapao/pt/downloads/publicacacoes.html

INPE - DPI. (2019a). *Operação Aritmética*. Manuais: Tutorial de Geoprocessamento. Retrieved March 22, 2019, from http://www.dpi.inpe.br/spring/portugues/tutorial/operacao.html

INPE - DPI. (2019b). *Segmentação de Imagens*. Manuais: Tutorial de Geoprocessamento. Retrieved March 25, 2019, from http://www.dpi.inpe.br/spring/portugues/tutorial/segmentacao.html

Jensen, J. R. (2005). *Introductory Digital Image Processing: A remote sensing perspective* (3rd ed., p. 526). Prentice-Hall.

Klink, C. A., Machado, R. B. A. (2005). Conservação do Cerrado Brasileiro. *Megadiversidade*, 1(1), 147–155. https://www.agencia.cnptia.embrapa.br/recursos/Texto_Adicional_ConservacaoID-xNOKMLsupY.pdf

Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data. *Revista Biometrics, 33*(1), 159–174. https://doi.org/10.2307/2529310

Lumbreras, J. F., Carvalho Filho, A., Motta, P. E. F., Barros, A. H. C., Aglio, M. L. D., Dart, R. O., Silveira, H. L. F., Quartaroli, C. F., Almeida, R. E. M., Freitas, P. L. (2015). Aptidão Agrícola das Terras do Matopiba. *XXXV Congresso Brasileiro de Ciência do Solo*, Natal, RN, Brasil. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1025303/aptidao-agricola-das-terras-do-matopiba

Malleson, R., Middlemiss, S., Line, F. (2018). *Forests 2020 - Year 1 Review*. https://storage.3.basecamp.com/3635915/buckets/2348392/uploads/987289735/download/Forests%202020%20Integrated%20Annual%20Review_Final%20(1).docx?disposition=attachment

MAPA. (2019). *AGROSTAT- Estatísticas de Comércio Exterior do Agronegócio Brasileiro*. MAPA. Retrieved December 16, 2019, from http://indicadores.agricultura.gov.br/agrostat/index.htm

MAPBIOMAS. (2021). *Statistics*. MAPBIOMAS. Retrieved March 15, 2021, from https://mapbiomas.org/en/download_estatisticas?cama_set_language=en

Menke, A. B., Carvalho Júnior, O. A., Gomes, R. A. T., Martins, E. S., & Oliveira, S. N. (2009). Análise das mudanças do uso agrícola da terra a partir de dados de Sensoriamento Remoto Multitemporal no município de Luís Eduardo Magalhães (BA- Brasil). *Sociedade & Natureza, 21*, 315–326. https://doi.org/10.1590/S1982-45132009000300007

Miranda, E. E., Magalhães, L. A., Carvalho, C. A. (2014). Proposta de delimitação territorial do MATOPIBA. EMBRAPA. *Nota Técnica*. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1037313/proposta-de-delimitacao-territorial-do-matopiba

MMA. (2009). Relatório Técnico de Monitoramento do Desmatamento do Bioma Cerrado, 2002 e 2008: Dados Revisados. *Relatório Técnico*. https://antigo.mma.gov.br/estruturas/sbf_chm_rbbio/_arquivos/relatorio_tecnico_monitoramento_desmate_bioma_cerrado_csr_rev_72_72.pdf

MMA. (2011a). Monitoramento do Desmatamento nos Biomas Brasileiros por Satélite - Monitoramento do Bioma Cerrado 2008–2009. *Relatório Técnico*. https://antigo.mma.gov.br/estruturas/sbf_chm_rbbio/_arquivos/relatoriofinal_cerrado_2008_2009_72.pdf

MMA. (2011b). Monitoramento do Desmatamento nos Biomas Brasileiros por Satélite - Monitoramento do Bioma Cerrado 2009–2010. *Relatório Técnico*. https://antigo.mma.gov.br/estruturas/sbf_chm_rbbio/_arquivos/relatoriofinal_cerrado_2010_final_72_1.pdf

MMA. (2015a). Mapeamento do Uso e Cobertura da Terra do Cerrado - Projeto TerraClass Cerrado 2013. *Relatório Técnico*. http://www.dpi.inpe.br/tccerrado/Metodologia_TCCerrado_2013.pdf

MMA. (2015b). Monitoramento do Desmatamento nos Biomas Brasileiros por Satélite - Cerrado 2010–2011. *Relatório Técnico*. https://antigo.mma.gov.br/images/arquivo/80120/PPCerrado/Relatorio%20Tecnico_Bioma%20Cerrado_2011vfinal.pdf

MMA. (2018a). *O Bioma Cerrado*. MMA. Retrieved October 25, 2018, from http://www.mma.gov.br/biomas/cerrado.html

MMA. (2018b). *Cerrado*. Projeto Cerrado-Jalapão. Retrieved December 06, 2018, from http://cerradojalapao.mma.gov.br/cerrado

MMA. (2018c). *Unidades de Conservação*. MMA. Retrieved September 30, 2018, fromhttp://www.mma.gov.br/areas-protegidas/unidades-de-conservacao.html

MMA. (2018d). *Mosaicos*. MMA. Retrieved October 5, 2018, from http://www.mma.gov.br/areas-protegidas/instrumentos-de-gestao/mosaicos.html

MMA. (2020). *Painel Unidades de Conservação Brasileiras*. MMA. Retrieved March 27, 2020, from https://app.powerbi.com/view?r=eyJrIjoiMjUxMTU0NWMtODkyNC00NzNiLWJiNTQtNGI3NTI2NjliZDkzIiwidCI6IjM5NTdhMzY3LTZkMzgtNGMxZi1hNGJhLTMzZThmM2M1NTBlNyJ9

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature, 403*, 853–858. https://doi.org/10.1038/35002501

NATURATINS. (2020). *Autorização de Queima Controlada - AQC*. NATURATINS. Retrieved July 31, 2020, from https://naturatins.to.gov.br/publicacoeseditais/autorizacao-de-queima-controlada---aqc/

Oliveira, M. T., Cassol, H. L. G., Ganem, K. A., Dutra, A. C., Prieto, J. D., Arai, E., & Shimabukuro, Y. E. (2020). Mapeamento da Vegetação do Cerrado–Uma Revisão das Iniciativas de Sensoriamento Remoto. Revista Brasileira de Cartografia, 72, 1250–1274. https://doi.org/10.14393/revbrascartogr

Ortiz, J. L., Freitas, M. I. C. (2005). Mapeamento do uso da terra, vegetação e impactos ambientais por meio de Sensoriamento Remoto e Geoprocessamento. *Revista Geociências, Unesp*, 24(1), 91–104. http://www.ppegeo.igc.usp.br/index.php/GEOSP/article/view/9743

Pessoa, V. L. S., Inocêncio, M. E. (2014). O PRODECER (Re)visitado: as engrenagens da territorialização do capital no Cerrado. *CAMPO-TERRITÓRIO: revista da geografia agrária*, 21, 1–22. http://www.seer.ufu.br/index.php/campoterritorio/article/view/26927/15947

Pires, M. O. (2000). Programas agrícolas na ocupação do Cerrado. *Sociedade e Cultura*, 3 (1 e 2), 111–131. https://www.redalyc.org/pdf/703/70312129007.pdf

Resende, F. C., Cardozo, F. S., Pereira, G. (2017). Análise ambiental da ocorrência de queimadas na porção nordeste do Cerrado. *Revista do Departamento de Geografia, USP*, 34, 31–42. https://doi.org/10.11606/rdg.v34i0.131917

Rudorff, B., Risso, J. et al. (2015). Análise Geoespacial da Dinâmica das Culturas Anuais no Bioma Cerrado: 2000 a

2014. *Relatório Síntese - Agrosatélite Geotecnologia Aplicada*. https://agrosatelite.com.br/cases/
Rudorff, B., Risso, J. et al. (2020). Análise Geoespacial da Soja no Bioma Cerrado: Dinâmica da Expansão | Aptidão Agrícola da Soja | Sistema de Avaliação para Compensação Financeira: 2001 a 2019. *Relatório - Agrosatélite Geotecnologia Aplicada*. https://agrosatelite.com.br/cases/
Salvador, M. A., & Brito, J. I. B. (2018). Trend of annual temperature and frequency of extreme events in the MATOPIBA region of Brasil. *Theoretical and Applied Climatology, 133*, 253–261. https://doi.org/10.1007/s00704-017-2179-5
Santos, C. C. M. (2016). Programa de Cooperação Nipo-Brasileira para o Desenvolvimento dos Cerrados- PRODECER: um espectro ronda os cerrados brasileiros. *Estudos Sociedade e Agricultura*, 24 (2), 384–416. https://revistaesa.com/ojs/index.php/esa/article/view/802
Sawyer, D., Mesquita, B. Coutinho, B., Almeida, F. V., Figueiredo, I., Lamas, I., Pereira, L. E., Pinto, L. P., Pires, M. O., Kasecker, T. (2017). Ecosystem Profile: Cerrado Biodiversity Hotspot. *Critical Ecosystem.*
Schmidt, I. B., Sampaio, M. B., Figueiredo, I. B., Ticktin, T. (2011). Fogo e artesanato de capim-dourado no Jalapão-Usos tradicionais e consequências ecológicas. *Revista Biodiversidade Brasileira*, 1(2), 67–85. https://revistaeletronica.icmbio.gov.br/index.php/BioBR/article/view/116
Schmidt, I. B., Fonseca, C. B., Ferreira, M. C., Sato, M. N. (2016). Implementação do Programa Piloto de Manejo Integrado do Fogo em três Unidades de Conservação do Cerrado. *Biodiversidade Brasileira*, 6, 55–70. https://revistaeletronica.icmbio.gov.br/index.php/BioBR/article/view/656
SEPLAN. (2003). *Plano de Manejo do Parque Estadual do Jalapão - PEJ*. http://gesto.to.gov.br/site_media/upload/gestao/documentos/Plano_de_Manejo_-_PEJ_-_Encarte_2_-_Planejamento.pdf
SEPLAN. (2012). *Atlas do Tocantins - Subsídios ao Planejamento da Gestão Territorial*, 6° edição. http://zoneamento.sefaz.to.gov.br/TO_AtlasTocantins2012_1/Atlas_do_Tocantins_2012.pdf
SEPLAN. (2017). *Zoneamento Ecológico-Econômico do Estado do Tocantins - Volume I- Meio Natural*. https://central3.to.gov.br/arquivo/443563/
Shimabukuro, Y. E., & Smith, J. A. (1991). The least-squares mixing models to generate fraction images derived from remote sensing multispectral data. *International Journal of Remote Sensing, 29*, 16–20. https://doi.org/10.1109/36.103288
Shimabukuro, Y. E., Arai, E., Duarte, V., Jorge, A., Santos, E. G. D., Gasparini, K. A. C., & Dutra, A. C. (2019). Monitoring deforestation and forest degradation using multi-temporal fraction images derived from Landsat sensor data in the Brazilian Amazon. *International Journal of Remote Sensing, 40*(14), 5475–5496. https://doi.org/10.1080/01431161.2019.1579943
Silva, C. P., Santos, I. G., Santos, A. F. (2017). Contribuição do Estado do Tocantins para as metas da Convenção da Diversidade Biológica. *Revista Desafios*, 4(4), 126–135. https://sistemas.uft.edu.br/periodicos/index.php/desafios/article/view/3879
Silva, P. S., Rodrigues, J. A., Santos, F. L. M., Pereira, A. A., Nogueira, J., DaCamara, C. C., & Libonati, R. (2020). Drivers Of Burned Area Patterns In Cerrado: The Case Of Matopiba Region. In *2020 IEEE Latin American GRSS & ISPRS Remote Sensing Conference (LAGIRS)* (pp. 542-547). IEEE. https://doi.org/10.1109/LAGIRS48042.2020.9165665
Tomasella, J., Vieira, R. M. S. P., Barbosa, A. A., Rodriguez, D. A., de Oliveira Santana, M., & Sestini, M. F. (2018). Desertification trends in the Northeast of Brazil over the period 2000–2016. *International Journal of Applied Earth Observation and Geoinformation, 73*, 197–206. https://doi.org/10.1016/j.jag.2018.06.012
USGS. (2019). *Landsat Missions*. USGS. Retrieved February 20, 2019, from https://www.usgs.gov/land-resources/nli/landsat/landsat-satellite-missions?qt-science_support_page_related_con=2#qt-science_support_page_related_con
Vaeza, R. F., Oliveira Filho, P. C., Maia, A. G., Disperati, A. A. (2010). Uso e ocupação do solo em Bacia Hidrográfica urbana a partir de imagens orbitais de alta resolução. *Floresta e Ambiente*, 17(1), 23–29. https://www.floram.org/article/10.4322/floram.2011.003/pdf/floram-17-1-23.pdf
Veloso, C. (2016, September 30). *Mosaico do Jalapão é reconhecido pelo Ministério do Meio Ambiente*. NATURATINS. Retrieved September 4, 2017, from https://naturatins.to.gov.br/noticia/2016/9/30/mosaico-jalapao-e-reconhecido-pelo-ministerio-do-meio-ambiente/
Veloso, C. (2019, January 11). *Parque Estadual do Jalapão completa 18 anos de criação*. NATURATINS. Retrieved January 25, 2019, from https://naturatins.to.gov.br/noticia/2019/1/11/parque-estadual-do-jalapao-completa-18-anos-de-criacao/
Vieira, R. M. D. S. P., Tomasella, J., Barbosa, A. A., Polizel, S. P., Ometto, J. P. H. B., Santos, F. C., ... & de Toledo, P. M. (2021). Land degradation mapping in the MATOPIBA region (Brazil) using remote sensing data and decision-tree analysis. *Science of The Total Environment*, 782, 146900.
WWF. (2019). *Cerrado*. WWF. Retrieved January 05, 2019, from https://www.wwf.org.br/natureza_brasileira/questoes_ambientais/biomas/bioma_cerrado/