



Land Use and Land Cover Mapping in a Priority Municipality for Deforestation Control Actions in the Amazon using GEOBIA

Mapeamento de Uso e Cobertura da Terra em um Município Prioritário para Ações de Controle de Desmatamento na Amazônia usando GEOBIA

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Abstract: The objective of this work was to detect land use and land cover changes in the municipality of Rondon do Pará, in the Brazilian Legal Amazon, through the Geographic Object-based Image Analysis (GEOBIA), aiming to identify whether its inclusion in the list of priority municipalities for actions to prevent, monitor and control deforestation in the Amazon (Decree 6.321/2007), has inhibited this process. The methodological procedure involved the calculation of vegetation indices to highlight interest classes, the segmentation of the images into geo-objects and the classification using Support Vector Machine (SVM) algorithm. Also, we evaluated the relationship between annual rates of particulate material with a diameter of fewer than 2.5 micrometers (PM_{2.5}) emitted from fires and deforestation in Rondon do Pará. The results show the reduction of deforestation rates but the conversion, in absolute values, of 984,47 km² of natural vegetation to anthropized areas along the 2006-2017 period, and the reduction of the average PM_{2.5} fire emissions from 31,107 tons year⁻¹ between 2002 and 2007 to 10,394 ton year⁻¹ in the post-inclusion period (2008-2019). This represents that the inclusion of Rondon do Pará in this list was beneficial, but the suppression of natural vegetation was not totally curbed, reinforcing that changes from environmental policies are gradual. Activities that do not use fire to suppress natural vegetation, such as selective logging, common in Rondon do Pará, had impact. This makes it necessary to intensify inspections and the development of sustainable actions in the region.

Keywords: Change detection. Geo-objects. Monitoring. Deforestation. Amazonia.

Resumo: O objetivo deste trabalho foi detectar mudanças no uso e cobertura da terra no município de Rondon do Pará (PA), por meio da Geographic Object-based Image Analysis (GEOBIA), com o objetivo de identificar se sua inclusão na lista de municípios prioritários para ações para prevenir, monitorar e controlar o desmatamento na Amazônia (Decreto 6.321/2007), inibiu esse processo. O procedimento metodológico envolveu o cálculo de índices de vegetação para destacar as classes de interesse, a segmentação das imagens em objetos geográficos e a classificação usando o algoritmo Support Vector Machine (SVM). Também avaliamos a relação entre as taxas anuais de emissões de material particulado com diâmetro menor que 2,5 micrômetros (PM_{2.5}) a partir de fogo e o desmatamento em Rondon do Pará. Os resultados mostram a redução das taxas de desmatamento, mas a conversão, em valores absolutos, de 984,47 km² de vegetação natural para área antropizada ao longo do período, e a redução da média de emissões de PM_{2.5} de 31.107 toneladas ano⁻¹ entre 2002 e 2007 para 10.394 toneladas ano⁻¹ no período após a inclusão (2008-2019). Os resultados demonstram que a inclusão de Rondon do Pará na lista foi benéfica, mas a supressão da vegetação natural não foi totalmente coibida, reforçando que mudanças derivadas de políticas ambientais são graduais. Atividades que não usam fogo para suprimir a vegetação natural, como exploração madeireira seletiva, comum em Rondon do Pará, tiveram impacto. Isso torna necessário intensificar as inspeções e o desenvolvimento de ações sustentáveis na região.

Palavras-chave: Detecção de mudanças. Geo-objetos. Monitoramento. Desmatamento. Amazônia.

1 INTRODUCTION

Due to the unrestrained advance of the deforestation frontier in the Legal Amazon, the municipality of Rondon do Pará, located in the state of Pará, was included in 2008 by the Ministry of Environment (MMA) in the List of Priority Municipalities (LPM) for actions to prevent, monitor and control deforestation in the Amazon, according to the Presidential Decree 6321 of December 2007 (BRASIL, 2007). This policy was implemented in the second phase of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), the major large-scale governmental conservation policy effort to preserve the Legal Amazon (ROITMAN et al., 2018). Launched in 2004, the PPCDAm integrated actions across different government institutions and proposed novel procedures for monitoring, environmental controlling, and territorial management. Priority status was determined based on three municipality-level criteria: (i) total deforested area; (ii) total deforested area over the past three years; and (iii) increase in the deforestation rate in at least three of the last five ones (BRASIL, 2007). The municipalities of this list are subject to measures for the integration and improvement of monitoring and control actions of organs from all governmental spheres, land and territorial planning and the incentive to environmentally sustainable economic activities (ARIMA et al., 2014; ASSUNÇÃO; GANDOUR; ROCHA, 2015). As deforestation goes beyond environmental consequences, resulting in social phenomena such as the expansion of agricultural activities and agrarian conflicts (SANT'ANNA; YOUNG, 2010), the need to ally government actions and the society to control deforestation is emphasized, increasing the efficiency of inspections and public policies, the implementation of projects to raise public awareness and the use of new techniques for strategic monitoring actions.

From 1st August 2006 to 31st July 2007, the period before the inclusion of Rondon do Pará in the LPM, the Brazilian Amazon Deforestation Satellite Monitoring Project (PRODES) estimated the total of 11,651 km² deforested in the Brazilian Legal Amazon. In this time period, the state of Pará was responsible for 5,526 km² of this total (47.43%), being the state of this region with the higher increase in deforestation rate (INPE, 2020). One factor to this situation was the pressure exerted in the region known as “Deforestation arc”, where Rondon do Pará is inserted. This region comprises lands in the Eastern and Southern portions of Pará, expanding to the Western and reaching the states of Mato Grosso, Rondônia, and Acre. This region concentrated about 80% of the deforestation in the Brazilian Legal Amazon during the last decades, covering an important area where the expansion of the Brazilian agricultural frontier towards the Amazon Primary forests occurred (SOARES-FILHO et al., 2006; FEARNSIDE, 2017; FONSECA et al., 2018). The anthropic pressure in this region has been promoting illegal deforestation, even on Public Lands, for wood exploration, cattle ranching, and the crop expansion. Livestock in this region is the greatest contributor to deforestation, occupying 63% of the deforested areas in the Deforestation arc in 2017 (FONSECA et al., 2018). Inserted in this regional context, Rondon do Pará has been considered one of the municipalities with the highest rate of deforestation in the Legal Amazon (INPE, 2020), justifying its inclusion in the LPM.

Deforestation monitoring actions aim to detect changes over time and are important for the diagnosis, planning, and management of Amazonian municipalities. The use of remote sensing data and geoprocessing tools enables quick analysis, essential for achieving less costly environmental and agrarian objectives. Among the main approaches, the Geographic Object-Based Image Analysis - GEOBIA allows the division of orbital images into geo-objects based on their spatial characteristics of context, format, and texture, constituting a differential approach in relation to the one based on pixel reflectance (pixel-by-pixel approach) (HAY; CASTILLA, 2008). While in the pixel-based approach the reference for classification is the individual value of each pixel, without taking into account the neighborhood influence in the decision process, GEOBIA is characterized by the increase of information related to objects, such as shape, texture, compacity and context, which is useful to analyze heterogeneous landscapes (BLASCHKE, 2010). Recent studies have reported the advantages of detecting landscape changes via GEOBIA because it considers key factors that transcend reflectance values (SCHULTZ et al., 2016; BELGIU; CSILLIK, 2018; CSILLIK et al., 2019), outperforming pixel-based classification methods. In this context, considering that the generation of geo-objects may favor the detection of clearings in new frontiers of deforestation, such as Rondon do Pará, we adopted the object-oriented GEOBIA approach to perform land use and land cover (LULC) classifications in the present study.

Thus, the objective of the present work was to use the GEOBIA object-oriented analysis approach to map LULC in the municipality of Rondon do Pará - PA, for the years 2006 and 2017, to monitor land use and land cover changes (LULCC) over more than a decade of its insertion in the LPM. We chose images from these years because 2006 represents the last complete year before the Decree 6321/2007, that established the inclusion of Rondon do Pará in the LPM, and 2017 represents the first complete year after its removal from the list of the ten Pará municipalities with more deforestation rates according to the PRODES statistics. We argue that this interval allows to understand how the deforestation dynamics was affected by the implementation of this environmental policy which has impacted public governance, business groups and civil society. An analysis of the impact of this insertion on the emissions from burning in Rondon do Pará was also performed since the use of fire is intrinsically linked to deforestation in the Deforestation arc, also known as “Fire arc”. The hypothesis of this work is that the impacts of environmental policy implementation of this magnitude can be perceived by medium-resolution remote sensing data and techniques for automated LULC classification, LULC analysis, change detection, and emissions from fires.

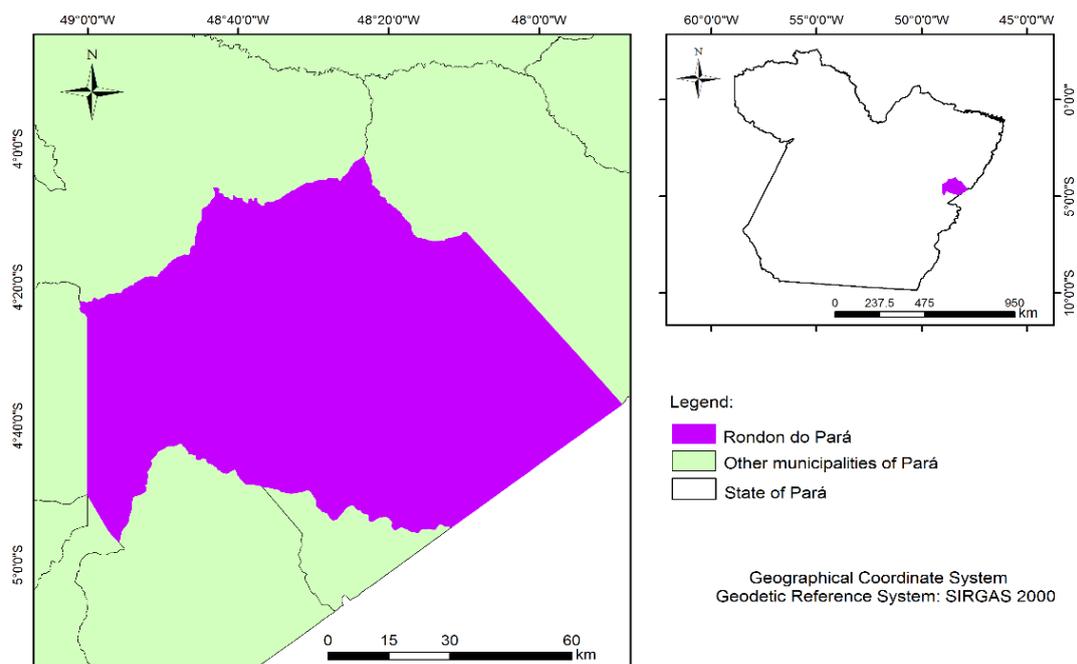
This paper is an extended version of Conceição and Chaves (2019), presented in XX Brazilian Symposium on GeoInformatics - GEOINFO 2019. The main increments are related to the insertion of (i) official annual deforestation rates for Rondon do Pará, derived from the PRODES Project, and their comparison with our results, and (i) estimate of fire emissions associated to deforestation, specifically the aerosol Particulate Material with a diameter less than 2.5 micrometers ($PM_{2.5}$), using the Brazilian Biomass Burning Emission Model with Fire Radiative Power (3BEM_FRP) model available in the PREP-CHEM-SRC 1.8.3 emission preprocessor (PEREIRA et al., 2016), to improve the discussion on the human-induced impact of clearings in this region, considering fire emissions associated with deforestation.

2 MATERIAL AND METHODS

2.1 Study area

The study area is the municipality of Rondon do Pará (Figure 1), latitude $4^{\circ}46'34''S$ and longitude $48^{\circ}04'02''W$. With an area of 8,257.63 km², this municipality is inserted in the Southeastern region of the Pará state and is 532 km away from the state capital Belém (IBGE, 2019).

Figure 1 – Geographic location of the study area, the municipality of Rondon do Pará.

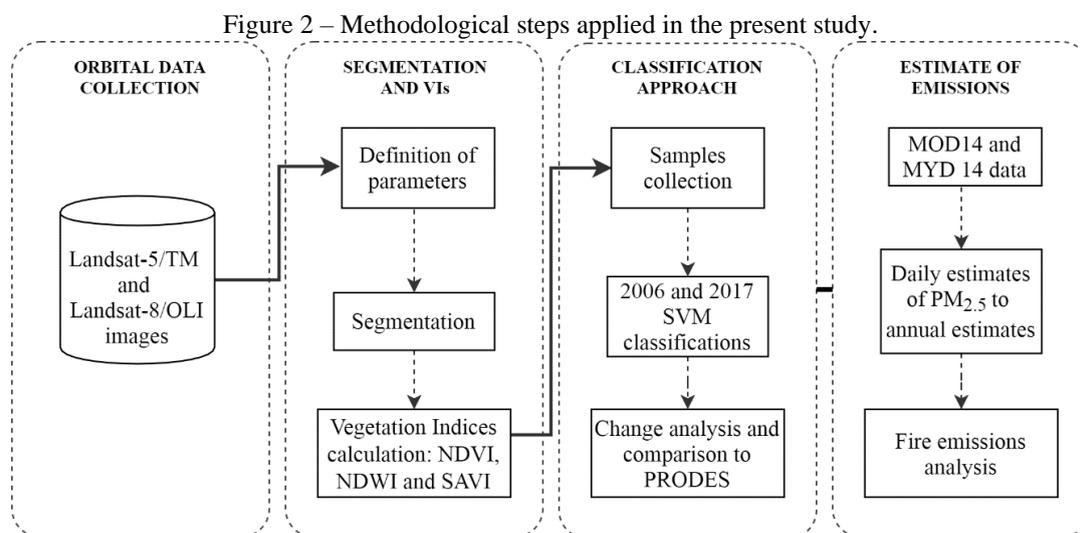


Source: The authors (2020).

The main economic activities of Rondon do Pará are agriculture and livestock, with an emphasis on intense logging and milk production (IBGE, 2019). The predominant vegetation cover is composed of two different forest formations: Subperenifolia Equatorial Forest and Hygrophilous Lowland Equatorial Forest (EMBRAPA, 1988). Reliefs from moderately to strongly wavy. The average annual precipitation is 1,710 mm, with a moderate deficit in the dry season (June to September). The region's hydrological year begins in October with the beginning of the rainy season and ends in September, the end of the dry season (CPRM, 2015). The predominant climate in the region is Aw, characterized as rainy tropical (KÖPPEN, 1936). In addition to the Federal Decree that placed it on the LPM, Rondon do Pará was also part of the “Green Arc Program” (Programa Arco Verde, in Portuguese), which aimed to bring incentives for sustainable development in municipalities targeted by environmental inspection operations between 2008 and 2009 (BRITO; BARRETO, 2010).

2.2 Methodological steps

The methodological steps (Figure 2) involved orbital data collection, segmentation and Vis calculation, LULC classification and accuracy analysis, and estimate of fire emissions.



Source: The authors (2020).

2.2.1 ORBITAL DATA

The orbital data selected were one image from the Landsat 5 satellite Thematic Mapper (TM) sensor, from 07/24/2006, and another from the Operational Land Imager (OLI) sensor onboard the Landsat 8 satellite, from 07/06/2017. These images correspond to the 223/63 path/row and are dated from the same annual period to avoid variations in brightness occasioned by changes in the solar angle, as well as significant phenological changes in vegetation cover and the local agricultural calendar. Both images were obtained already georeferenced from the United States Geological Survey website (USGS, 2017). The two images were projected for the Universal Transverse Mercator (UTM) projection, datum SIRGAS 2000, zone 22 South.

2.2.2 SEGMENTATION APPROACH AND VEGETATION INDICES CALCULATION

The segmentation – and the LULC classifications - involved the implementation of the GEOBIA approach in the eCognition Developer® 64 (TRIMBLE GEOSPATIAL, 2009). The images were segmented into geo-objects using the Multiresolution Segmentation (MRS) algorithm, which groups the pixels of each geo-object according to parameters assigned to each spectral band: smoothness, color, weight, and, especially, scale factor, shape and compactness (ESPÍNDOLA; CAMARA, 2007). The segmentation parameters applied were defined based on the performance of previous tests and their adherence to the Landsat's image

characteristics, defined as: 80 for scale factor, 0.6 for shape and 0.3 for compactness. The selection of parameters are commonly predicted by tests and trial and error approaches, aiming to be adjusted to the targets, since each image has specific characteristics (TOURE et al., 2016; WATKINS; VAN NIEKERK, 2019). The idea of this process is to first group spatially adjacent pixels into spectrally homogeneous objects and then conduct the LULC classification using objects as the minimum processing (TORRES-SÁNCHEZ, 2015).

In addition to the spectral, spatial, morphological, contextual and temporal attributes, three vegetation indices were calculated as a strategy to increase the spectral separability of the mapped LULC classes, improving, thus, the segmentation result: Normalized Difference Vegetation Index (NDVI) (ROUSE JR et al., 1974), Eq. (1); Normalized Difference Water Index (NDWI) (GAO, 1996), Eq. (2); and Soil-Adjusted Vegetation Index (SAVI) (HUETE, 1988), Eq. (3); chosen because they are sensitive to variations in green vegetation, water bodies and soil background, respectively.

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

where NIR = reflectance in the Near-infrared spectral band and RED = reflectance in the Red spectral band.

$$NDWI = \frac{NIR-SWIR}{NIR+SWIR} \quad (2)$$

where NIR = reflectance in the Near-infrared spectral band and SWIR = reflectance in the Shortwave infrared spectral band.

$$SAVI = \frac{NIR-RED}{NIR+RED+0.5} * 1.5 \quad (3)$$

where NIR = reflectance in the Near-infrared spectral band, RED = reflectance in the Red spectral band, 0.5 and 1.5 = soil brightness correction factor.

2.2.3 LAND USE AND LAND COVER CLASSIFICATION APPROACH

Samples dataset was composed following a stratified sampling method, which defines a specific number of samples for each class, considering the entire study area (FAO, 2016). The stratification is recommended to improve the precision of the accuracy and area estimates (OLOFSSON et al., 2014). We collected 100 representative samples (segments) of the major LULC classes of the study area: Natural vegetation (natural forested areas, considering native and secondary vegetation), and Anthropized areas (crop fields with crops and pasturelands). For each secondary LULC class, Water (water bodies) and Urban area (city and allotments), we collected 20 samples, because they are less representative and without spatial dispersion, located only in specific small regions of the study area. All samples were collected based on the visual LULC interpretation key developed by the TerraClass Project, responsible for categorizing LULC in the deforested polygons detected by PRODES (ALMEIDA et al., 2016). For dubious areas, we analyzed MODIS Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) vegetation indices time-series profiles derived from the SATVeg web-based tool (ESQUERDO et al., 2020).

The LULC classifications for 2006 and 2017 were performed using the SVM algorithm, a supervised and non-parametric machine learning technique based on structural risk minimization strategies that reduce misclassification errors selecting a small number of critical boundary occurrences between the landscape typologies (PAL; FOODY, 2010). This method computes an optimal hyper-plane that maximizes the margin between different LULC classes by using a small number of training cases, which are called support vectors (WITTEN; FRANK; MARK, 2011). The SVM algorithm performs well with a limited number of training samples and can identify complex LULC patterns in high-dimensional feature sets derived from heterogeneous landscapes (MOUNTRAKIS; IM; OGOLE, 2011). The classification was done taking into consideration the spatial resolution of the Landsat images (0.0009 km² of mapping scale). The Overall Accuracies of both LULC classifications were measured based on PRODES data available in the TerraBrasilis website

(<http://terrabrasilis.dpi.inpe.br/>). For Anthropized areas, we consider the deforestation accumulated mask mapped by PRODES until 2006 and 2017, respectively. For Natural areas, we consider the data not mapped as deforestation by PRODES within the municipality boundaries. To perform the accuracy analysis, we inserted 100 validation points for each principal class of interest and evaluated them considering the PRODES data as a reference. The insertion of validation points followed the stratified random sampling method proposed by Olofsson et al. (2014). After, we performed a LULCC analysis to detect the impacts from the insertion of Rondon do Pará in the LPM, and a comparison to PRODES data for the municipality to validate our results.

2.2.4 ESTIMATE OF FIRE EMISSIONS

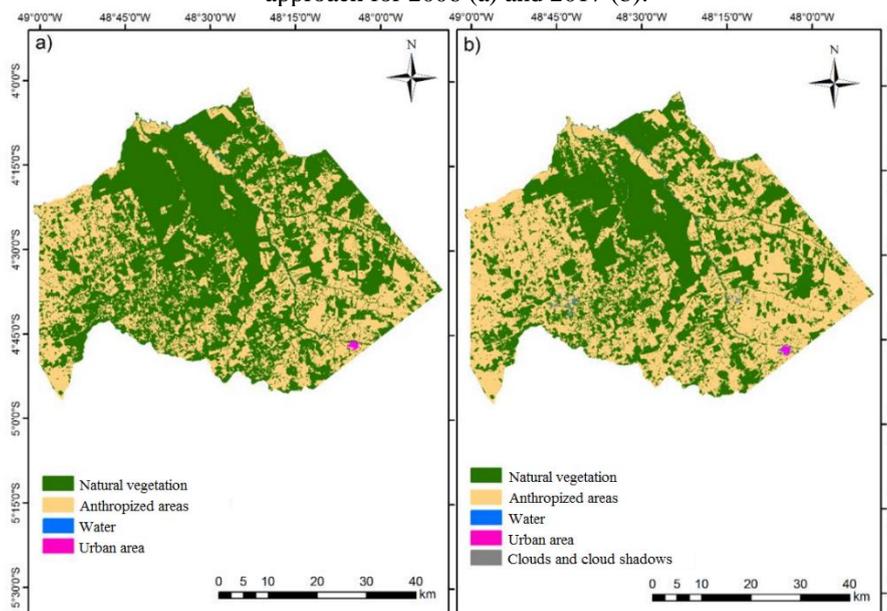
The aerosol species emitted from fires analyzed in this study was the $PM_{2.5}$. Although $PM_{2.5}$ compose only 0.5% of the total fire emission components (NRC, 2004), this aerosol species is considered a good tracer of others emitted from fires and a primary human-health risk (JOHNSTON et al., 2012; DE OLIVEIRA ALVES et al., 2017). The analyzed period was from 2002 to 2019, allowing to understand fire emission patterns before and after the insertion of the study area in the LPM. Annual estimates of $PM_{2.5}$ emitted from fires in the study area were generated using the Brazilian Biomass Burning Emission Model with Fire Radiative Power (3BEM_FRP) available in the PREP-CHEM-SRC 1.8.3 emissions preprocessing tool (PEREIRA et al., 2016). This model is more appropriate to estimate fire in South America in comparison to global emission inventories because it is parameterized to this continent (SANTOS, 2018).

The active fire products derived from Moderate Resolution Imaging Spectroradiometer sensors (MODIS, MOD14 and MYD14 products) (GIGLIO et al., 2016) were considered as the only input data in 3BEM_FRP and fires the only active emission source in PREP-CHEM-SRC 1.8.3. The outputs of the tool consisted of the daily emission of a series of gases and aerosol species associated with fires in South America, including $PM_{2.5}$, with a spatial resolution of 0.1° . These daily estimates of $PM_{2.5}$ were clipped to the limits of Rondon do Pará established by the IBGE (2019) and then aggregated into annual estimates by summing daily values. The applied method is detailed in Mataveli et al. (2019).

3 RESULTS AND DISCUSSION

The application of GEOBIA resulted in two LULC classifications for Rondon do Pará, one representative of the year 2006 and other from 2017 (Figure 3).

Figure 3 – Land use and land cover (LULC) classifications of Rondon do Pará (Pará), obtained from the GEOBIA approach for 2006 (a) and 2017 (b).



Source: The authors (2020).

Deforestation monitoring in the Brazilian Legal Amazon is commonly evaluated by using PRODES data. Considering it as a reference, the Overall Accuracies for both LULC classifications were 0.75 for 2006 and 0.79 for 2017. As the PRODES methodology is based on visual interpretation and manual classification, these values represent a substantial agreement. The calculation of specific vegetation indices and the definition of geo-objects adherent to different LULC patterns in our work contributed to this agreement. The differences can be explained by the mapping scale considered in each one. Although PRODES deforestation areas are collected at 0.0009 km², this official data only reports cleared land equal to or exceeding 0.0625 km² to maintain consistency with long-term data (DE OLIVEIRA et al., 2020). Also, the mapping scale in PRODES is fixed in 1:75.000 to standardize the interpretation made by remote sensing specialists. In our work, this scale follows the full resolution of the Landsat images. By visual interpretation of the two LULC classifications derived from the GEOBIA approach applied to Landsat images considering the TerraClass Project interpretation key (COUTINHO et al., 2008; ALMEIDA et al., 2016), we noted an advance of Anthropized areas in Rondon do Pará after 2006, especially driven by the expansion of agricultural practices to the Eastern and Southern portions of the municipality, and pasture to the Northern and Western portions. The quantification of the area corresponding to each LULC class shows that, despite the beneficial results from the inclusion of Rondon do Pará in the LPM, the suppression of natural vegetation was not totally curbed in the municipality. Natural vegetation decreased from 4,944.67 km² in 2006 to 3,954.62 km² in 2017, representing an accumulated loss of 989.04 km² during this 11-years period. On the other hand, there was an increase of 984.47 km² in Anthropized areas (Table 1).

Table 1 – Quantification of land use and land cover (LULC) classes and variation in Rondon do Pará during the period between 2006 and 2017.

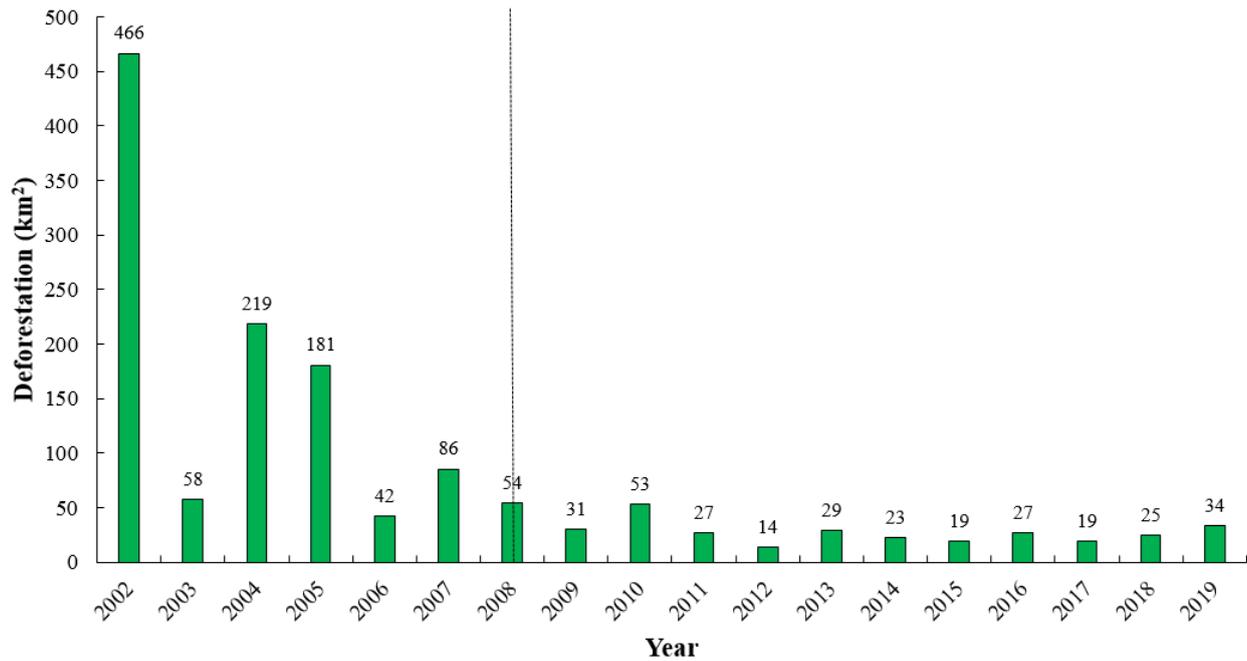
LULC class	Area in 2006 (km ²)	Area in 2017 (km ²)	Variation (km ²)
Natural vegetation	4,943.67	3,954.62	- 989.04
Anthropized áreas	3,297.71	4,282.18	+ 984.47
Water	7.78	7.69	- 0.08
Urban area	7.08	7.89	+ 0.81

Source: The authors (2020).

The variation in the Water LULC class (from 7.78 to 7.69 km²) was not significant but may be explained by the presence of riparian forest covering areas of water and silting in the Ararandeuá river, as described in Rego, Fernandes and Lima (2011). An increase in the Urban area LULC class was also identified (from 7.08 to 7.89 km²) and is explained by the common increasing process that small and medium-sized cities of Pará have been presenting in the last decades. Rondon do Pará had 47,284 inhabitants in 2007, according to data from the State Executive Secretariat for Planning, Budget, and Finance - SEPOF/PA (2007). In 2017, the estimated population was 50,925 inhabitants (IBGE, 2019), a 7.7% increase. This low-growth can be explained by the rural vocation of the municipality and by the soil erosivity in the urban area and its surroundings, a factor that causes frequent losses to residents and creates risk areas unviable the building housing (ROSA et al., 2017).

The variations in Natural vegetation and Anthropized areas LULC classes show that the inclusion of Rondon do Pará in the LPM did not eliminate deforestation in the study area until 2017, as observed from the values of Table. Considering that this policy needs an adaptation period for its fully functioning, since the municipality will not have the Zero-deforestation goal proposed by PPCDAm in the first year (MOUTINHO et al., 2016), we consider that this policy is promising. This time of response to the implementation of environmental policies demonstrates that the observation of concrete results is not always immediate but occurs in the medium to long term. The referred policy imposed a great number of disciplinary controls to the Amazonian municipalities included in the LPM, in particular the prohibition of deforestation and the intense monitoring of this process, which is linked to the banning of rural credit from official banks, effectively paralyzing production on many rural properties (SCHMINK et al., 2017). Aiming to corroborate this scenario of gradual deforestation control, we analyzed the PRODES annual deforestation rates for Rondon do Pará (Figure 4).

Figure 4 – Annual deforestation rates estimated by PRODES in the municipality of Rondon do Pará between the years 2002 and 2019. The dashed line indicates the beginning of the inclusion of the study area in the LPM.



Source: INPE (2020).

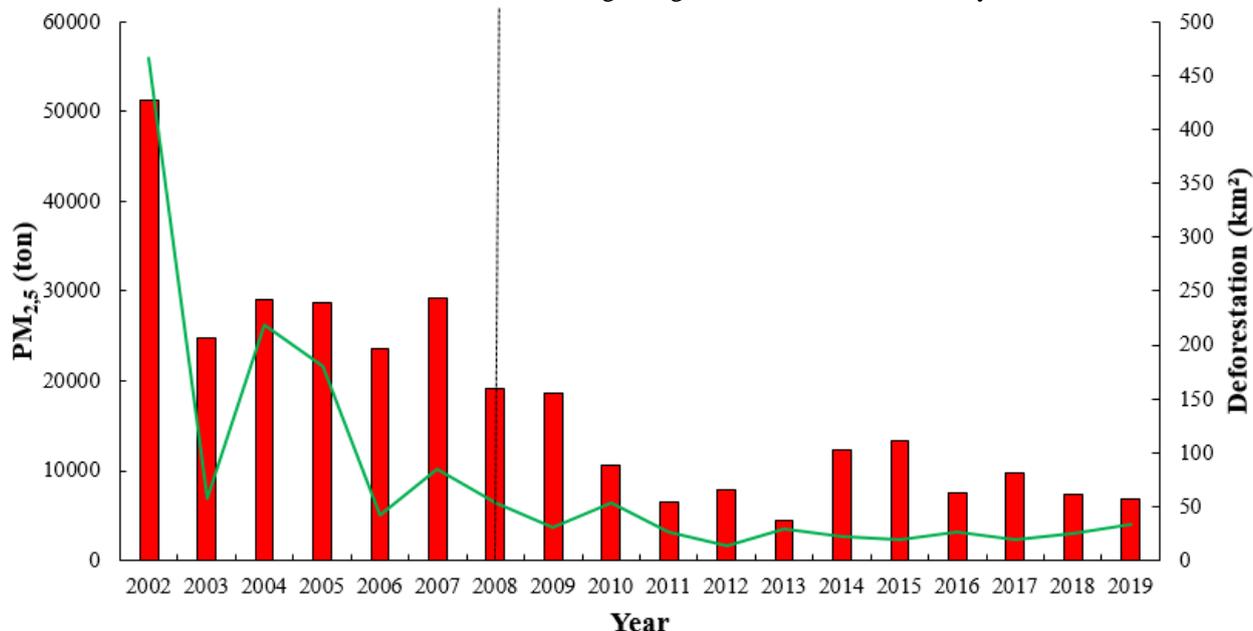
PRODES is the official Brazilian Federal program for monitoring deforestation in the Legal Amazon, aimed at mapping and quantifying annual deforestation accurately in the Brazilian Legal Amazon since 1988 (VALERIANO et al., 2004). The method applied by PRODES enables the analysis of historical deforestation series using masks for not mapping an area previously deforested that may have regenerated later (INPE, 2020). The observed pattern in Rondon do Pará has a high deforestation rate from 2002 to 2008, a pre-LPM period, with an average of 175 km² per year. After entering the LPM, the average rate decreased to 29 km², a decrease of 83%. This gradual reduction is an indicator that inclusion of the municipality in the LPM was positive for reducing deforestation, as it is already showing concrete results and is alignment with the requirements of two environmental agreements: (i) the “Green Municipalities Program” (GMP) (Programa Municípios Verdes, in Portuguese), a Pará state aiming to attend demands of the MMA, and (ii) the pact signed with the Federal Public Ministry (MPF) in the “PR/PA/GAB/10N°28/2011 Term” (MPF, 2011), which requests that 80% of the municipality rural properties must be registered in the Environmental Rural Registry (CAR, in Portuguese) as well as the maintenance of the annual deforestation rate below 40 km² based on PRODES data. Only in 2010, year affected by extreme climate events and consequent droughts in the Amazon (ANDERSON et al., 2015), the latter requirement was not achieved. This anomalous event may have enabled a more effective deforestation in the municipality due to the favorable conditions for igniting fires.

Despite the inclusion of the municipality in the LPM, its location in the Deforestation arc hinder controlling the loss of Natural vegetation since the intensive advance of agriculture and pasture for cattle herds in this region even with the increase in inspection (RODRIGUES-FILHO et al., 2015; FEARNSSIDE, 2017). Selective logging, extensive livestock, and land speculation also are decisive for the increase in deforestation in this region, as shown by Parizzi et al. (2017), who evaluated LULC dynamics in the sub-basin of the Guamá River where a large portion of Rondon do Pará is located. Another activity that contributes to deforestation is the charcoal production, characteristic of the Southeastern region of Pará (FILGUEIRAS et al., 2008). Many charcoal producers have moved from urban to rural areas to establish charcoal plants, due to the proximity to feedstock, increasing the deforestation linked to the anthropic action of logging to coal production (THÉRY et al., 2011).

Considering this intense LULC dynamics, Rondon do Pará still has eligibility criteria to remain in the LPM. As imposed in the Bill n° 322, of 28th September 2012, a municipality should remain in the LPM if it has an increase in the deforestation rates during at least two of the last three years. An alternative to overcome

this situation is the creation of Conservation Units in the municipality; according to Bastos et al. (2014), there is only one in Rondon do Pará, the Parque Ambiental da Prainha. Regarding fire emissions, we noted that, despite the accumulated loss of Natural areas between 2006 and 2017, annual PM_{2.5} emitted from fires have been decreasing after its inclusion in the LPM (Figure 5).

Figure 5 - Annual total of PM_{2.5} emitted from fires in the municipality of Rondon do Pará between the years 2002 and 2019. The dashed line indicates the beginning of the inclusion of the study area in the LPM.



Source: The authors (2020).

Considering the entire period analyzed, the annual average PM_{2.5} emitted from fires in the study area was 17,30 tons. In the pre-inclusion period (2002-2007) this average was 31,11 ton year⁻¹, whereas the post-inclusion period (2008-2019) presented an average of 10,394 ton year⁻¹, that is, there was a decrease of about 40% on the annual average in comparison to the 2002-2019 period and 66% to the annual average of the pre-inclusion period, respectively. This result demonstrates that despite the accumulated loss of Natural vegetation in the 11-year period analyzed, the annual rate of deforestation may be decreasing, which would show a positive point for the inclusion of Rondon do Pará in the LPM. This can be verified by PRODES annual deforestation estimates (Figure 4), since, in the pre-inclusion period, the annual deforestation average rate was 175 km² year⁻¹ and post-inclusion this average decreased to 29 km² year⁻¹. Also, this result may have been influenced by deforestation in the study area for selective logging and continuous logging exploration, common in Rondon do Pará, activities that do not use fire to suppress natural vegetation. The decrease in emissions may also have been caused by the difficulty of the MODIS sensor in detecting active fires in small areas (GIGLIO et al., 2016), common when we have the landscape fragmentation process occurring in Rondon do Pará.

4 CONCLUSION

The inclusion of Rondon do Pará in the LPM for the control of deforestation was beneficial to contain the annual deforestation rates but did not eliminate, in absolute values, the process until 2017, because the suppression of natural vegetation was not totally curbed in the municipality, which reinforces that the changes derived from environmental policies are gradual. As the local deforestation is directly linked to the growth of agriculture and wood extraction, since the economic basis is in the predatory exploitation of forest resources, it is necessary to intensify the implementation of public policies that encourage sustainable development in the municipality. In light of this, we reinforce the relevance of the continuity of this municipality in the LPM, considering that this policy, linked to the other agreements and pacts previously cited, is promising for curbing the deforestation process in the region.

Monitoring actions to identify the suppression of natural vegetation is essential to direct policies and subsidize the allocation of financial resources for inspection and mitigation of environmental degradation processes. Thus, it is important to use the best possible techniques. In this case, GEOBIA proved to be useful for the detection of spatial patterns linked to the deforestation process, favoring the accurate separability of LULC classes of anthropic use and natural vegetation, as well as natural resources such as water bodies.

Regarding fire emissions, we may conclude that they are decreasing after the insertion of Rondon do Pará in the LPM and follow the deforestation rate pattern of PRODES but closer attention must be paid in the near future due to the increasing deforestation rates for the Amazon as a whole and the particular risk of respiratory health impacts, favored by fire occurrence, in the era of the COVID-19 pandemic.

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Authors contribution

According to the CRediT roles: K.V.C.: Conceptualization, Formal analysis, Investigation, Methodology, Writing—original draft preparation. M.E.D.C.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing—original draft preparation. G.A.V.M.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Interest conflicts

The authors declare no conflicts of interest.

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