MAPPING NATURAL NON-FOREST VEGETATION REMOVAL IN THE BRAZILIAN AMAZON – A PILOT PROJECT

C. Almeida[1,] D. Silva [2],C. G. Messias[1], L. S. Soler [1*], L. H. Gusmão[1], L. E. P. Maurano, T. Souza[1], I. Soares[1], D. Barradas[1], I.P. Cunha[1], E. Bastos[1], A. Belluzo[1], C. Quadros[1], B. Pechini [1], F.Pinheiro[1] ,L.J. Silva [1]

[1] INPE, National Institute for Space Research, Av. dos Astronautas 1754, São José dos Campos, 12227-010 Brazil (claudio.almeida, cassiano.messias, luis.maurano, thiago.lima)@inpe.br, (lusoler, gusmaogeotecnologias, igor312, delmatosb, cunhaigorperes, edu.fmbastos, amanda.belluzzo, camilabquadros, brunapechini, fcpinheiro, liberiojunior25)@gmail.com

[2] WWF, World Wide Fund for Nature, WWF-Brasil, CLS 114 Bloco D Asa Sul, Brasília, 70377-540 Brazil (danielsilva@wwf.org.br)

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ABSTRACT :

The increasing pressure from agriculture and pasture activities over non-forest vegetation areas revealed the need of INPE to extend forest regular monitoring to non-forested areas. Non-forest vegetation consists of savannahs, shrub lands, grasslands or seasonal floodplains that occupy 279 thousand km^2 (6,63 %) of Brazilian Amazon biome extension. Addressed ecosystem services of non-forest vegetation vary from climate, soil, carbon storage, biodiversity, water and fire regulation to cultural benefits and living of the population. The challenge in monitoring non-forest removal lies in climatic seasonality, high variability of phytophysiognomies and cloud coverage. In this work we developed a method to map non-forest vegetation from 2000 to 2021 in a pilot area enclosing five municipalities in Roraima and Amapá states. Considering the total area of 47 thousand km², 58 % was originally forest and 37 % was non-forest vegetation. In 2020, soybean planted areas occupied 60 thousands hectares in these municipalities. We adapted PRODES protocol to non-forest features using visual interpretation of Landsat and SENTINEL-2 satellite images. Regional expertise supported the interpretation keys to distinguish non-forest removal from seasonal changes or other land use changes. A baseline map for 2000 is provided together with biannual and annual increments for 2002-2018 and 2019-2021, respectively. Results show removal of non-forested areas even overpassing deforestation in some municipalities. Accumulated non-forest removal was 3.133,06 km^2 or 17,44 % of the non-forest area enclosed. This work consolidated the method to be applied in the Brazilian Amazon biome allowing a uniform historical mapping series of deforestation and non-forest removal.

1. INTRODUCTION

Brazilian land change monitoring systems have been improved in the last couple of years regarding new satellite data, semi-automatized image processing and selection, as well as image interpretation (Almeida et al. 2021, Soler et al. 2021). PRODES, INPE´s renowned deforestation project has been recognized as contributing significantly to decrease deforestation in the region between 2004 and 2012, by providing valuable data (Messias et al., 2021). For many years the efforts were made towards tropical forest vegetation, however the increase of agricultural and pasture land over non-forested vegetation has motivated the implementation of a regular monitoring system to quantify and qualify losses in these phytophysiognomies.

Originally, non-forest vegetation in the Brazilian Amazon biome occupied an area about half of France. Non-forest vegetation ecological relevance is very high as most flora and fauna are unique and contributions to regional hydrological and climate regulation are essential (Strand et al. 2018). Beyond that, mapping non-forest vegetation dynamics can help land suitability and zoning analyses to improve land management and living conditions. Land use in these areas has occurred in the last couple decades especially along the main rivers in central wetlands (Reno and Novo, 2019). Recently non-forest removal have also been associated to agricultural intensification in drier portions of Amapá and Roraima States mainly for grains production (Barbosa et al., 2011), added to more consolidated areas in the border to Cerrado and Pantanal biomes (INPE,2021).

In the last decade, PRODES project extended the mapping area to other Brazilian biomes (Almeida et al. 2020), including the challenging tropical savannah (Cerrado) where climatic seasonality and the variability of phytophysiognomies can lead to misclassification of disturbances in non-forest vegetation. However, areas of non-forest vegetation within the Amazon differ significantly from Cerrado in climatic seasonality and cloud coverage, which can affect even more land cover change detection in these regions (Sano et al, 2010).

So far, the continuous and systematic forest and non-forest (FNF) monitoring system in the Amazon provides essential outcomes to support public policies of environmental protection (Overbeck et al.., 2015). Spatial and temporal analysis of historical series can drive sustainable economic practices under law enforcement and natural resource management. Not only can market regulations for trading forest certificates benefit from trustful FNF monitoring systems, but also conservation policies of greenhouse gases emissions mitigation through the avoidance of vegetation removal (Soares et al., 2016).

Misinterpretations of land cover changes and uncertainty in carbon estimates can be reduced throughout accurate and up-to-date forest and non-forest maps (Sano et al. 2021). Besides, verified delimitation of non-forest vs. forest phytophysiognomies allows better updates of non-forest inventories (dating from 2016), as well as of carbon estimates adopted for climate negotiations under UNFCCC (Brasil, 2021). In this context, mapping non-forest vegetation removal has been incorporated into PRODES system aiming to provide accurate annual figures of land cover losses not only in forest, but also in

* Corresponding author

non-forest domains. Preliminary FNF mapping in the Brazilian Amazon can be found such as Sano et. al (2017) or Santos et al.(2022), but they fail at spatial and/or temporal scales. The lack of a systematic methodology to identify features using well defined keys of interpretation that enclose the variety of phytophysiognomies occurring with non-forested areas inside the Brazilian Amazon biome is still poorly discussed. Thus, aiming to fill in the lack of data of natural vegetation dynamics beyond tropical forest phytophysiognomies, this work focuses on releasing the non-forest vegetation removal maps from 2000 to 2021 for a pilot project area enclosing five municipalities in Roraima and Amapá states.

2. CHARACTERIZATION OF THE STUDY AREA

The Brazilian Amazon biome holds 279.360,26 km^2 of non-forest vegetation type (Figure 1), which represents 6,63% of these phytophysiognomies that consist of savannahs, transitional areas, shrub lands, grasslands with sandy areas (*campinas* and *campinaranas)* and seasonal flooded lowlands. The states of Pará, Roraima, Amazonas and Mato Grosso hold the largest portions of non-forest areas in the Brazilian Amazon, summing more than 230 thousand km² of non-forest areas. On the other hand, Roraima, Amapá and Rondônia have the largest percentages of non-forest inside their territory, which correspond respectively to 27, 18 and 10 %.

A detailed analysis of different phytophysiognomies occurring inside non-forest areas reveals the savannahs and transitional areas respond together to more than 50% of land cover, while *campinaranas* and dense ombrophilous forest correspond to 28% of non-forest phytophysiognomies in the Brazilian Amazon biome. The pilot project area, i.e. the study area of this paper encloses five municipalities (Figure 2), as follows: Alto Alegre, Boa Vista and Bonfim in Roraima state (RR), and Itaubal and Macapá in Amapá state (AP). Their total area is 47.438,97 km², out of which 27.872,93 km² (58%) was originally forest and a significant portion 17.964,66 km² (37%) was non-forest vegetation back in a couple decades ago (IBGE, 1978). In 2020, soybean planted area was about 60 thousand hectares in these municipalities (IBGE, 2020).

In the north-eastern portion of Roraima state three out of five municipalities studied in this paper present a singular type of savannah named *lavrado*, which extends for 40 thousand km² and characterises non-forest areas in that state (McGill, 1966; Miranda, 2000; Barbosa et al. 2007; Barbosa et al. 2017). The *lavrado* consists of grassy savannahs of low altitude (< 100m) and steppe shrublands of high altitude (> 600 m). Different from central and south of the Amazon biome, annual rainfall in Roraima varies between 1.100 to 1.700 mm, with the rainy season between May and August (60% of annual precipitation), and a dry season between December and March (10% of annual precipitation) Barbosa and Fearnside (2005).

Mapping land cover change in these areas is challenging as spectral response of combined phytophysiognomies and can be misclassified as bare soil resulting from anthropic activities. In addition, savannahs can be distinguished from other changes mostly due to its particular landscape dynamics. Extensive plains under erosive processes can be flooded and small ponds are formed during the drier periods when non-forest removal can be detected. Thus, previously to land cover change mapping it is required a careful mapping of intermittent ponds to avoid misclassification to shadows of clouds. However, the most challenging distinction of features in the *lavrado* is the annual land use change dynamics, which is not easily revealed by land cover change mapping as no specific shapes or geometric patterns are observed. In these cases, most visual interpretation must count on inter annual changes in spectral responses, which can be very subtle. Also interpreters must count on experts on image enhancements to avoid over/under estimates of pixel values when the set of parameters chosen extrapolates suitable intervals that agree to the number of gray levels in the images.

Amapá holds 97,2 % of preserved forest, which is the second largest percentage among all Brazilian Amazon states. Deforestation there occurs along the main roads BR-2010 and AP-156 (Messias et al., 2021). The main agricultural land use in the studied municipalities located in Amapá are soybean, cassava and rice (IBGE, 2020). A relevant phytophysiognomy occurs inside these municipalities and it is named 'pioneer formation vegetation'. These areas are characterised by vegetation with a high above ground biomass that is seasonally flooded following climatic and water Amazonian cycles. Because of that, these are key transitional areas of extreme relevance to local species, being thus highly sensitive to long term anthropic disturbance observed in the last decades (Renó and Novo, 2013, 2019). Thus, based on such studies specific interpretation keys for these pioneer formations were developed to allow appropriate land cover change mapping.

Cloud coverage in the study area is recurrent all year round, especially in Roraima state. Consequently, non-observed areas or areas under cloud coverage must be tackled by using remote sensing strategies, being also computed in land cover change estimates under PRODES protocol. Thus, in this paper we delivered the non-forest vegetation removal history (and non-observed area) from 2000 to 2021 inside five municipalities within two Federal States considered a pilot project area, illustrated in detail in Figure 2.

3. METHODOLOGY

The adopted method to map vegetation removal in non-forest areas was developed using the PRODES protocol as a baseline (Almeida et al., 2021). Visual image interpretation is a big foundation of the confidence level of Brazilian monitoring systems, whose differential is to avoid false positives deforested patches at the most, and also to prevent omissions or true negatives (Almeida et al. 2020). Therefore, as the methods used to map deforestation in forest areas, we developed specialised interpretation keys that enable the distinction of non-forest removal from seasonal changes in non-forest vegetation, or from other land cover changes. In order to properly characterise non-forest phytophysiognomies and to map their removal using orbital images, a detailed literature and a cartographic review were performed. Supported by vegetation experts with large fieldwork experience it was possible to establish features that exemplify and standardise such interpretation keys.

The mapping of non-forest removal was done manually using optical satellite images interpretation. In the period between 2000 and 2014, we used images retrieved from Landsat satellites series (Thematic Mapper -TM, Enhanced Thematic Mapper Plus - ETM + and Operational Land Imager – OLI sensors). In the period between 2016 and 2021, we adopted Sentinel 2A and 2B satellites images (Multispectral Instrument - MSI sensor). Image repositories from the National Aeronautics and Space Administration (NASA) at https://earthexplorer.usgs.gov/ and the European Space Agency (ESA) at https://scihub.copernicus.eu/ provided orthorectified images with no need for additional geometric correction.

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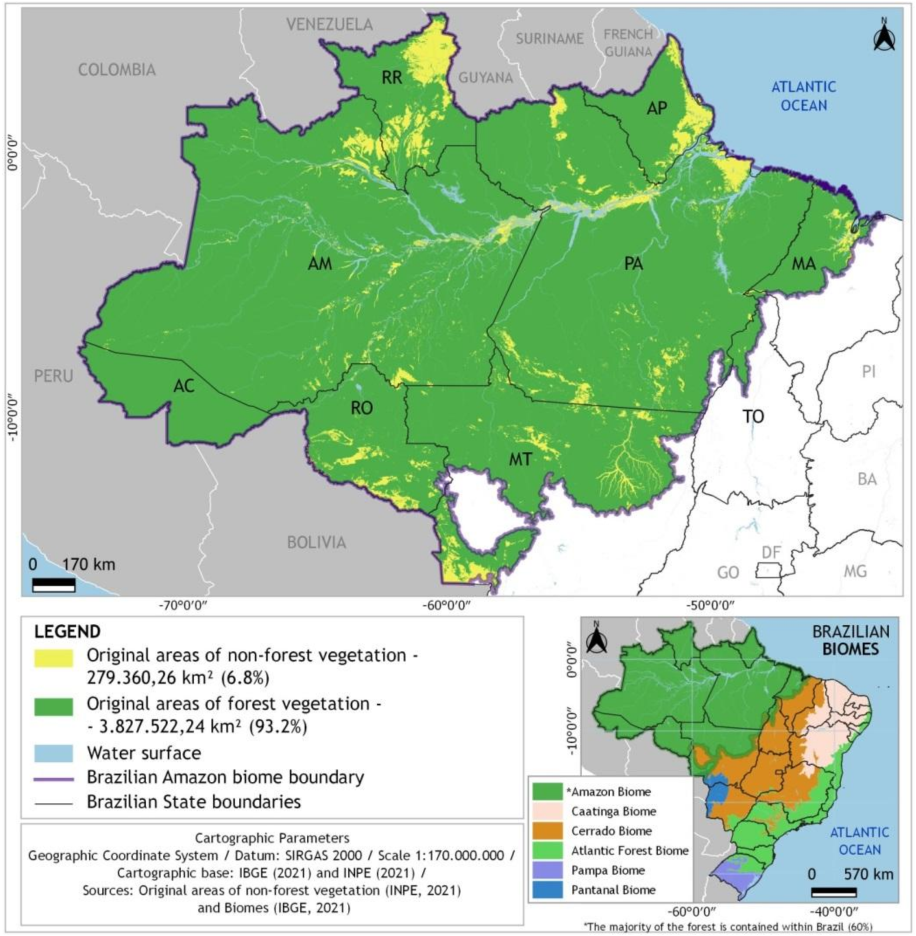

Figure 1 – Original vegetation map illustrating forest (green) and non-forest (yellow) vegetation domains in the Brazilian Amazon in perspective to other biomes and federal states.

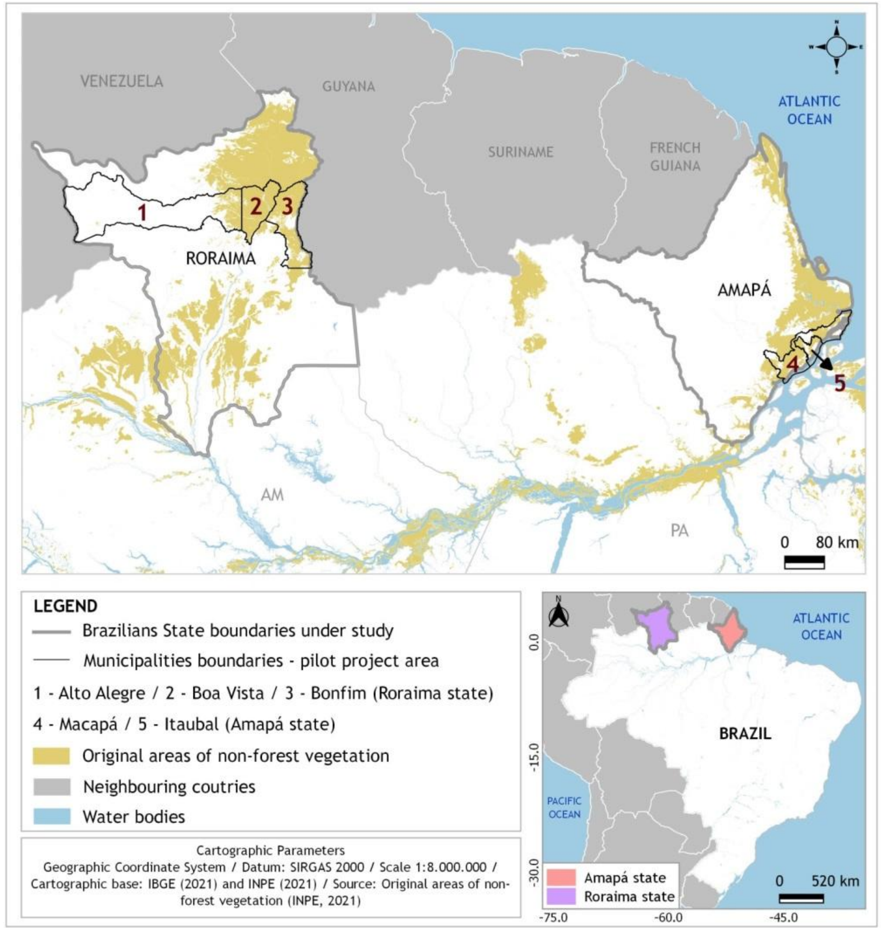

Figure 2 – Original areas of non-forest vegetation in the context of the pilot project area comprising three and two municipalities respectively in Roraima and Amapá states, in perspective to the regional and national extents.

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Image selection process was performed adopting used-defined Google Earth Engine (GEE) scripts that allowed the selection of images with the least percentage of cloud coverage within an ideal period associated to the drier period of each Landsat scene, as described in Almeida et al. (2021). Cloud coverage in some portions of the Amazon biome is recurrent even in the dry season (Soler et al. 2021), which lead us to adopt secondary images for a number of Landsat scenes under high percentage of clouds. Due to their higher temporal resolution when compared to Landsat, the Sentinel products were composed in mosaics of images that overlapped Landsat grid scenes. Whenever possible these mosaics were built considering images acquired within the ideal period. Complemented methods of cloud detection using image classification to deal with cloud coverage were used and are described in Soler et al. (2021).

TerraAmazon software (http://www.terraamazon.dpi.inpe.br/) was chosen as the main tool to undertake the technical procedures of mapping. The software allows an interactive data work flow among interpreters and auditors, with a clever customized vector edition tool that speeds interpretation with guaranteed efficiency and data quality. TerraAmazon is developed in the Open Source Library TerraLib, both developed by INPE (http://www.terralib.org) and distributed under GNU LGPL license (Camara et al., 2008). TerraAmazon runs online and offline – a demand to attend home office requirements during the COVID-19 pandemic period – managing complete flux of data, processes and users allowing the remote production of land cover mapping projects.

Image visual interpretation was done using colour compositions of satellite images, for instance 5R/4G/3B to TM's products. In this sensor bands 5, 4 and 3 correspond to short-wavelength infrared, near infrared and red channels, respectively. In these colour compositions adopted the vegetation appears in green tones. Additionally, stretched histograms using user-defined thresholds were built for image contrast operations to improve feature distinction in the satellite images.

Non-forest areas within the Amazon biome are constituted by savannahs with herbaceous vegetation, shrubby or even arboreal areas, grasslands and flooded lowlands. The visual interpretation considered five elements, to mention: colour, shades, texture, shape and context of features. As the removal of non-forest vegetation was mapped during the dry season, areas predominantly composed by herbaceous vegetation can be distinguished in the colour compositions by appearing in a shaded dark magenta coloration, with a smooth to medium texture in the wet season when their colour tones may be green due to the increase in biomass. Native shrubby and arboreal vegetation appear in medium to dark green and medium to rough texture (Figure 3).

A team of analysts identified polygons of non-forest vegetation removal visually. The year of 2000 was chosen as the baseline map that provides an accumulated non-forest removal. Between 2002 and 2018 the increment maps of non-forest removal were produced on a biannual basis, and annually between 2019 and 2021. After each new year mapped an exclusion mask was created and then used as base to map the next year. This procedure guaranteed that only new increments of non-forest removal were mapped. The maximum and minimum interpretation scales were correspondingly 1:75.000 and 1:250.000. Minimum interpretation area was 0,01 km².

To produce the 2000 baseline map of accumulated non-forest removal, the analysts compared images from 2000 to images from the 1980s and 1990s. In this step, delimited features of non-forest removal and intermittent ponds were mapped for the year 2000. After that, interpreters identified increments of non-forest vegetation removal between 2002 and 2021 by comparing the mapped year to the year immediately before that one. For example, when mapping increments of non-forest removal for the year 2004, interpreters would compare features in the colour composition of 2004 to those mapped in 2002.

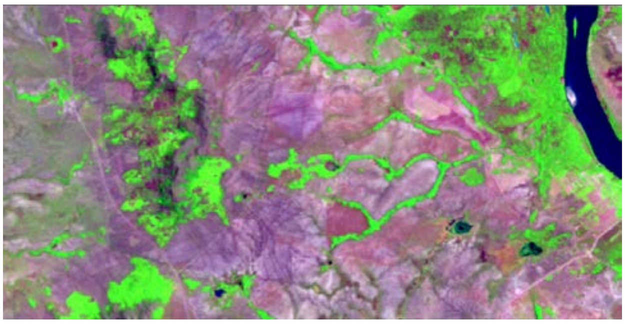

Figure 3 – Example of an area constituted by natural non-forest vegetation in the municipality of Boa Vista, Roraima state. Areas in magenta are herbaceous vegetation, green tones are shrubby and arboreal vegetation, and blue are water bodies.

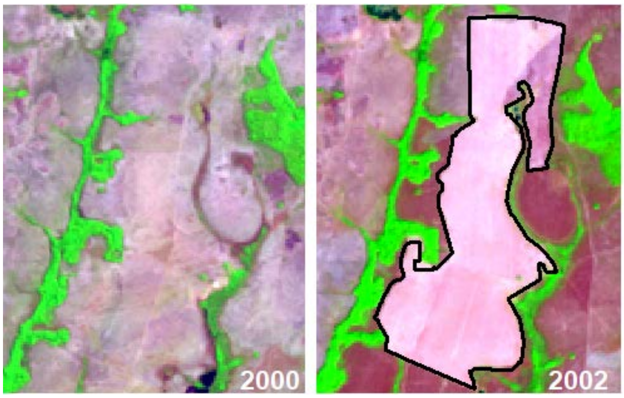

Figure 4 – Example of bare soil detection distinguished due to anthropic vegetation removal revealed between 2000 and 2002. Bare soil feature is surrounded by herbaceous vegetation (darker magenta) and shrub lands (green tones).

Figure 5 – Examples of urban area detection (image on the left), and agricultural areas (image on the right) at Boa Vista municipality in Roraima state, both revealing removal of non-forest vegetation.

A large number of removal increments were detected as bare soil, especially when vegetation suppression has taken place close to the satellite images date of acquisition. In these cases, non-forest removal features stand out in the colour composites (Figure 4). The visual detection is possible due to an increase in reflectance in both the short-wavelength infrared and red channels, added to a reduction at the near infrared when compared to preserved non-forest area at images from the previous year. Sometimes, in non-forest areas with herbaceous or grassy vegetation a quick regeneration may occur after vegetation removal, making the identification harder when the date of acquisition was much ahead the removal date. Non-forest vegetation removal may also be identified in satellite images as features of anthropic land uses and land covers. Examples are urban areas, agricultural areas, planted pastures, forestry and artificial dams (Figure 5).

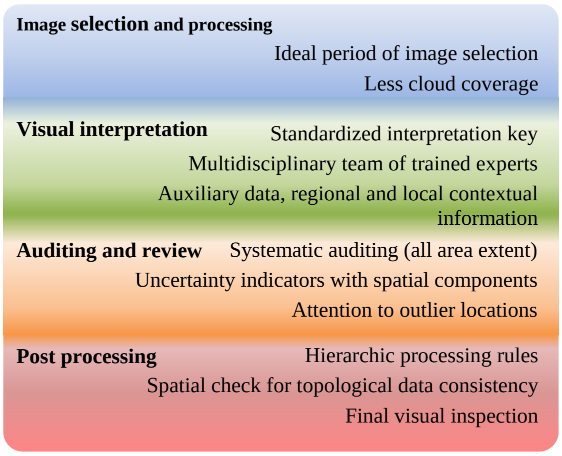

Figure 6 - Scheme of methodological steps developed to map non-forest removal in the Brazilian Amazon biome.

Locations where cloud coverage overlapped at both, the core and secondary images, were mapped as non-observed areas. A cloud detection tool available at TerraAmazon software was used to detect clouds and their shadows. After the mapping of each year had been completed, the totality of polygons was submitted to auditing processes. Expert auditors verified the refinement of the polygons outline, corrected false positives and mapped eventual omitted polygons. At last, in the post processing step the final vector file was checked to correct topological incongruences. Figure 6 illustrates the methodological steps adopted in this study.

4. RESULTS

The accumulated estimates of non-forest removal in the pilot project area until 2021 was 3.133,06 km^2, which represents 17,44% of non-forest vegetation existing in the area. The results showed that non-forest removal in this area has increased significantly in the last decades, even surpassing the percentage of forest removal or deforestation. PRODES data indicate that the deforestation reached 1.753,24 km² until 2021, which corresponds to 6,37 % of the pilot project area.

Figures 7 and 8 indicate the annual increments in percentage (bars) and accumulated area (lines) of non-forest removal and deforestation, respectively. Figures 9 and 10 show the spatial distribution in area of non-forest removal indicating the biannual/annual historical series in each municipality of the pilot project area.

Even though deforestation has decreased over the last two decades, non-forest losses were substantial in the study area. It can be observed by the steeper curves of Figure 7 than in Figure 8, especially after 2006. The results per municipality show that the accumulated non-forest removal in area until 2021 and percentage biannual/annual increment values (within 2000-2021) peaked 564,42 km² (21,70%) in Alto Alegre, 1070,55 km² (30,08 %) in Boa Vista and 83,00 km² (13,72 %) in Bonfim. Non-forest removal patterns have concentrated along the main rivers and roads as can be observed in Figure 9. Accumulated deforestation until 2021 and percentage biannual/annual increment values (2000-2021) accounted for 829,06 km² (3,69 %), 19,35 km² (7,85 %) and 398,41 km² (20,71 %) of original forest areas, respectively in the aforementioned municipalities.

In Itaubal and Macapá the accumulated non-forest removal and percentage biannual/annual increment values between 2000 and 2021 were 141,60 km² (19,39 %) and 516,92 km² (16,23 %) (Figure 7 and 10). In forest areas, the accumulated deforestation until 2021 was 90,88 km² and 415,53 km² , i.e. 19,0 %, and 17,57 % of the original forest areas in these municipalities. Non-forest removal patterns in studied municipalities in Amapá have concentrated into the countryside along roads and distant from the coastal areas, and mainly between 2000 and 2013 as observed in Figure 10.

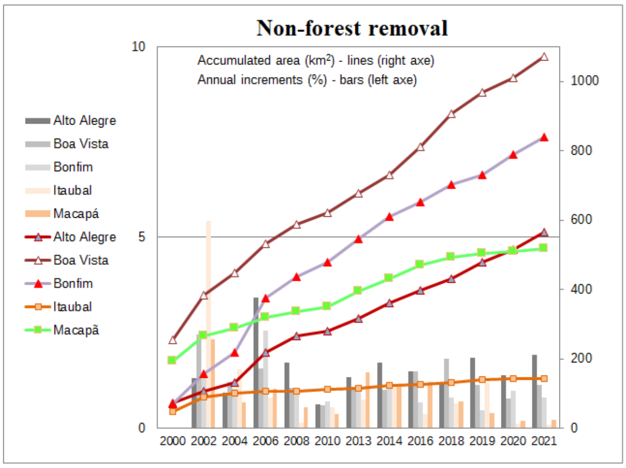

Figure 7 – Non-forest removal outcomes within the municipalities of the pilot area. Accumulated area in km² is shown in lines (left axe) and annual increments in percentage (right axe). Source: elaborated by authors (Almeida et al.2022).

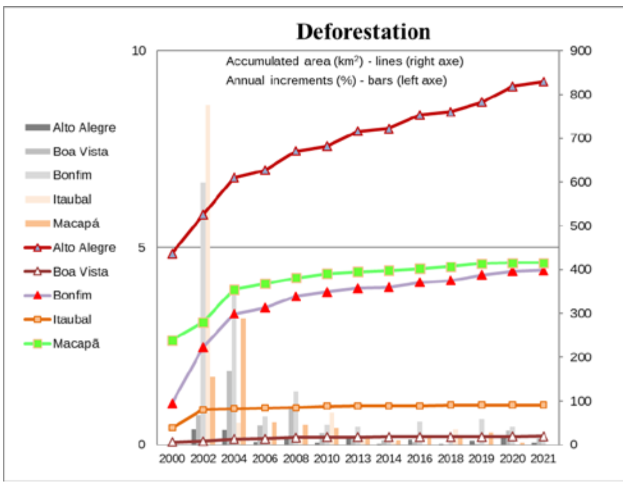

Figure 8 – Deforestation outcomes within the municipalities of the pilot area. Accumulated area in km² is shown in lines (left axe) and annual increments in percentage (right axe). Source: elaborated by authors (Almeida et al.2022)

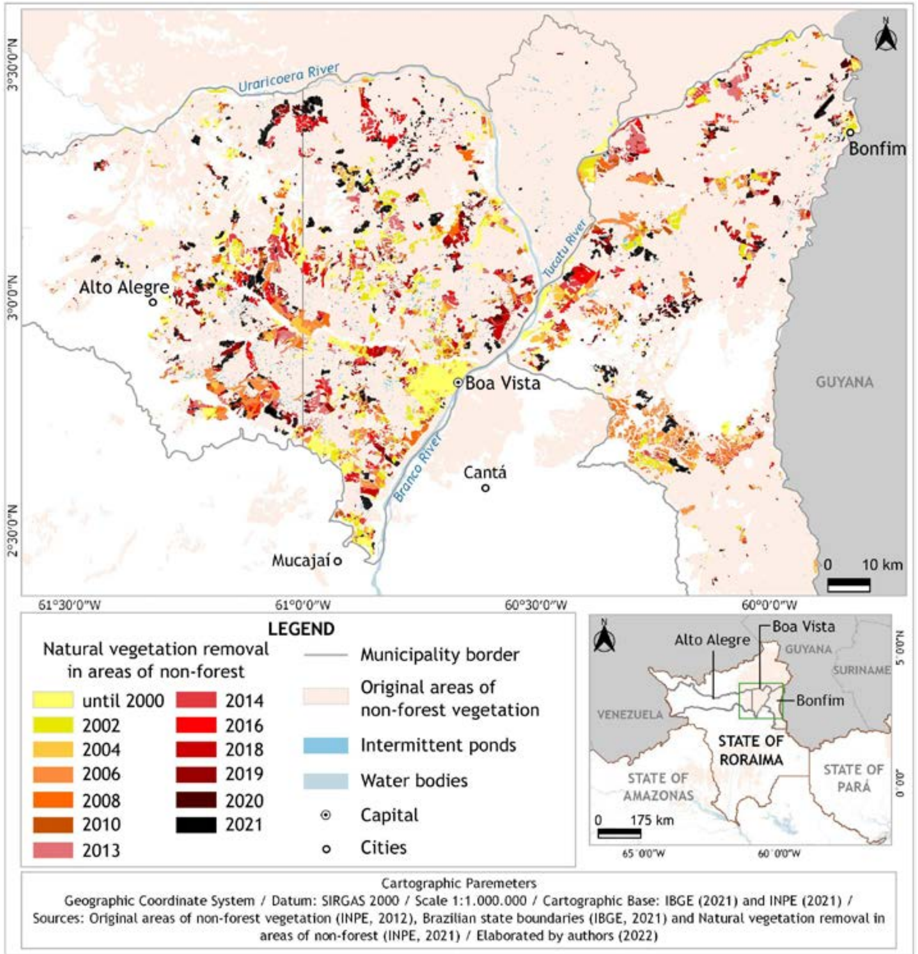

Figure 9 – Non-forest removal historical series from 2000 to 2021 mapped to Alto Alegre, Bonfim and Boa Vista in Roraima state. Original areas of non-forest vegetation, intermittent ponds, water bodies, capitals and other cities are also illustrated.
Source: elaborated by authors (Almeida et al.2022).

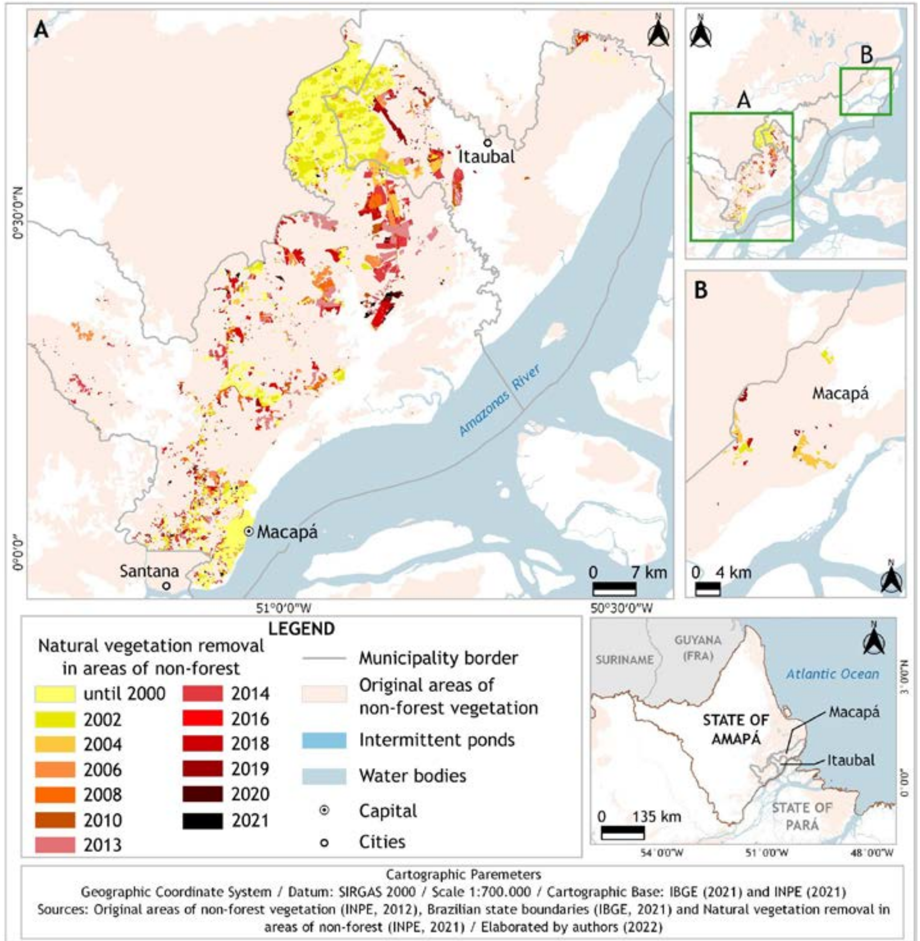

Figure 10- Non-forest removal historical series from 2000 to 2021 mapped to Itaubal and Macapá in Amapá state. Original areas of non-forest vegetation, intermittent ponds, water bodies, capitals and other cities are also illustrated.
Source: elaborated by authors (Almeida et al.2022)

5. DISCUSSION

The non-forest removal in the study area occurred mainly in The high accumulated area of non-forest removal observed in the municipalities of Roraima (Alto Alegre, Boa Vista, and Bonfim) is driven mostly by agricultural and road expansion in the region. This is because most of the agribusiness and agricultural production areas in *lavrado* are concentrated in the region of Boa Vista (Barbosa et al. 2007; Barbosa and Campos, 2011). The main crops established after non-forest removal in the aforementioned municipalities are soybean and corn added to some well-established areas of irrigated rice and planted forests with *Acacia mangium*. According to Carmo et al. (2008), official state data estimates 650 km^2 of the *lavrado* had been occupied by large agribusiness projects by 2008. It is clear then that non-forest removal in these portion of Roraima is a challenge to be faced and confident land cover change estimates can help to burst regional and local governance by environmental agencies. Flawed data previously provided by large agro companies underestimate the area of non-forest removal inside *lavrados*, mainly due to permissive methodology that misclassified anthropogenic land uses (Barbosa and Campos, 2011; Urquiza et al. 2018).

In the state of Amapá, non-forest removal can be associated to the increasing expansion of agricultural frontier at the large scale (Silva, 2016). The savannahs of Amapá, alleged to be the last frontier for soybean plantations in Brazil, has attracted new farming activities due to low land prices and promises of infrastructure improvement (Silva 2016). In addition, disputed land tenure regularization processes allow local farmers to easily lease or sell their land at low prices, which contributed to a 200% increase in the soybean planted area in Roraima state in an astonishing fast period of three years' time (IBGE, 2017).

According to Hilário et al. (2017), the increase in soybean cultivation in Amapá was mainly concentrated in Itaubal, Tartarugalzinho and Macapá. Silva (2016) projected for Amapá a soybean increase in planted area of 4 thousands km^2 by 2026, which represents nearly 40% of the non-forest areas covered by savannah in the state.

In the context of a growing concern of Brazilian and international institutions for conservation of non-forested natural ecosystems, and of urgent request of the civil society to include such ecosystems in the Soy Moratorium, the PRODES/INPE´s team presented the results of this pilot project to the Working Group of the Amazon Soy Moratorium. This group is composed by NGOs and private sector companies, represented by the Brazilian Vegetable Oils Industry Association (ABIOVE). ABIOVE then offered support for future data validation based on fieldwork observations.

6. CONCLUSIONS

This work is an initial effort to build a uniform historical mapping series of both forest and non-forest disturbance in the Brazilian Amazon. It will represent the non-forest baseline map to compose the historical series of PRODES project, and its increment maps shall be incorporated in the regular annual monitoring of the Brazilian Amazon.

These results indicate that non-forest vegetation is under risk inside municipalities within the study area, especially in Roraima state. Considering the relevance of this vegetation for a number of ecosystem services such as carbon stocks, biodiversity, cultural heritage among others, further studies are required to evaluate how these phytophysiognomies have been affected in terms of ecological functioning due the reduction of their area.

The lessons learned here have consolidated the monitoring methods and became the basis of an ongoing mapping of non-forest vegetation removal from 2000 to 2022 for the whole region. After completing this historical series, PRODES project shall achieve a complete and updated spatial coverage of natural vegetation conversion in the Brazilian Amazon biome. At last, it relevant to mention that land cover change monitoring is being extended to all other Brazilian biomes based on PRODES methodology. It is being carried out by INPE and partners supported by the PRODES Project and BIOMAS Project (Almeida et. 2020), and shall be concluded throughout 2022-2023. This means that 100% of the Brazilian territory will have an updated and highly accurate monitoring data within a short time.

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