PRODES MONITORING EXPANSION INTO NON-FOREST VEGETATION AREAS IN THE BRAZILIAN AMAZON: FIRST MAPPING OUTPUTS IN TWENTY-ONE MUNICIPALITIES IN THE STATE OF MATO GROSSO

Cassiano G. Messias[1], Cláudio A. Almeida[1], Luiz E. Maurano[1], Daniel E Silva[2], Luciana S. Soler[1], Marcos Adami[1], Bernardo Pires[3], Pedro Garcia[3], Vagner L. Camilotti[1], Luiz H. A. Gusmão[1], Thiago C. de Lima[1], Amanda P. Belluzzo[1], Camila B. Quadros[1], Delmina C. M. Barradas[1], Douglas R. V. Moraes[1], Eduardo F. M. Bastos[1], Fábio C. Pinheiro[1], Igor P. Cunha[1], Jefferson J. de Souza[1], Lucélia S. de Barros[1], Rodrigo de Almeida[1], Bruna M. P. Bento[1], Dayane R. V. Moraes[1], Deborah L. C. Lima[1], Hugo C. Castro Filho[1], Igor S. Santos[1], João F. S. K. C. Pinto[1], Libério J. Silva[1], Liliane C. L. Araújo[1], Manoel R. R. Neto[1], Marlon H. H. Matos[1], Murilo B. Silva[1], Noeli A. P. Moreira[1], Raíssa C. S. Teixeira[1], Raquel P. N. Filho[1], Vivian Renó[1], Diego M. Silva[1], Eduardo H. S. Chrispim[1], Jacqueline O. Santos[1], Sandra B. Santos[1], Thayse Azevedo[1], Adeline M. Maciel[1], Mariane S. Reis[1], Gabriel C. Gonçalves[1], Adriano Venturieri[4]

[1]National Institute for Space Research (INPE), São José dos Campos, 12227-010, Brazil; [2]World Wide Fund for Nature (WWF), Brasília, 70377-540 Brazil; [3]Brazilian Association of Vegetable Oil Industries (ABIOVE), São Paulo, 04603-004, Brazil; Embrapa Roraima Oriental, Belém, 66095-903, Brazil. First author's e-mail: cassiano.messias@inpe.br

ABSTRACT

This work aims to show the preliminary results of natural vegetation removal mapping in non-forest areas, as part of the Brazilian Amazon Rainforest Monitoring Program by Satellite (PRODES). These results cover twenty-one municipalities located in the state of Mato Grosso, and correspond to the mapping of the accumulated removal of natural vegetation up to 2000, and the biannual/annual removal increments from 2002 to 2021. The results showed that the removal reached 29,38% of original non-forest vegetation in the study area. The highest values of loss occurred up to 2004, slowing down between 2005 and 2013, and again increasing as of 2014. The results provided by the adopted methodology are promising and suitable to be used in a systematic annual monitoring of Amazonian non-forest areas starting from 2023.

Keywords **—** non-forest, vegetation removal, deforestation, monitoring, Amazon biome, INPE

1. INTRODUCTION

The Brazilian Amazon Rainforest Monitoring Program by Satellite (PRODES), developed by the National Institute for Space Research (INPE), has been monitoring and releasing deforestation rates in the Brazilian Amazon since 1988 [1]. PRODES is one of the most important and recognized programs of rainforest monitoring in the world and its results are crucial for the elaboration and assessment of policies and agreements to control deforestation and greenhouse gas emissions [2]. INPE's transparency regime has enabled technology transfer and its capacity program has trained teams from several countries [3].

Historically, PRODES has never monitored non-forest areas within the Amazon. These areas cover 279,360.23km², which represent 6.63% of the Amazon biome in Brazil. Non-forest phytophysiognomies are constituted by savannahs, transitional areas, shrublands, grasslands with sandy areas (*campinaranas*), and seasonal flooded lowlands, among others. The largest extensions of these areas are located in the states of Pará, Roraima, Amazonas, and Mato Grosso [4].

Up to 2021, INPE has monitored forest areas within Amazon and the entire Cerrado biome. In 2022, the institute released the first results of deforestation mapping in Caatinga, Pampa, Atlantic Forest, and Pantanal biomes. In the interest of monitoring the whole Brazilian territory, PRODES program expanded into the Amazonian non-forest areas [4].

In a pilot project, a historical series of natural non-forest vegetation removal from 2000 to 2021 was accomplished in three municipalities in Roraima and in two others in the state of Amapá. The results showed a removal of 17.44% of non-forest vegetation in those municipalities by 2021, surpassing their percentage of deforestation that was 6.33% in the same period [4].

In this paper, we expanded the methodology into other twenty-one municipalities in the state of Mato Grosso, Brazil, located in the "arc of deforestation". This is a contact area to Cerrado biome, with high rates of deforestation linked to the advance of the agricultural frontier lead mainly by soybean and grazing pastures for livestock.

2. MATERIAL AND METHODS

The study area corresponds to twenty-one municipalities in the state of Mato Grosso (Figure 1), selected for analysis as

each presented at least 3,000 ha (30 km²) of planted soybeans in Amazonian non-forest ecosystems. This selection was done based on maps of soybean plantations of 2019/2020 harvest provided by Agrosatélite [5].

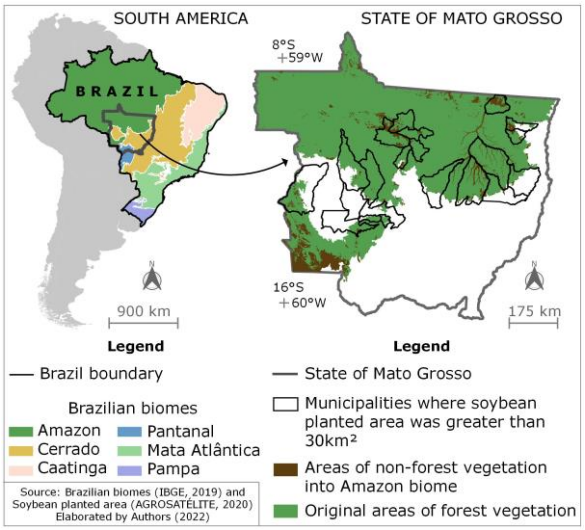

Figure 1. Mapped municipalities: Brasnorte, Campo Novo do Parecis, Canabrava do Norte, Canarana, Comodoro, Diamantino, Gaúcha do Norte, Ipiranga do Norte, Itaúba, Nortelândia, Nova Canãa do Norte, Nova Marilândia, Nova Maringá, Nova Ubiratã, Porto Alegre do Norte, Querência, Ribeirão Cascalheira, Santa Cruz do Xingu, Sinop, Tabaporã, Tangará da Serra.

We adapted the conventional PRODES methodology, by the elaboration of interpretation keys based on a bibliographic and cartographic survey. These were used to interpret remote sensing images acquired in the dry period [8]. This period was selected due to reduced cloud cover and expected increase in deforestation events [3]. This mapping was produced considering the new geographical boundaries of the Amazon biome provided by IBGE at the scale 1:250,000 [6], which is also the current limit adopted by all INPE monitoring programs.

Landsat images were retrieved from 2000 to 2014, and after 2016 only Sentinel-2 data were used. All images were analyzed using the false color composite short-wavelength infrared (R) /near infrared (G)/ red (B), respectively bands 5, 4 and 3 for the Landsat sensors Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), and 11, 8 and 4 for Sentinel-2 Multispectral Instrument (MSI).

The mapping was performed by a team of 20 analysts, based on the visual interpretation of satellite images on TerraAmazon software. Maximum and minimum mapping scales were 1:75,000 and 1:125,000, with a minimum mapping area of 0.01 km².

A base map was produced consisting of the accumulated removal of non-forest vegetation up to 2000. To obtain such a map, the analysts compared images from 2000 to auxiliary images dating from the 80's and 90's, enabling experts to map features of non-forest vegetation removal revealed in the baseline year of 2000 (Figure 2).

The increments of non-forest vegetation removal were mapped biennially between 2002 and 2018, and annually from 2019 to 2021. These increments were identified by comparing images of a given year to the images of the previous year. An exclusion mask was updated with the new identified polygons of vegetation removal at each year, to prevent overlay errors between former and recent increments.

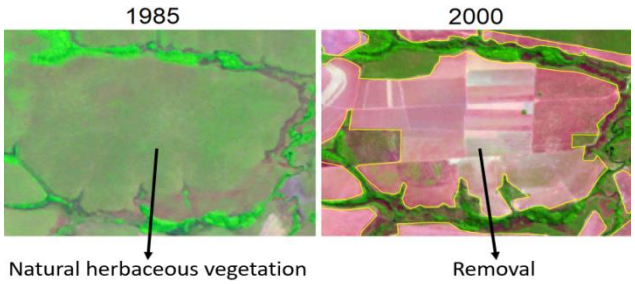

Figure 2. Illustration of non-forest vegetation removed between 1985 and 2000. In the color composition 5R/4G/3B (Landsat/TM) bare soil can be seen in shades of magenta, while shrub lands and riparian forests appear in shades of green.

At last, expert auditors evaluated the finished product by checking all mapped polygons and, whenever necessary, promoting adjustments in order to eliminate false positives or, to eventually add the occasional omitted polygons. The final vector file was checked in a post-processing step to fix possible topological incongruences. To build the graphic shown in Figure 3 of the annual historical series, we assigned the removal values of unmapped years as half the increment mapped in the following biennial map. As such, the following year also should register half the previously calculated value.

3. RESULTS AND DISCUSSION

The studied municipalities lost 2,076.36 km² (13.56%) of non-forest vegetation until 2000 and 2,419.77 km² (15.81%) between 2001 and 2021, totaling 4,496.13 km² (29.38%) out of the 15,305.24 km² of its natural coverage. The historical series of non-forest removal and deforestation in the municipalities are shown in Figure 3. Figure 4 shows the spatial location of non-forest removal in those areas.

Mato Grosso is one of the Amazon's most critical states regarding deforestation levels. Historically, it has registered the highest deforestation rates in the Amazon [1], with much higher deforestation density levels than that found for the entire biome from 2001 to 2006. The historical series of non-forest removal showed a similar pattern (Figure 3). PRODES data show that deforestation in the municipalities under study reached 46,257.49 km² (42.90%) until 2021, out of which 29,741.13 km² (27.58%) had been deforested before 2000.

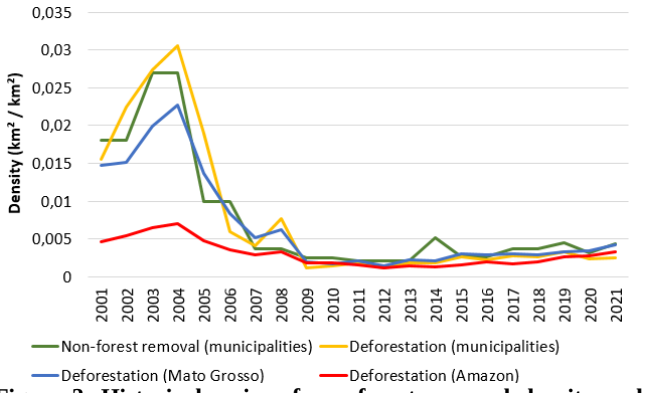

Figure 3. Historical series of non-forest removal density and deforestation (forest suppression) in the twenty-one municipalities studied compared to deforestation figures in the state of Mato Grosso and in the Brazilian Amazon as a whole.

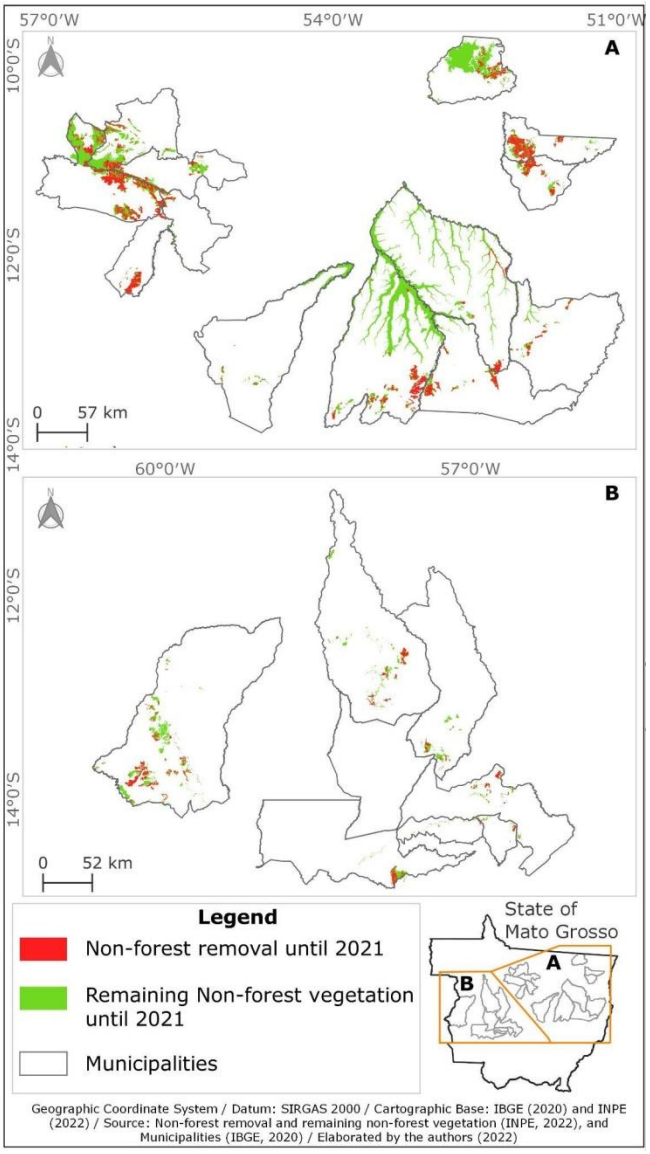

Figure 4. Natural non-forest vegetation removal in the municipalities of Mato Grosso state, Brazil.

The dynamics of non-forest removal differed among the municipalities. In Canabrava do Norte, Diamantino, Ipiranga do Norte, Porto Alegre do Norte and Sinop more than half of their non-forest vegetation has been already converted to other land uses; and among them many had the proportion of non-forest removed surpassing the lost area of forest (Figure 5). In others municipalities such as Comodoro, Nortelândia, Nova Canaã do Norte, Nova Marilândia, Nova Maringá, Santa Cruz do Xingu, Sinop, Tabaporã, and Tangará da Serra, non-forest removal occurred mostly in the last twenty years. The expansion in area of grain production and pasture for livestock grazing are the core proximate causes for non-forest removal, but a variety of drivers and actors may be associated with the observed dynamics [10, 11].

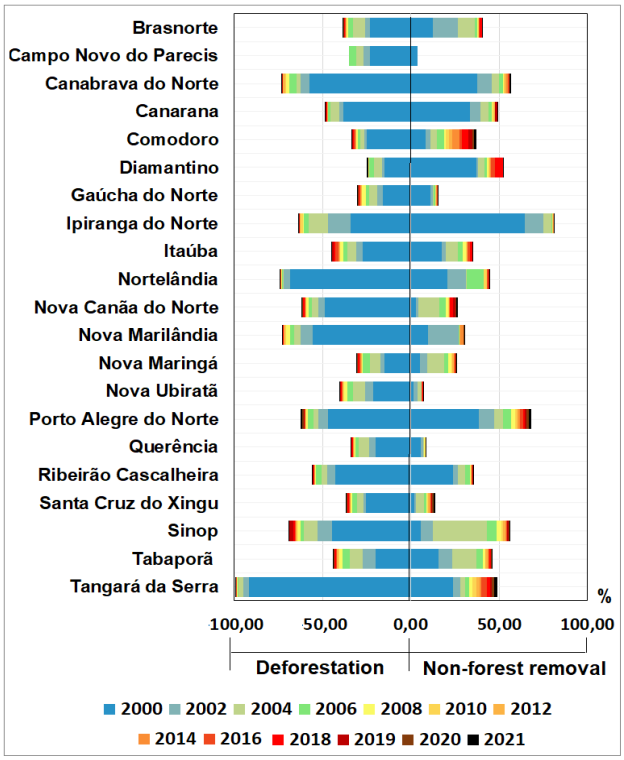

Figure 5. Percentage of natural non-forest vegetation removal and deforestation in each of the twenty-one municipalities of Mato Grosso state.

Deforestation and non-forest ecosystems conversion are given in density (i.e. the amount of vegetation removal in km^2 per each given km^2) to facilitate the comparison (Figure 5). High values of non-forest removal were registered in the studied municipalities until 2004. Such suppression density values overpassed the ones observed in the whole state of Mato Grosso and also in the entire Amazon, considering the same period. However, from 2005 to 2012, deforestation density was strongly reduced in the municipalities and also at the state and biome levels. This phenomenon might be attributed to the implementation of

public policies to control deforestation and to the strengthening of law enforcement in the field supported by the Real-Time Deforestation Detection System (DETER), added to the beginning of soy moratorium [1].

Despite the decrease in vegetation removal after 2005, controlling efforts have been less effective in non-forest areas. This is likely due to the absence of monitoring systems like PRODES and DETER in non-forest areas, which may have contributed to the advance of anthropic activities over such vegetation types together with inexistent agreements under the soy moratorium in those areas.

Similarly to forest areas in Mato Grosso and in the whole Amazon, the rate of natural vegetation loss in non-forest areas has also shown an increasing trend from 2014 onwards (Figure 3). However, this trend is not as accentuated as the one observed in the beginning of the 2000s in that state. It is probably related to the westward advancing of the deforestation frontier (the so-called "arc of deforestation") in the last two decades in the Amazon, which has created new deforestation hotspots [9, 10].

Nonetheless, it is important to notice that the slowing pace of forest and non-forest conversion in the evaluated municipalities since 2004 do not reflect the overall land dynamics in the Amazon. Roraima and Amapá states, for example, show constant rates of non-forest vegetation removal in the last 20 years even though deforestation rates have declined [4]. This is linked to the dynamics of agricultural expansion and differences in land suitability. Thus, the low rates of non-forest conversion observed in the studied municipalities here are not to be taken for granted in other areas of non-forest vegetation in the biome.

Alarming forest losses in the Amazon reached the highest rate in 16 years in 2021. The dismantling of law enforcement, that has contributed to reducing deforestation rates in the Amazon in the past, has been pointed out as one of the main factors of such unprecedented forest destruction and fragmentation [1, 12, 13], and are expected to occur over non-forest areas as well across the biome.

4. CONCLUSIONS

This work shows preliminary results of the systematic non-forest vegetation monitoring under implementation within PRODES for the Brazilian Amazon. The results showed that non-forest removal reached 29.38% in the 21 municipalities with non-forest occurrence in the state of Mato Grosso. Despite the decreasing rates of non-forest conversion after 2004 that followed deforestation trends, non-forest removal rates started to increase again as of 2014. The implementation of the non-forest systematic monitoring within the PRODES program shall provide to national and subnational governments in Brazil a robust tool to implement public policies to reduce conversion, to improve law enforcement over these ever before monitored areas, and to support the geographic expansion of private sectoral agreements that aim to clean commodity supply chains from deforestation and conversion, as the Amazon Soy Moratorium, that still not includes such natural ecosystem under its scope.

5. ACKNOWLEDGEMENTS

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