Extending DETER into non-forest vegetation areas in the Brazilian Amazon

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Abstract. *The Deforestation Detection System for Non-Forest Vegetation (DETER NF), which became operational on August 1, 2023, was introduced by the National Institute for Space Research (INPE) in the Brazilian Amazon. It covers all states within the biome, providing daily alerts for non-forest areas, including vegetation removal and burn scars. Between August 2022 and July 2023, during its pilot phase, it identified 575.22 km² of non-forest vegetation loss and 8,036.99 km² of burn scars. Among the Amazonian states, Roraima standed out as a hotspot for non-forest vegetation loss.*

1. Introduction

The National Institute for Space Research (INPE) has been monitoring the land cover changes in the Brazilian Legal Amazon (ALB) since 1988 through the Brazilian Amazon Monitoring Program by Satellites (PRODES). PRODES aims to map the annual increments of complete forest vegetation removal based on remote sensing imagery and annually release the deforestation rate in the ALB [Almeida et al. 2021]. PRODES data has enabled the development of public policies to control deforestation in the Amazon and plays a pivotal role in the preservation and sustainable development of this critical biome [Messias et al. 2021; Soler et al. 2021].

INPE also emits daily alerts regarding changes in forest cover, though the Real-Time Deforestation Detection System (DETER), created in 2004 in the context of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) [Casa Civil 2004]. DETER has enabled the identification of priority areas for law enforcement, leading to the seizures of machinery used in deforestation and increased fines for environmental violations [Assunção et al. 2019].

Despite the importance of PRODES and DETER in providing important information on deforestation in forest formations, there was a gap in the knowledge about the spatial and temporal distribution of vegetation loss in non-forest (NF) formations, an important area which covers ~280,000 km² (6.6%) of the Amazon biome. NF formations takes various forms, including: open formations like savannas and grasslands; seasonally flooded areas with sandy soils and sparse tree cover; ecotones; isolated forest patches with characteristics ranging from deciduous to semi-deciduous and broadleaf; as well as naturally barren land areas [IBGE 2012]. To fill the gap concerning the status of vegetation loss in NF areas in the Brazilian Amazon, in 2023, INPE introduced a systematic mapping of NF area loss, known as PRODES NF [Almeida et al. 2023; Messias et al. 2023]. PRODES NF revealed a loss of 29,247.44 km² of NF formations (10.46% of its total extent) by the year 2022, with states like Mato Grosso experiencing around 32% of this loss [Messias et al., article submitted].

Building upon the achievements of DETER in monitoring forested regions within the Amazon biome, an extension of this system, known as DETER NF, has been developed. DETER NF now provides daily monitoring coverage for NF areas, issuing alerts for both the removal of primary NF vegetation and the detection of scars from burned areas. In this study, we present the methodology employed by DETER NF and show its initial findings.

2. Methodology

The Deforestation Detection System for Non-Forest Vegetation (DETER NF) aims to issue daily alerts about non-forest loss and burn scars that occur in areas originally constituted by NF phytophysiognomies within the Brazilian Amazon (Figure 1). DETER NF covers approximately 280,000 km² distributed across all states within the biome.

DETER NF operates in alignment with the PRODES calendar year, which starts on August 1st of a given year and extends through July 31st of the subsequent year. The methodology is particular about observing exclusively NF areas within the NF mask monitored by PRODES NF. Consequently, the methodology utilizes an exclusion mask that encompasses all regions where NF loss was identified in the preceding year, essentially covering the entire area that was previously mapped by PRODES NF.

The DETER NF pilot project is based on images from the Wide Field Imaging Camera (WFI) sensor aboard the Brazilian satellite Amazonia-1. These images have 64 m spatial resolution and a temporal resolution of 5 days. Color composites including the 3R/4G/2B bands were used, where band 4 corresponds to near-infrared, band 3 to red, and band 2 to green. An additional composition of 4R/3G/2B was also used, together with soil and shadow fractions generated through the Spectral Linear Mixing Model (SLMM). A total of 27 satellite orbits was necessary to monitor the entire biome.

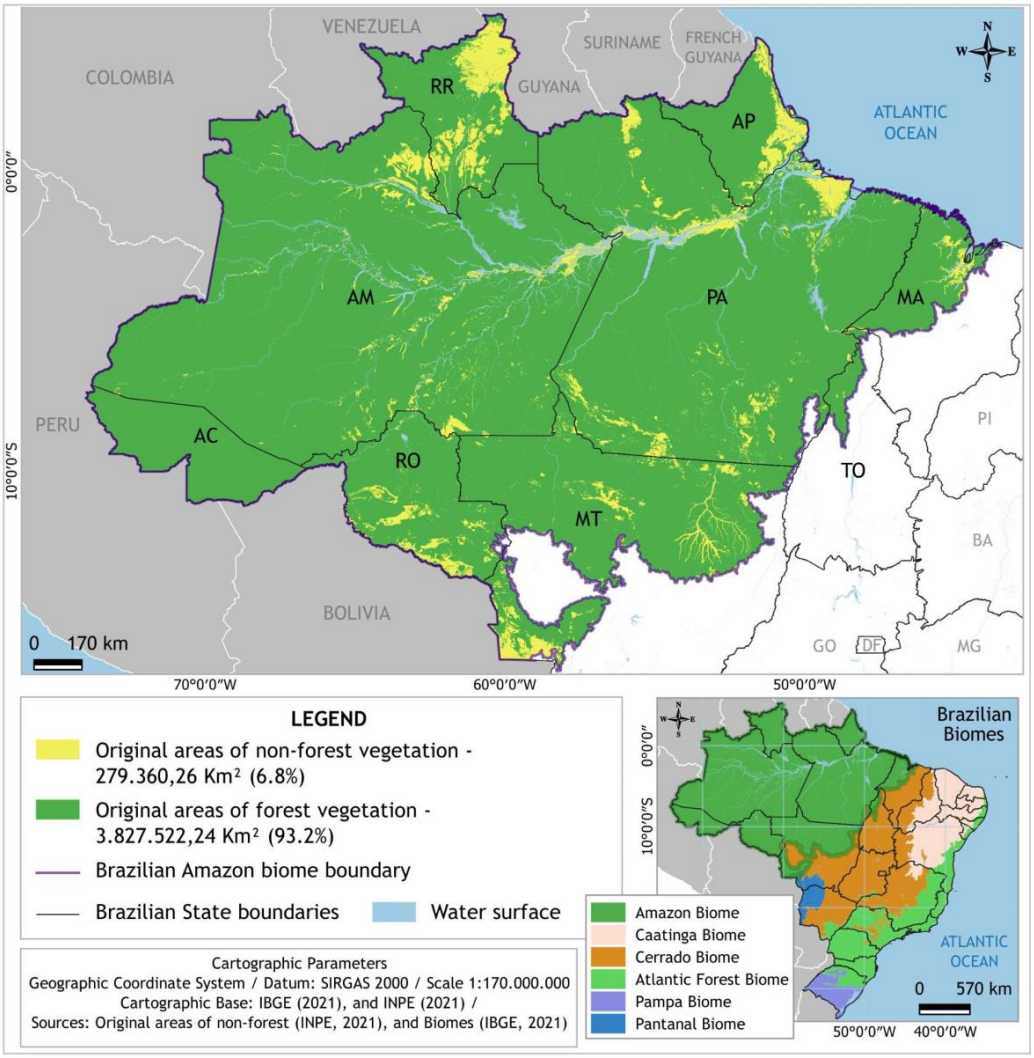


Figure 1: Spatial location of the Amazon biome and its compartmentalization into forest and non-forest areas, according to PRODES.

Mapping was conducted using a multi-user PostGIS database, configured through the TerraAmazon interface [INPE/FUNCATE 2023]. A team of analysts visually examined satellite images and delineated polygons to represent areas of vegetation loss and burned areas. The interpretation was conducted at a 1:100,000 scale, and the minimum mappable area was set at 3 hectares. The entire mapping process underwent rigorous auditing by specialists in NF vegetation. Four distinct alert classes were identified: Vegetation Loss with Exposed Soil, Vegetation Loss with New Vegetation, Mining and Burn scars (see Table 1 for details).

Images were interpreted from August to November 2022 and from March to July 2023. The months with higher cloud cover in the Amazon (December to February) were not observed, as vegetation loss events during those months could be detected in subsequent months' images. The mapping process involved comparing images from the analyzed month to the previous month (Figure 2), along with supplementary Sentinel-2

images, previously used in PRODES NF in 2022 and 2021. In total, 174 images from the Amazônia-1 satellite were interpreted during these nine months of observations.

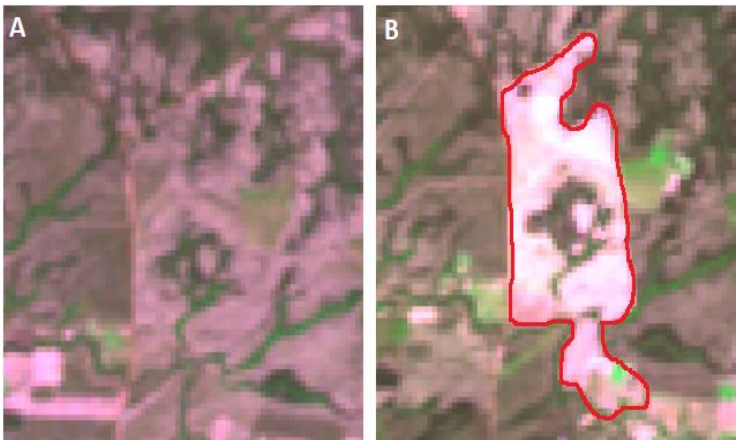


Figure 2: A) Non-forest natural vegetation area observed in an orbital image taken by the Amazônia 1 satellite in August 2022. B) The same area in the September 2022 image, highlighting a detected vegetation loss event (outlined in red).

The interpretation uncertainties were minimized using a time-series of auxiliary images with higher spatial resolution, including Sentinel-2 and Planet imagery. Fire spots provided by the Queimadas project [INPE 2023] were essential in identifying fire scars. Moreover, records of observations and photographs collected during fieldwork conducted in non-forest vegetation areas across eight municipalities in Roraima played a crucial role in developing interpretation guidelines and clarifying any ambiguities. This fieldwork, March 20 to 28 in 2023, was conducted by a team of researchers from different institutes and universities, including INPE and EMBRAPA RORAIMA. To ensure data accuracy, consultations were made with specialists in Amazonian NF vegetation, when necessary.

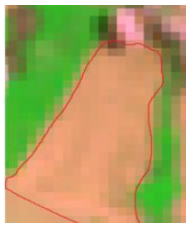
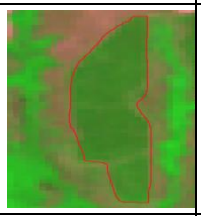
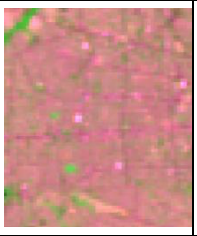
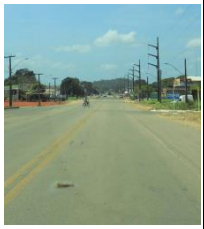
We conducted an analysis of warning hotspots using Kernel density maps. The suppression increments were reprojected onto the Albers Equivalent Conic Projection, with the SIRGAS 2000 datum, to calculate polygon areas. Subsequently, we extracted the centroids of these polygons along with their associated area attributes. To assess the hotspots, we applied a Kernel density estimator to the polygon centroids. This estimation was weighted based on the deforested area and implemented with a 30 km radius.

3. Results and Discussion

The interpretation key developed to identify suppression features and fire scars in non-forest areas of the Amazon is illustrated in Table 1. This key played a crucial role in assisting the detection of the classes mapped by DETER NF.

Table 1: Interpretation key for identifying features related to burn scars and suppression of non-forest natural vegetation, with fieldwork images in Roraima

Observed feature	WFI 3R/4G/2B	Fieldwork photograph	Visual elements for identifying features in satellite images
Non-forest natural vegetation with recent fire			Non-forest natural vegetation with recent fire occurrence, which does not qualify as vegetation loss in non-forested areas (NF). Recent wildfires display a purple to brown color, appearing dark due to a substantial amount of ashes and the absence of photosynthetically active vegetation. The surface texture ranges from smooth to moderately textured, with an irregular shape.
Non-forest natural vegetation, with not so recent fire and the beginning of regrowth.			Non-forest vegetation with a slightly less recent vegetation loss occurrence. They exhibit a purple to brown coloration, of medium shade, owing to a significant amount of ashes, yet featuring herbaceous in regrowth, already photosynthetically active. Surface texture ranges from smooth to moderately textured with an irregular shape.
Suppression of non-forest vegetation with exposed soil.			After the removal of all non-forest vegetation, exposed soil is identified in magenta hues, ranging from light to dark, depending on the physical characteristics of the soil. The texture is smooth or moderate (in the presence of remaining shrubs), and the shape is regular.
Non-forest suppression with secondary herbaceous or green agriculture.			When the time interval between the loss of non-forest natural vegetation and its detection allows for vegetation regeneration or the introduction of agricultural cultivation or pasture. This use differs from natural herbaceous areas by displaying light to medium green coloration, typically smooth or moderately textured surfaces, and a regular shape.

Suppression of non-forest vegetation with pasture or dry agriculture.			During fieldwork, it was quite common to observe areas of mature crops, particularly millet. They appear in the images as a light salmon color, typically featuring a smooth texture and geometric shape. In the images, they often resemble exposed soil.
Silviculture			Areas covered by silviculture or reforested with native species can vary in color, typically displaying a dark green hue, smooth texture, and either a regular or irregular shape.
Urban area			Urban areas are covered by surfaces of various compositions, including concrete, rooftops, soil, and vegetation. Reflectance varies, resulting in different colors and shades. Linear roadways are visible, and the texture is rough.
Artificial reservoirs			Artificial reservoirs, due to inundating areas covered by natural vegetation, are considered non-forest vegetation loss. They typically exhibit colors ranging from black to dark blue, especially when they have lower sediment content. The texture is smooth, and the shape is irregular.
Mining		No mining photos were taken during fieldwork	Mined areas typically accompany watercourses. These areas exhibit a range of colors, varying from dark to light shades, depending on the type of ore and the presence of sediments. The texture of the mined area is typically smooth but with an irregular shape due to excavations and extraction activities.

Between August 2022 and July 2023, 575.22 km² of NF loss were detected through the DETER NF (considering the sum of the classes NF loss with exposed soil, NF loss with vegetation, and mining). Roraima was the state with the largest identified area of NF loss in the Amazon, with 251.49 km² of alerts (43.71% of the total alerts in the biome). Mato Grosso and Rondônia also had significant values, with alerts covering 155.27 km² and 80.65 km², respectively (26.99% and 14% of the total) (Figure 3).

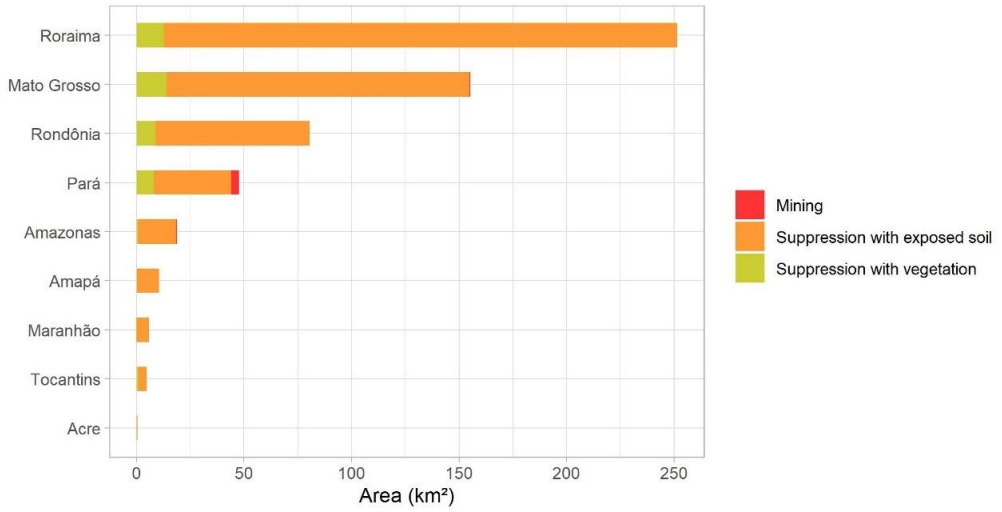


Figure 3: Contribution of each Amazonian state to the non-forest vegetation loss between August 2022 and July 2023.

Among the ten municipalities with the largest area of identified NF loss alerts, four are located in Roraima (RR), three in Mato Grosso (MT), two in Rondônia (RO), and one in Pará (Figure 4). These municipalities accounted for 71.56% of the total alert area detected during the period, demonstrating a significant spatial concentration of NF loss.

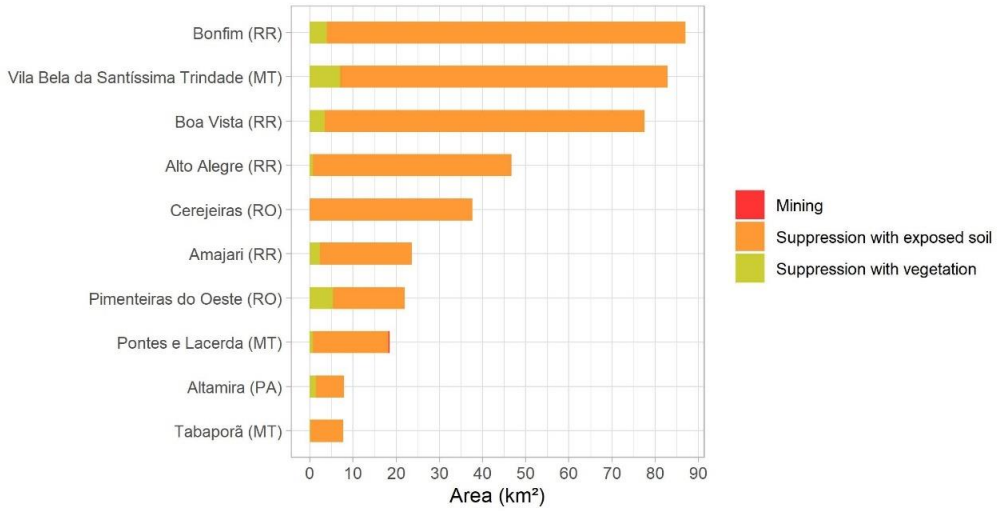


Figure 4: Contribution of the ten municipalities with the largest area of non-forest vegetation loss alerts in the Amazon, between August 2022 and July 2023.

At both the state and municipal levels, the class of deforestation with exposed soil was the most prevalent, while warnings originating from mining activities were the least common. The predominance of the exposed soil class can be attributed to the inherent characteristic of the DETER system, which issues warnings immediately after a deforestation event, often leaving the soil without vegetation cover. The deforestation class with vegetation tends to be more common when cloud cover prevents the immediate

recording of the suppressed area, allowing for the revegetation by grass and herbaceous species. Although the mining class contributed the smallest area of warnings, it's worth noting that it was concentrated in the state of Pará, known for its mining activity [Enríquez, 2014].

During the analyzed period, the *lavrado* savannas in Roraima showed the highest concentration of NF loss, where the municipalities of Bonfim, Boa Vista, Alto Alegre, and Amajari are located (Figure5). The historical series of PRODES NF data revealed that NF loss remained at low levels in Roraima until the early 2000s but intensified over the past two decades, particularly since 2014 [Messias et al., article submitted]. Evidence pointed to the expansion of soybean cultivation as the main cause [Barbosa and Campos 2011; Rodrigues 2023; Silva and Oliveira 2018].

NF loss hotspots were also observed in the southwest of Mato Grosso (Figure 5), a region that has already been significantly impacted due to intensive NF loss, especially up until the early 2000s [Almeida et al. 2023]. Other areas with NF loss, although less prominent compared to those mentioned earlier, include the bordering areas with the Cerrado biome, the southeastern portion of Rondônia, the Amazon River floodplains, and some municipalities near Macapá in the state of Amapá (AP) (Figure 5).

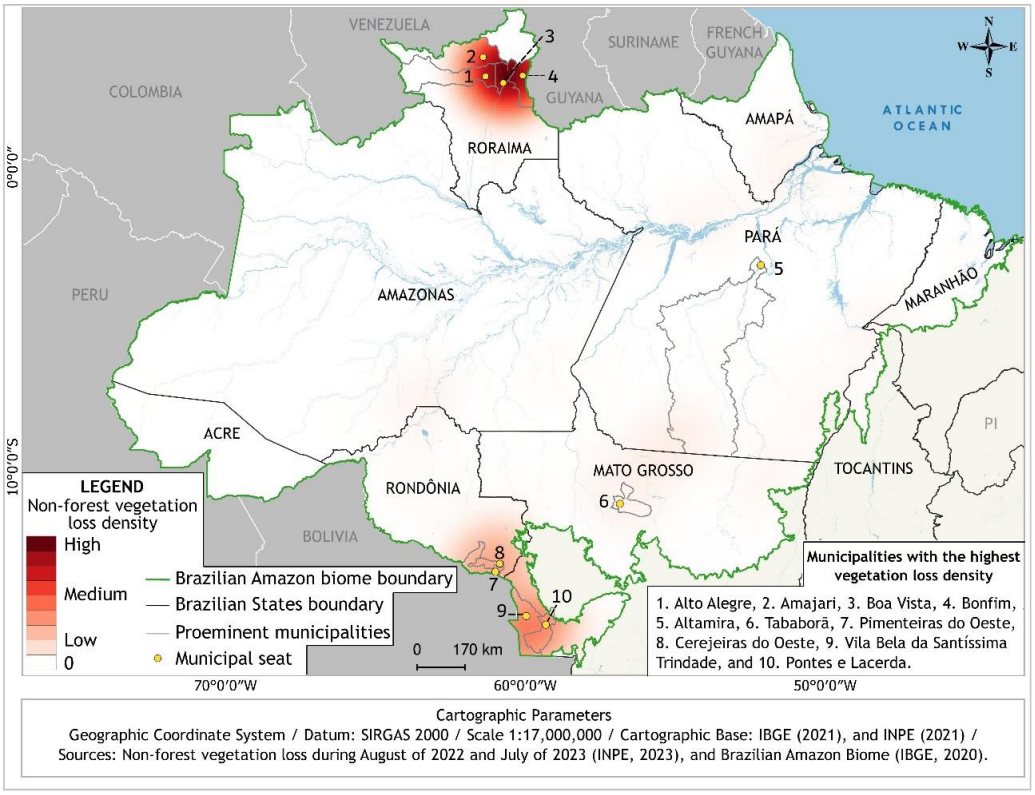


Figure 5: Map of non-forest vegetation loss density in the Amazon, between August 2022 and July 2023.

A total of 8,036.99 km² of burn scars were detected in NF areas during the same period. Pará concentrated 2,493.71 km² the largest area among the states in the Amazon (31% of the total; Figure 6). Roraima had 2,317.48 km² of burn scars identified (28.83%), and Mato Grosso had 1,735.18 km² (21.59%). Among the 10 municipalities with the

largest area of NF affected by fires, four are in Roraima, four in Pará, and two in Mato Grosso (Figure 7). These municipalities accounted for 49.37% of the total detected.

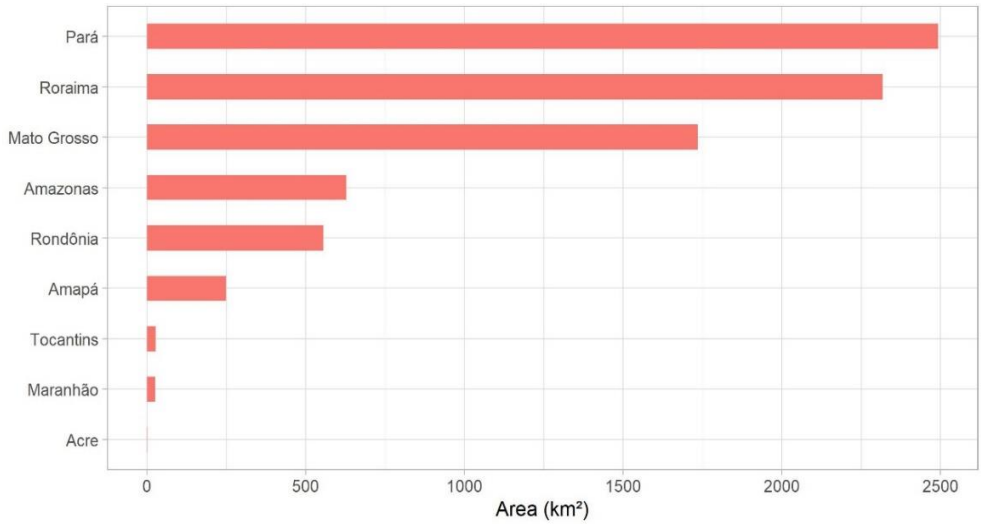


Figure 6: Contribution of each Amazonian State to the occurrence of fires in non-forest natural vegetation, between August 2022 and July 2023.

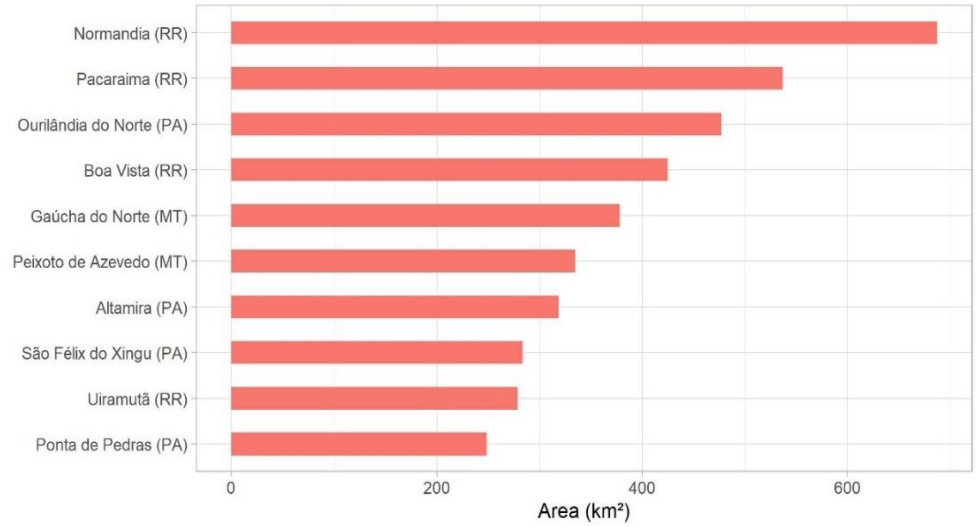


Figure 7: Contribution of the ten municipalities with the largest area (km²) of burn scars in non-forest natural vegetation in the Amazon, between August 2022 and July 2023.

Roraima was also the main hotspot of burn scars (Figure 8). Being the largest continuous area of savannas in the biome, the *lavrados* accumulates a great amount of fuel material during the dry season, prone to fire [Barbosa et al. 2007]. On the other hand, fire is used to manage the savanna for pasture and also to clean the land for other uses [Costa et al. 2011; Silva and Oliveira 2018].

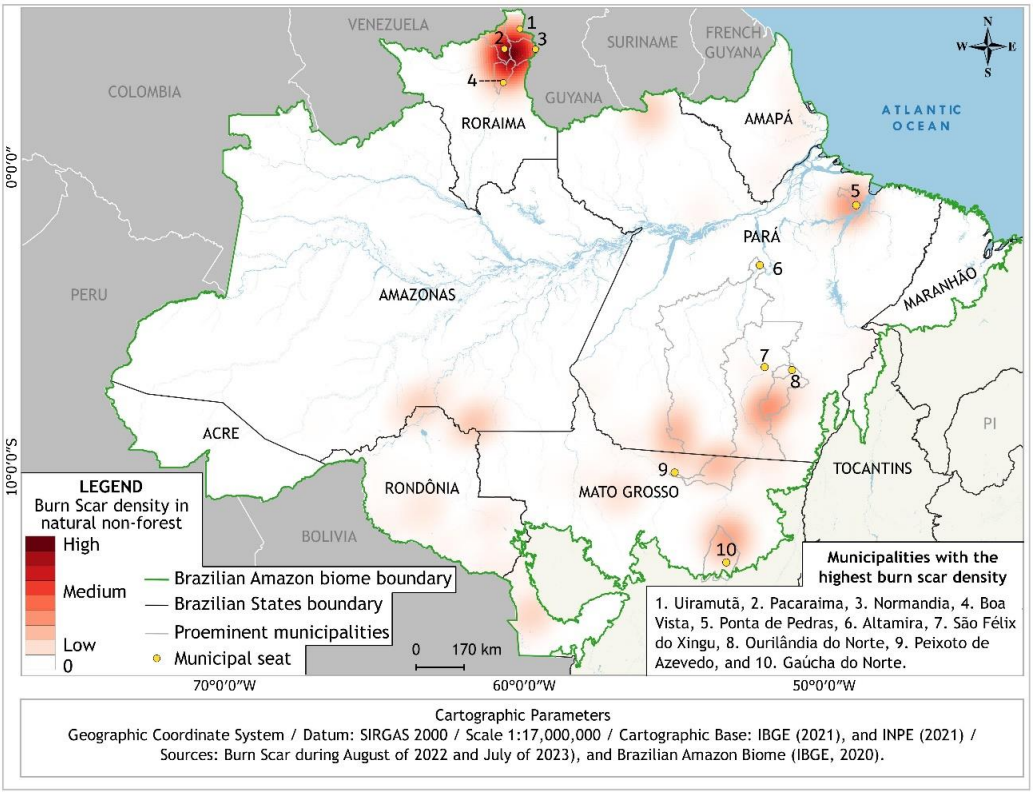


Figure 8: Map of burn scar density in non-forest natural vegetation in the Amazon, between August 2022 and July 2023.

Concentrations of burn scars were also notable in Marajó (northeastern Pará, Figure 8), where fire is commonly used for the management of natural pastures for cattle breeding [Schaan 2010]. In the central-south regions of Amazonas and Pará, there were also non-forest areas with intense occurrences of fires, some of them already heavily impacted by human activities [Carrero and Fearnside 2011; Mataveli et al. 2021], while others had relatively preserved vegetation. The occurrence of fires was also common along the Xingu River plain, within the Xingu Indigenous Park.

4. Final Remarks

The products presented here are the result of a pilot project for monitoring non-forest areas of the Amazon using DETER. The data from DETER NF aims to assist the government in its decision-making and enforcement processes. DETER must not, under any circumstances, be considered an official annual value for the suppression of non-forest original vegetation. However, it is expected that the values presented here will have a high correlation with PRODES NF, which will likely be demonstrated when it is released, either at the end of 2023 or the beginning of 2024.

DETER NF has been operational since August 1, 2023. Federal and state agencies responsible for environmental command and control actions, such as the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), the Chico Mendes Institute for Biodiversity Conservation (ICMBio), and State Environmental Secretariats,

have daily access to the alerts. While the data is not yet publicly available to the entire society, it will soon be accessible on the website http://terrabrasilis.dpi.inpe.br.

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