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DETER Monitoring on Non-Forest Vegetation in the Brazilian Amazon

Monitoramento DETER em Áreas de Vegetação Não-Florestal na Amazônia Brasileira

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Abstract: In this study, we present the initial results of the pilot project applying the Near Real-Time Deforestation Detection System (DETER), initially designed for monitoring forest ecosystems (DETER Amazon), recently expanded to surveil an area of approximately 280,000 km² of non-forest natural vegetation (NF) in the Brazilian Amazon. The system issues two types of alerts: 1) NF suppression alerts, categorized into three classes (suppression with exposed soil, suppression with cultivated area, and suppression by mining) and 2) burn scars, based on an adapted methodology from DETER Amazon and images with low spatial resolution (64 m) but high temporal resolution (two or three days to assess the entire biome). The pilot project period was from August 2022 to July 2023, with a total area of suppression alerts covering 575.22 km², predominantly composed of the NF suppression class with exposed soil, and 8,036.99 km² of burn scar areas. The majority of NF suppression alerts occurred in the states of Roraima, Mato Grosso, Rondônia, and Pará. Additionally, Amazonas and Amapá stood out among the states with a higher area of burn scar alerts. Savannas were the most affected non-forest physiognomies, with 5,037 km² (6.5%) of their area impacted by suppression and fire. Comparative analysis with other monitoring systems in the Amazon demonstrated the effectiveness of DETER NF in monitoring non-forest areas in the biome.
Keywords: Deforestation. Land Use and Land Cover Change (LUCC). Monitoring system. Savannas. Near real time detection.

Resumo: Neste estudo apresentamos os primeiros resultados do projeto piloto da aplicação do Sistema de Detecção de Desmatamentos em Tempo Quase Real (DETER), inicialmente criado para o monitoramento de ecossistemas florestais (DETER Amazônia), recentemente estendido para monitorar uma área de ~280 mil km² de vegetação natural não florestal (NF) na Amazônia brasileira. O sistema emite dois tipos de alertas: 1) alertas de supressão de NF, classificados em três categorias (supressão com solo exposto, supressão com área cultivada e supressão por mineração) e 2) cicatrizes de queimadas; com base em uma metodologia adaptada para esse tipo de vegetação a partir do DETER Amazônia e imagens de baixa resolução espacial (64 m), porém de alta resolução temporal (dois ou três dias para avaliar todo o bioma). O período do projeto piloto foi de agosto de 2022 a julho de 2023, com uma área total de alertas de supressão de 575,22 km², predominantemente composta pela classe de supressão de NF com

solo exposto, e 8.036,99 km² de área de cicatrizes de queimadas. A maioria dos alertas de supressão de NF ocorreu nos estados de Roraima, Mato Grosso, Rondônia e Pará. Além desses, Amazonas e Amapá também se destacaram entre os estados com maior área de alertas para cicatrizes de queimadas. As savanas foram as fitofisionomias não florestais mais afetadas, com 5.037 km² (6,5%) de sua área atingida por supressão e fogo. A análise comparativa com outros sistemas de monitoramento na Amazônia demonstrou a eficácia do DETER NF para monitorar áreas não florestais no bioma.
Palavras-chave: Desmatamento. Mudança de uso e cobertura da terra. Sistema de monitoramento. Savanas. Detecção em tempo quase-real.

1 INTRODUCTION

The Amazon holds the largest tropical forest in the world and plays a key role in the Earth's climate, water and carbon systems, being home to a diverse and endemic biodiversity and human cultural spaces (SPA, 2021). However, the biome has been primarily impacted by the expansion of the agricultural frontier into its ecosystems, leading to significant consequences for ecosystem services, biodiversity, indigenous populations, and its role in local, regional, and global climate regulation (DAVIDSON *et al.*, 2012; ALVES DE OLIVEIRA *et al.*, 2021; BUTT *et al.*, 2023; FLORES *et al.*, 2024).

With the largest forest area occurring in Brazil, the Amazon biome has been the target of comprehensive Brazilian monitoring programs since the 1980s. The first and oldest is the Brazilian Amazon Rainforest Monitoring Program by Satellite (PRODES), conducted by the National Institute for Space Research (INPE). PRODES aims to map the annual increments of natural forest vegetation removal using remote sensing imagery and provides annual deforestation rates for the Brazilian Amazon since 1988 (ALMEIDA *et al.*, 2022). INPE also conducts a complementary project called Near Real-Time Deforestation Detection System (DETER), established in 2004 with a primary focus on near real-time deforestation detection (CASA CIVIL, 2004). Nowadays, DETER employs remote sensing imagery to detect the ongoing removal and degradation of forested areas and alert the control authorities (INPE, 2023a). DETER has played a pivotal role in providing timely and critical information to support environmental conservation efforts (ASSUNÇÃO *et al.*, 2019).

However, due to methodological constraints, an area of 280,000 km² characterized as dominant natural non-forest vegetation types (NF vegetation) has remained unmonitored. In the Brazilian Amazon, these vegetation types include different formations such as: savannas and grasslands; seasonally flooded regions with sandy soils and scattered trees; ecotones; isolated patches of forest with deciduous, semi-deciduous, and broadleaf characteristics immersed in a non-forest vegetation matrix; and natural areas of bare terrain (IBGE, 2012). These formations receive names such as pioneering formations, ecological refuges, "*lavrados"*, "*campinas*", and "*campinaranas*" (IBGE, 2012), the two latter also known as white-sand ecosystems (ADENEY *et al.*, 2016). Despite the current sparse knowledge about the dynamics of vegetation suppression in these areas, non-forest ecosystems play a vital role in biodiversity conservation, serving as habitats for endemic species across various taxa (BARBOSA *et al.*, 2007; ADENEY *et al.*, 2016; DE CARVALHO; MUSTIN, 2017). In 2023, INPE released PRODES NF system – a comprehensive historical dataset documenting the vegetation suppression of natural non-forest areas (ALMEIDA *et al.*, 2023). The outcomes from the PRODES NF system revealed a suppression of 29,247.44 km² (~10% of the total area) of natural non-forest vegetation up to 2022 (MESSIAS *et al.*, 2024).

In alignment with the methodological scheme adopted in the near real-time deforestation surveillance of the Brazilian Amazon forests, an expansion of DETER was implemented to NF areas. This new monitoring system is called Near Real Time Deforestation Detection System for Non-Forest Vegetation (DETER NF). DETER NF aims to provide daily monitoring coverage for areas previously masked as NF in the PRODES system. DETER NF issues alerts for both the suppression of natural NF vegetation and the scars of burned areas. In this study, we present the methodology employed in DETER NF and its initial findings from August 2022 to July 2023. This paper is an extended version of MESSIAS *et al.* (2023a), presented at the XXIV Brazilian Symposium on GeoInformatics (GEOINFO 2023).

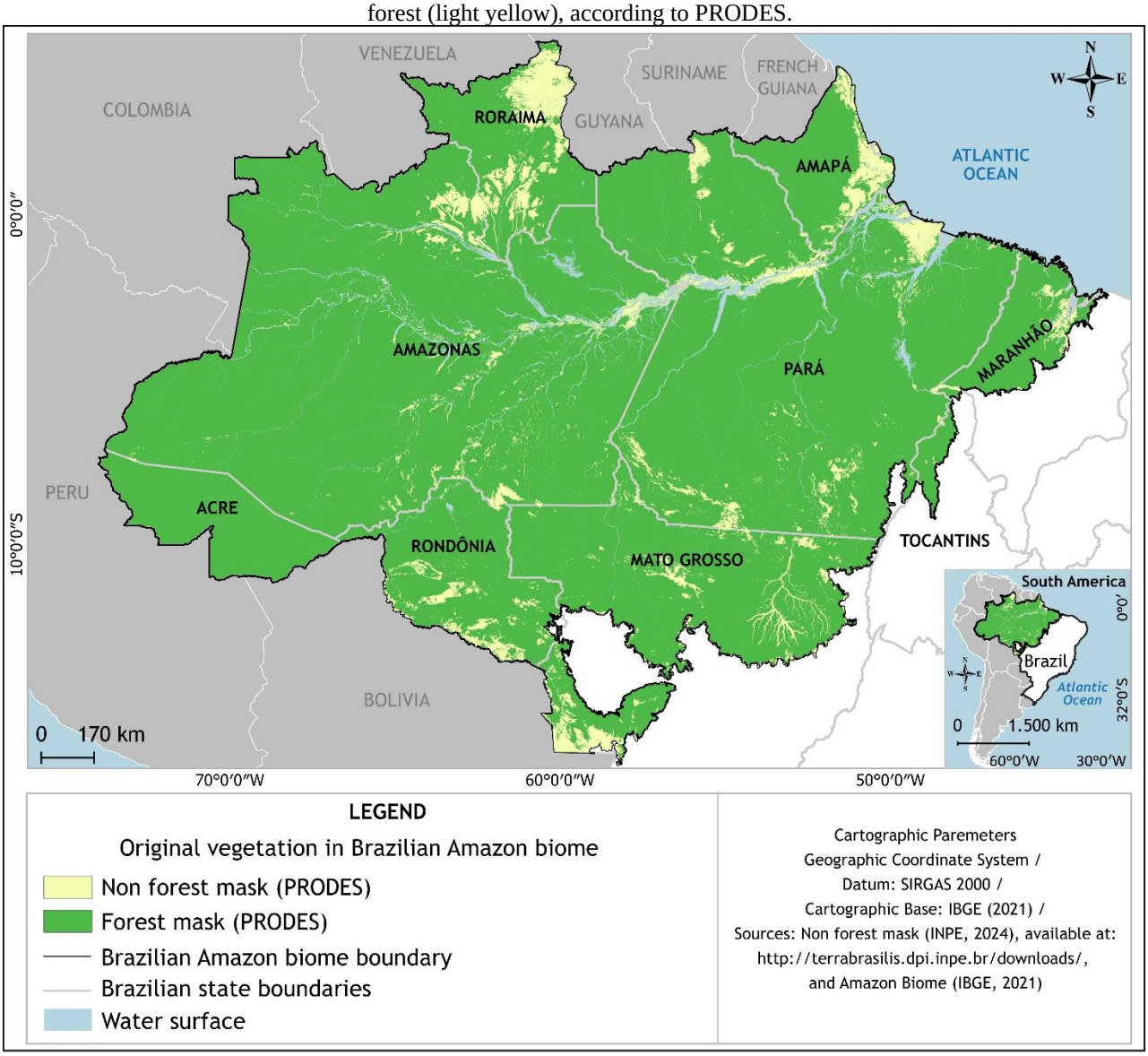
2 MATERIAL AND METHODS

2.1 Study area

DETER NF monitors the area masked as natural non-forest vegetation by PRODES experts (ALMEIDA *et al.*, 2022), within the Brazilian Amazon biome. DETER NF monitoring area encompasses an extension of 280,000 km² (6,67% of the Brazilian Amazon biome; Figure 1) composed of various predominantly open vegetation types, including savannas and grasslands, seasonally flooded areas, ecotones, isolated patches of forest, and natural areas with bare terrain (IBGE, 2012). In general, savannas, pioneering formations, and *campinaranas* constitute most of the non-forest areas monitored by DETER NF.

The NF vegetation occurs disjointed across the nine Amazonian states. Table 1 presents the area occupied by NF formations for each state, its proportion relative to the state area, and the proportion relative to the total NF area. The states of Pará and Roraima together encompass 45% of the NF area, reaching approximately 80% of the area monitored by DETER NF with the states of Amazonas and Mato Grosso. When analyzed in proportional terms to the states' areas, Roraima and Amapá exhibit the highest proportions compared to the others, with approximately 27% and 18%, respectively.

Figure 1 – Spatial location of the Brazilian Amazon biome showing the areas masked as forest (dark green) and non-forest (light yellow), according to PRODES.



Source: The authors (2024).

Table 1 - Distribution of natural non-forest (NF) vegetation inside PRODES NF mask in the nine states of the Brazilian Amazon biome.

State	NF area (km²)	NF area (%)	NF area/State area (%)
Acre	70.05	0.03%	0.04%
Amapá	25,883.22	9.26%	18.31%
Amazonas	48,506.46	17.36%	3.11%
Maranhão	7,988.48	2.86%	3.07%
Mato Grosso	45,068.97	16.13%	4.99%
Pará	6,6845.3	23.92%	5.37%
Rondônia	23,295.41	8.33%	9.81%
Roraima	60,902.11	21.79%	27.31%
Tocantins	932.08	0.33%	0.34%

Source: The authors (2024).

2.2 Imagery and ancillary data

DETER NF's approach, in the pilot project, is based on the visual interpretation of optical satellite images acquired by the Wide Field Imaging Camera (WFI) sensor, onboard of the Brazilian satellite Amazonia-1. Nonetheless, higher spatial resolution images, such as MSI/Sentinel-2 and Planet constellation data sets are eventually used to support DETER NF monitoring. The main characteristics of these images are summarized in Table 2.

Table 2 - Summary of the main satellite image characteristics used in DETER NF.

	WFI/Amazonia-1	MSI/Sentinel-2	Planet
Spectral bands (μm)	B2 (0.52-0.59)	B4 (0.65 – 0.68)	B1 (0.45 - 0.51)
	B3 (0.63-0.69)	B8a (0.85 – 0.88)	B2 (0.5 - 0.59)
	B4 (0.77-0.89)	B11 (1.56 – 1.65)	B3 (0.59 - 0.67)
Spatial resolution (m)	64	10-20	3
Revisit time (days)	5	5	Daily
Swath (km)	850	290	~34 x 20
Use in DETER NF	Main observed data set	Ancillary data set (interpretation doubts)	
Source	www.dgi.inpe.br/catalogo/explore	scihub.copernicus.eu/	www.planet.com

Source: BRAZ; D'ALGE (2021), ESA (2022), NICFI (2024).

Other ancillary data used in DETER NF monitoring include:

1) Masks derived from PRODES NF since 2022. The accumulated loss of NF vegetation is used to avoid detections in areas that suffered previous vegetation loss. The delimitation of NF area established by PRODES is also used to define the area of interest in DETER NF;
2) Fire spot data provided by the Queimadas Programa (INPE, 2023c) utilized to assist in guiding the mapping of the class Burn scars on natural non-forest vegetation (Section 2.3);
3) Field data from observations and photographs obtained during fieldwork carried out in NF areas across eight municipalities in Roraima (between March 20 to 28 in 2023; see in MESSIAS et al., 2023b), used to improve the classification guidelines and reduce uncertainties;
4) Official Brazilian vegetation thematic data at the 1:250,000 scale (IBGE, 2022). Although this data is not part of the DETER NF methodology, it was included in the analysis of results presented herein.

2.3 Monitoring methodology

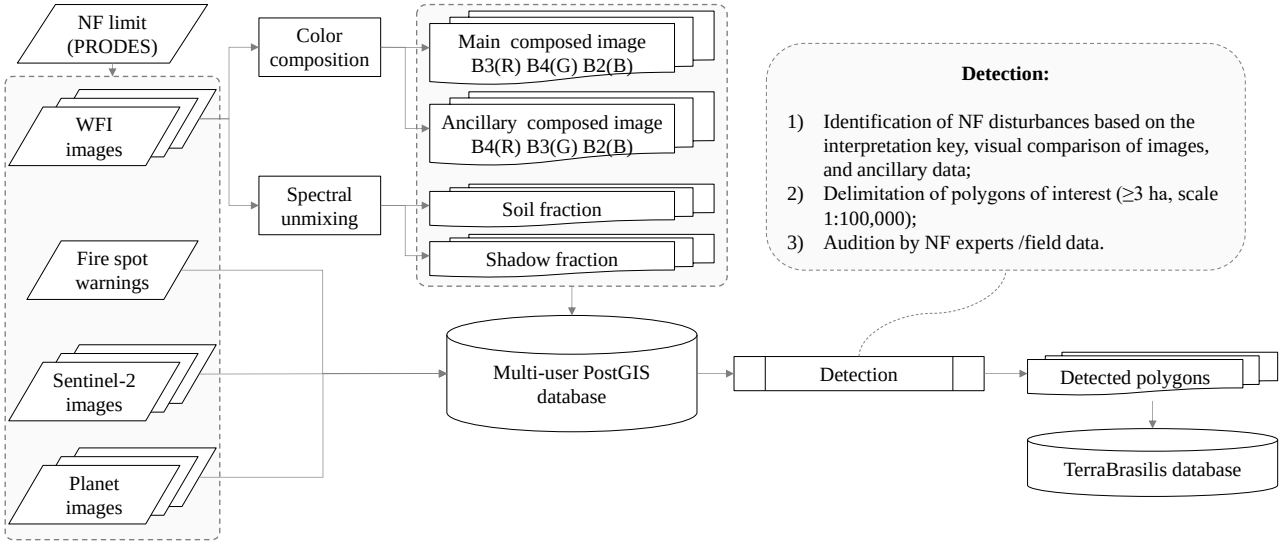
Figure 2 summarizes the methodological steps within DETER NF. Firstly, we select the main and

ancillary images within the NF limits established by PRODES (ALMEIDA et al., 2022) for the analyzed period. DETER NF operates in alignment with the PRODES calendar year, which starts on August 1st of the previous year and extends through July 31 of the year of interest. Based on the WFI images, a team of trained interpreters derives two types of color composites: 1) B3(R) B4(G) B2(B) and 2) B4(R) B3(G) B2(B). The first color composition is considered the interpretation standard. The second one is used to provide different perspectives in cases of interpretation doubts. The WFI images are also used to derive the soil and shadow fractions, using the Linear Spectral Mixture Model (LSMM) (SHIMABUKURO; SMITH, 1991; SHIMABUKURO et al., 2010). The mapping process is then continued using a multi-user PostGIS database, configured through the TerraAmazon interface (INPE; FUNCATE, 2023).

The mapping process involves the visual comparison of images from recent and previous months (Figure 3), along with supplementary Sentinel-2 images used in PRODES NF for previous years. In this step, a team of analysts visually examines the main and ancillary satellite images to delineate polygons corresponding to four distinct alerted classes: 1) Non-forest suppression with exposed soil; 2) Non-forest suppression with cultivated areas; 3) mining; and 4) Burn scars on natural non-forest vegetation. These classes are identified via image interpretation keys (Chart 1), and for the case of the class Burn scars on non-forest natural vegetation, also using the fire spot data from the Queimadas Programa (INPE, 2023c).

The image interpretation is conducted at a 1:100,000 scale, with the minimum mappable area set to 3 ha. Areas previously detected as vegetation loss by PRODES NF are masked from this analysis. The detected polygons are then subjected to rigorous auditing by specialists in NF vegetation and eventually used to improve the interpretation guidelines. In this sense, we highlight the pivotal role of field information (available in MESSIAS et al., 2023b). Other entries of the interpretation keys are available in Messias et al. (2023b) and Messias et al. (2023a). The detected polygons are made available via the TerraBrasilis platform (INPE, 2023d).

Figure 2 – DETER NF detection flowchart.



Source: The authors (2024).

Particularly regarding the data processed in this paper, the WFI images were sensed from August to November 2022 and from March to July 2023. We discarded the images from December to February due to their usual high amount of cloud cover. Any vegetation loss event during this period is expected to be detected in later months. In total, 174 images from the Amazônia-1 satellite were interpreted during this period, distributed in 21 satellite Path/Row positions. Ancillary Sentinel-2 images correspond to those previously used in PRODES NF in 2021 and 2022.

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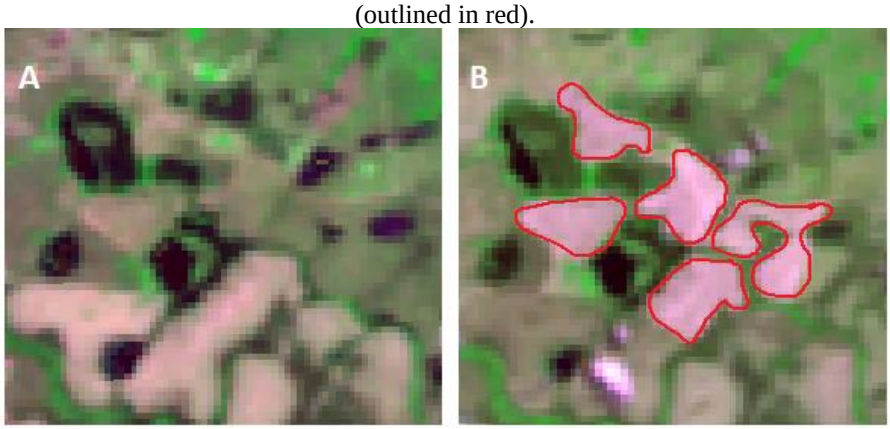
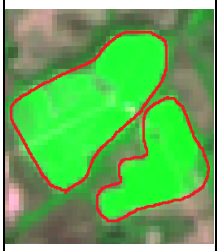
Figure 3 – A) Natural non-forest vegetation area observed in an orbital image acquired by WFI/Amazonia-1 satellite (038/015) in August 10, 2022. B) The same area in September 19, 2022, highlighting a detected vegetation loss event (outlined in red).



Source: The authors (2024).

Chart 1 – Interpretation keys developed in the context of DETER NF to identify features related to burn scars and suppression of non-forest natural vegetation.

Observed feature	**WFI 3R/4G/2B**	**Fieldwork image**	**Visual elements for identifying features in satellite images**
Burn scars on natural non-forest vegetation			Recent wildfires in non-forest natural vegetation 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 suppression with exposed soil			After the removal of all non-forest vegetation, exposed soil normally 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 cultivated areas			Occurs when the time interval between the loss of non-forest natural vegetation and its detection allows for 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.
Mining			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.

Source: The authors (2024).

2.4 Alert analysis

Here, we quantified the total area of alerts for each class of interest per Amazonian state, municipalities, and type of the predominant NF vegetation. This last analysis was done by superposing our data with the Vegetation thematic data from the Legend_1 in IBGE (2022).

We further analyzed the occurrence of DETER NF alerts hotspots using Kernel density maps. The detected polygons were reprojected to the Albers Equivalent Conic Projection at SIRGAS 2000 datum, to guarantee proper values of polygon areas considering the large extent of the Amazon region. Subsequently, we extracted the centroids of these polygons with their associated area attributes and applied the Kernel density. This estimator was weighted based on the alert area and implemented with a 30 km radius.

In this analysis, we grouped the alerts from the classes of *Non-forest suppression with exposed soil*, *Non-forest suppression with cultivated areas*, and *Mining*, into NF loss. Alerts of *Burn scars on natural non-forest vegetation* correspond to degradation events within NF areas and were analyzed separately. We employ the term "vegetation suppression" for non-forest formations as the term "deforestation" is exclusively used to forested regions within the context of INPE projects.

To assess the consistency of DETER NF results with those obtained from PRODES NF, we conducted a Spearman's rank correlation rho test.

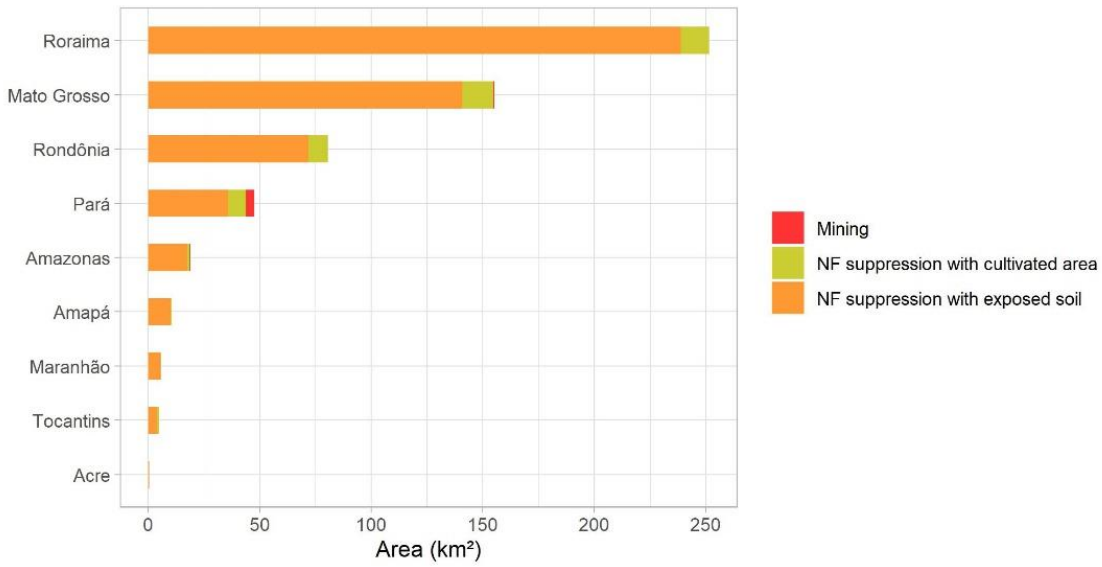
3 RESULTS

3.1 Non-forest vegetation loss alerts

Between August 2022 and July 2023, DETER NF identified 575.22 km² of NF loss alerts. The area of these alerts, detected by state, is presented in Figure 4. Table 3 illustrates the relationship between the areas detected by DETER NF and PRODES NF, in the same period. DETER NF and PRODES NF showed a strong correlation of 0.97 (S = 4; p = 0.0002).

The higher amount of NF loss within the Amazonian states was detected in Roraima, accounting for 251.49 km² (43.71% of total biome alerts). Mato Grosso and Rondônia also had significant values, with NF loss alerts covering 155.27 km² and 80.65 km², respectively (26.99% and 14% of the total). The geographical distribution of these alerts is presented in Figure 5, including the location of the 10 municipalities with the largest detected area of NF loss. Roraima state recorded the highest number of municipalities with NF loss (4), followed by Mato Grosso (3), Rondônia (2) and Pará (1). These municipalities accounted for 71.56% of the total area detected during the period of our analysis.

Figure 4 – Contribution of each Amazonian state to non-forest (NF) vegetation loss alerts detected by DETER NF between August 2022 and July 2023.



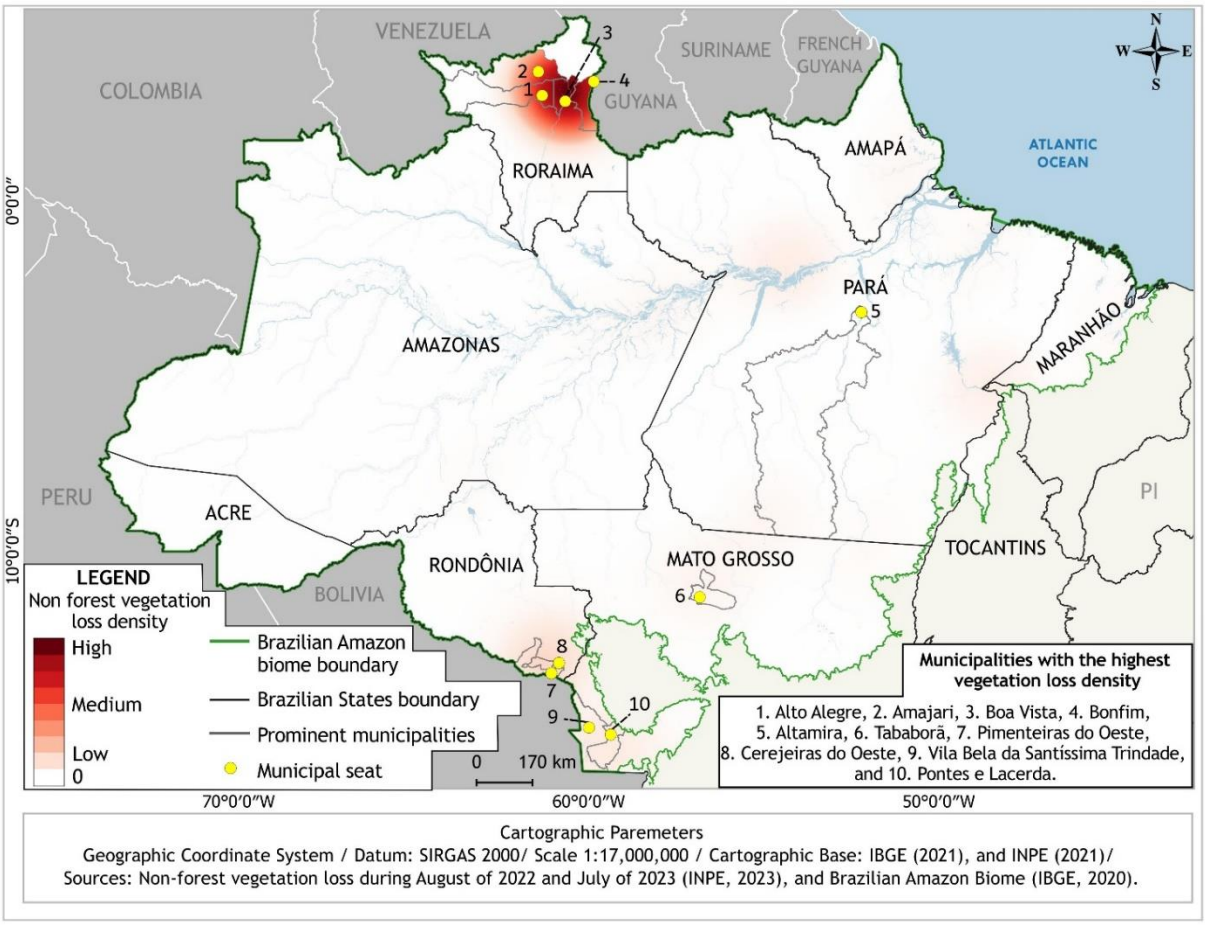
Source: The authors (2024).

Table 3 – Relationship between the areas detected by DETER NF and PRODES NF, from August 2022 to July 2023. Spearman's rank correlation rho test: S = 4; p = 0.0002; r = 0.97.

States	PRODES NF (2023)	DETER NF (2023)
Acre	0.24	0.46
Amazonas	28.76	18.84
Amapá	13.88	10.45
Maranhão	18.8	5.68
Mato Grosso	82.69	155.27
Pará	73.65	47.60
Rondônia	65.53	80.65
Roraima	292.65	251.49
Tocantins	8.66	4.79
Biome	584.86	575.23

Source: The authors (2024).

Figure 5 – Map of non-forest vegetation loss density in the Amazon detected by DETER NF between August 2022 and July 2023.



Source: The authors (2024).

Table 4 presents the total detected area of NF loss by type of vegetation. Regarding the loss of NF vegetation types, the largest absolute area occurred in Savannas, accounting for 62.32% of the detected area. Currently, Ecotones (forest-savanna transition) are the second highest absolute NF loss (23.53% of NF loss in the area of interest). More than 85% of the detected alerts come from these two types of vegetation.

Table 4 – Non-forest vegetation (NF) loss and Burn scars alerts detected by DETER NF stratified by dominant vegetation type in the Brazilian Amazon. *There are intrinsic differences between the area labeled as water in the PRODES NF mask and the vegetation map from IBGE. Vegetation suppression polygons and burn scares were detected in water areas regarding IBGE, as they may occur in seasonal flooding areas.

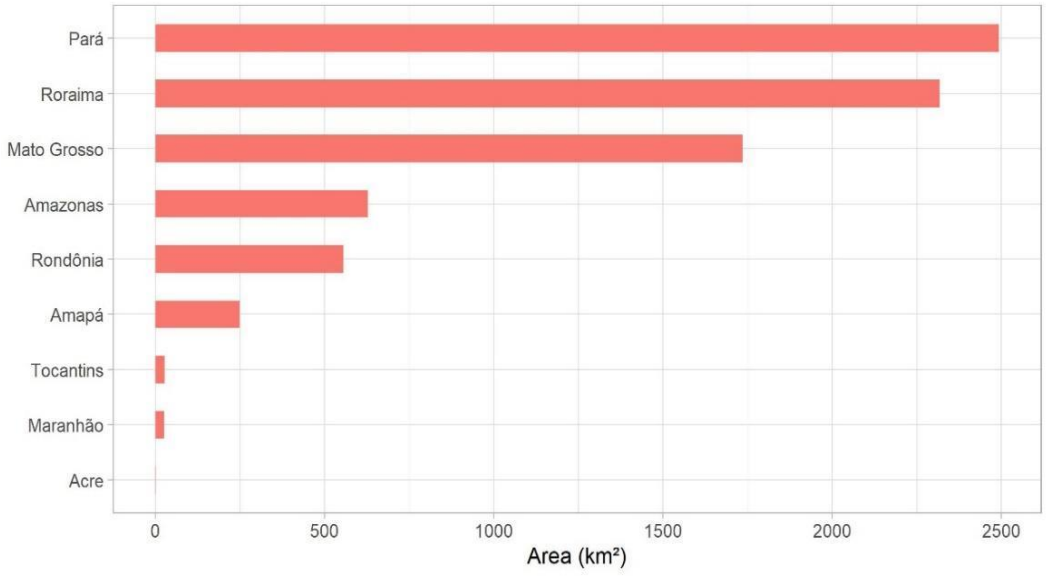
Vegetation types	Total area (km²)	NF suppression			Burn scars		
		Lost area (km²)	%	Lost area/Total loss (%)	Burned area (km²)	%	Burned area/Total burn (%)
Savanna	77,428.90	358.47	0.46	62.32	4,679.12	6.04	58.22
Ecotones	58,022.82	135.34	0.23	23.53	1,275.09	2.20	15.87
Dense Ombrophilous Forest	44,358.87	20.90	0.05	3.63	235.72	0.53	2.93
Campinarana (white-sand vegetation)	37,040.58	10.38	0.03	1.80	99.02	0.27	1.23
Pioneer formations	31,474.98	21.55	0.07	3.75	709.34	2.25	8.83
Open Ombrophilous Forest	10,561.81	14.53	0.14	2.53	276.29	2.62	3.44
Savanna-steppe	7,059.11	1.27	0.02	0.22	397.78	5.64	4.95
Evergreen Seasonal Forest	4,838.88	7.71	0.16	1.34	136.43	2.82	1.70
Water*	4,707.81	0.89	0.02	0.15	13.03	0.28	0.16
Semi-deciduous Seasonal Forest	2,351.38	4.21	0.18	0.73	111.08	4.72	1.38
Deciduous Seasonal Forest	1,824.67	0.00	0.00	0.00	104.08	5.70	1.30
Total	279,669.81	575.23	0.21	100.00	8,036.99	2.87	100.00

Source: The authors (2024).

3.2 Burn scars on natural non-forest vegetation alerts

A total of 8,036.99 km² of alerts of burn scars on NF vegetation were detected by DETER NF during the analyzed period (August 2022 to July 2023). The state of Pará showed the largest area of alerts (2,493.71 km² or 31% of the total alerted area, see Figure 6), followed by Roraima and Mato Grosso, respectively with 2,317.48 km² (28.83%) and 1,735.18 km² (21.59%) of alerts. The 10 municipalities with the largest number of alerts are located in Roraima (4), Pará (4) and Mato Grosso (2). These municipalities accounted for 49.37% of the total detected alerts (Figure 7).

Figure 6 – Contribution of each Amazonian state to the burn scars on natural non-forest vegetation, between August 2022 and July 2023.

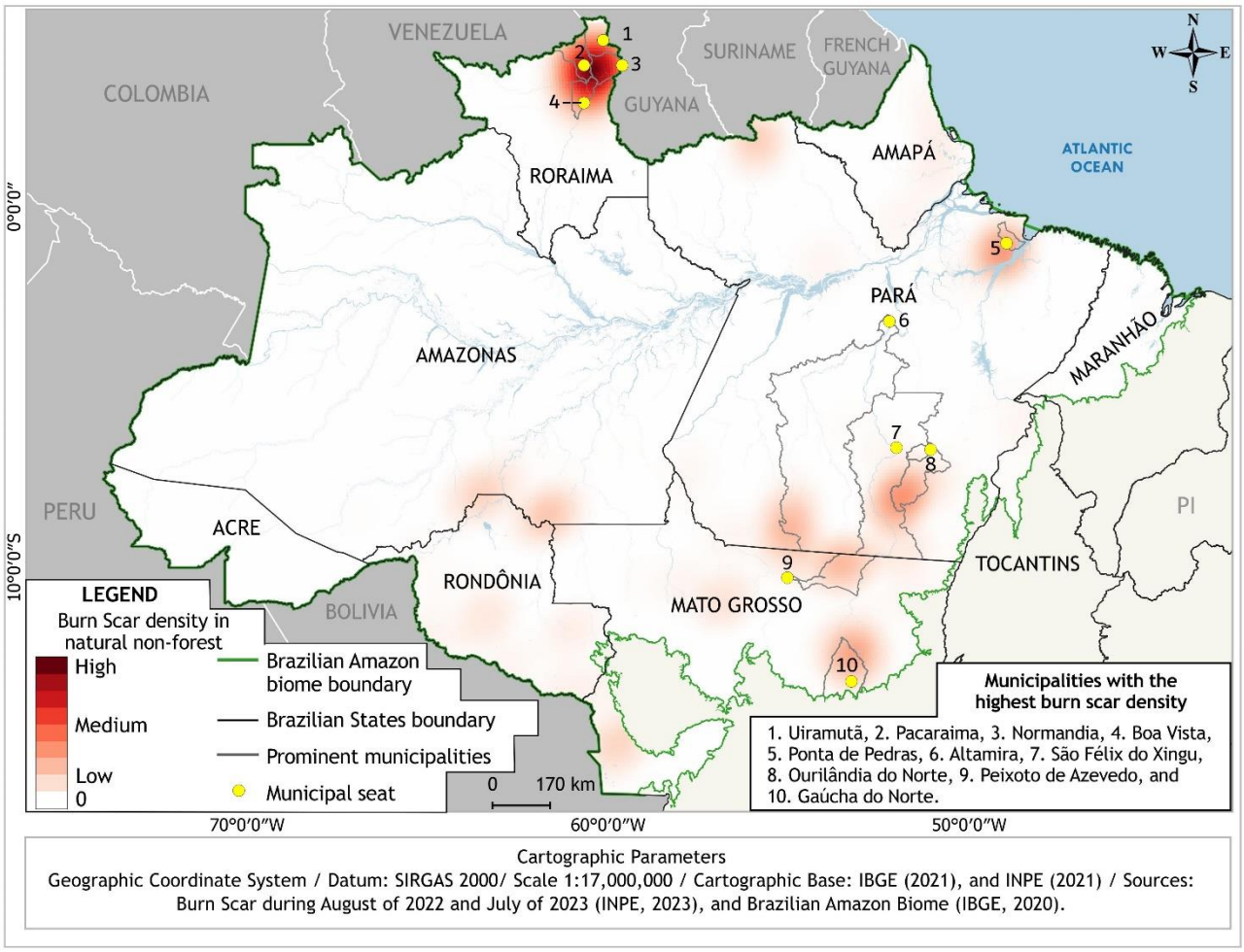


Source: The authors (2024).

The area of burn scars stratified by dominant vegetation type is shown in Table 4. Similar to NF suppression, most burn scars were detected in areas dominated by savannas (58.22%) and, secondarily,

Ecotones (15.87%).

Figure 7 – Map of burn scar alerts density on non-forest natural vegetation in the Amazon, between August 2022 and July 2023.



Source: The authors (2024).

4 DISCUSSION

In this study we presented the adapted methodology and initial results from DETER for monitoring NF areas in the Brazilian Amazon. The area with alerts in the DETER NF system within the analyzed period was 575.22 km², which is closely aligned with the value of vegetation suppression reported by the PRODES NF system (584.86 km²) (INPE, 2023d). Both systems showed a strong correlation between them. The small divergence between values of DETER NF and PRODES NF are similar to the long term differences observed in the systems monitoring forest vegetation (ALMEIDA et al., 2021). On average, between 2016 and 2021, PRODES and DETER (both focused on forest areas) had a ratio of 1.46 ± 0.14 SD (i.e., for each km² detected by DETER, PRODES detected a mean additional 0.46 km²). For NF areas in 2023, the ratio was 1.01. The differences in results between PRODES and DETER arise from their distinct methodologies. Whereas PRODES provides annual data on Amazonian vegetation suppression, DETER issues daily alerts for suppression and wildfires (ALMEIDA et al., 2022). DETER uses lower spatial resolution (64 m for forest-focused systems) with high temporal resolution, covering the entire biome every two or three days (ALMEIDA et al., 2022). In contrast, PRODES uses high-resolution images (10-30 m) with lower temporal resolution (ALMEIDA et al., 2022). Therefore, DETER usually reports lower values compared to PRODES. The only discrepancies comparing DETER NF and PRODES NF were observed in Mato Grosso and Rondônia states (Table 3), attributed to the misidentification of clearing activities and areas previously affected by fire, underscoring the need for improved clearing detection in these regions. In such instances, we propose employing images with higher spatial resolution to accurately confirm significant features identified by DETER NF.

To minimize false-positive alerts for government oversight, DETER maps only areas with low uncertainty, reducing the actual mapped area later covered by PRODES (ALMEIDA *et al.*, 2021; ALMEIDA *et al.*, 2022). Additionally, the burned area also influences the PRODES/DETER relationship. A study by ALMEIDA *et al.* (2021) showed a strong negative correlation ($r = -0.80$, $p < 0.05$) between fire spots and the PRODES/DETER ratio in forest areas, suggesting that an increase in burned areas tends to decrease the PRODES/DETER ratio. This may explain the 1.01 ratio found between DETER NF and PRODES NF, contrasting with the slightly higher 1.46 average ratio between DETER and PRODES for forest areas found by ALMEIDA *et al.* (2021). Nonetheless, the similar trends in results between systems suggest the adapted methodology for NF monitoring was effective, indicating the potential use of DETER NF for rapid monitoring and control, despite its lower spatial resolution compared to PRODES NF, which discloses only annual aggregate loss values.

The states of Roraima, Mato Grosso, Rondônia, and Pará were the ones that concentrated the most alerts for both vegetation suppression and burn scars in non-forest vegetation. In line with PRODES NF, these states emerged as the main hotspots for NF vegetation suppression in the last decade (MESSIAS *et al.*, 2024). These states comprise over 80% of both the savanna and savanna-forest ecotone areas within the DETER NF monitored area, the vegetation types most affected by both suppression and fires. Apart from savannas constituting the largest area in the DETER NF monitored region, another factor associated with this vegetation type is the suitability of its soils for agriculture and pastures, being more susceptible to clearing compared to densely forested areas (SILVA; OLIVEIRA, 2018). The Amazonian savannas, which are among the least protected ecosystems in the Amazon, have suffered significant coverage loss (MESSIAS *et al.*, 2024). This is attributed not only to suppression and conversion to other uses but also to their susceptibility to fire for pasture management and grazing, rendering them one of the most threatened ecosystems in the Amazon (DE CARVALHO; MUSTIN, 2017; HILÁRIO *et al.*, 2017; MUSTIN *et al.*, 2017).

In Roraima, as well as in Amapá, which showed also a significant area of burn scar alerts, the most probable cause for the increase in NF loss is the recent expansion of soybean cultivation (BARBOSA; CAMPOS 2011; RODRIGUES 2023; SILVA; OLIVEIRA 2018). Both states have been considered the last agricultural frontier in the Amazon (SILVA, 2016; STAEVIE, 2018), mainly due to subsidies and flexibility in state environmental legislation by the state governments (BARBOSA; CAMPOS, 2011; YOKOMIZO; COSTA, 2016; SILVA; OLIVEIRA, 2018). On the other hand, the presence of extensive burn scar alerts is primarily attributed to the use of fire for managing the savanna for pasture and land clearing for various purposes (COSTA *et al.*, 2011; SILVA; OLIVEIRA, 2018). The historical series of PRODES NF data has shown that NF loss remained at low levels in Roraima until the early 2000s but intensified over the past two decades, particularly since 2014, making Roraima the third state in accumulated NF loss, as per PRODES NF data (ALMEIDA *et al.*, 2023; MESSIAS *et al.*, 2024) and the first and second in DETER NF alerts of suppression and burn scars, respectively. The *lavrado* savannas in Roraima showed the highest concentration of NF loss alerts among all regions, where the municipalities of Bonfim, Boa Vista, Alto Alegre, and Amajari are located. Being the largest continuous area of Savannas in the biome, the *lavrado* accumulate a great amount of fuel material during the dry season, making them prone to fire (BARBOSA *et al.*, 2007).

In the state of Pará, the presence of the municipalities of Altamira, São Félix do Xingu, and Ourilândia do Norte among the top 10 with the highest alert area for NF suppression and burn scars can be attributed to their location in the Terra do Meio region, which has been significantly affected by forest conversion to pastures (MERTENS *et al.*, 2002; ESCADA *et al.*, 2005; LU *et al.*, 2013; NEVES *et al.*, 2014; LI *et al.*, 2018; INPE, 2023b). Concentrations of burn scar alerts were also prominent in Marajó (northeastern Pará, Figure 7), where fire is commonly used for managing natural pastures for cattle breeding (SCHAAN, 2010). In the central-south regions of Amazonas state, there were also NF areas with intense occurrences of burn scar alerts. This region, mostly along BR-319 and BR-320 and particularly in savanna areas, shows a concentration of land use changes with a shift from family farming to large livestock properties (BRASIL, 2008; MACEDO; TEIXEIRA, 2009; CARRERO; FEARNSIDE, 2011; MATAVELI *et al.*, 2021), supporting DETER NF findings.

The alert hotspots identified in the southwestern region of Mato Grosso have already undergone significant NF loss, particularly in the early 2000s (ALMEIDA *et al.*, 2023; MESSIAS *et al.*, 2024).

According to PRODES NF, Mato Grosso state had the highest absolute area of NF vegetation loss (14,469.20 km²), ranking second in relative terms (32.1%) (MESSIAS *et al.*, 2024). The state also holds the second position in terms of forest loss in the Brazilian Amazon (INPE, 2023b) and boasts the largest cultivated area (75.91% of the total) and the largest cattle herd in the country (35.68%) (IBGE, 2023). The concentration of suppression alerts and burn scars in the transition zone with the Cerrado and Pantanal, and in the northern region, specifically along the Rio Xingu and Parque do Xingu, bordering Pará, is associated with the expansion of the agricultural frontier, particularly soy cultivation, into these two biomes (SILVA *et al.*, 2011; GOLLNOW *et al.*, 2018; PICOLI *et al.*, 2020; KUSCHNIG *et al.*, 2021), and the observed pressure around the BR-163 highway (FEARNSIDE, 2007; YOSHIKAWA; SANGA-NGOIE, 2011; GOLLNOW *et al.*, 2017).

A similar trend as the one seen in Mato Grosso is evident in the savannas of Rondônia, where, despite the majority of the NF area being situated within protected zones (ROSA, 2017), the state has ranked fourth in the lost area detected by PRODES NF, showing a growing pattern of losses over the last decade (MESSIAS *et al.*, 2024). The recent changes in land use are primarily attributed to the conversion of natural areas into pastures, with an expanding portion dedicated to soybean production (ALVES *et al.*, 2010; COSTA *et al.*, 2017; SANTOS *et al.*, 2022).

In terms of DETER NF alerted classes, we observed a predominance of the *suppression with exposed soil* class, with alerts from mining activities being the least frequent. This pattern is consistent with the findings in other DETER systems (DOBLAS *et al.*, 2022). The prevalence of the exposed soil class can be partially explained by the system's rapid detection, as alerts are typically issued shortly after the vegetation suppression event, often leaving the soil exposed. Alerts involving *suppressions with cultivated area* tend to be more prevalent when cloud cover hinders immediate detection, allowing natural or cultivated grasses and herbaceous species to grow in a short time interval. The *mining* class represented the smallest area of alerts and was concentrated in the state of Pará, which is known for its significant mining activities (ENRÍQUEZ, 2014).

Since DETER NF aims to identify disturbances within NF vegetation in the Amazon, identifying the underlying causes of these disturbances is beyond the scope of this project at the moment. However, given the correlation found by MESSIAS et al. (2024) between deforestation and NF suppression in the Amazon, it is plausible to infer that the factors discussed earlier are common across the dominant vegetation typologies in the landscape (whether forest or non-forest vegetation). This assumption is also supported by the "leakage effect" of vegetation suppression from forested areas to NF vegetation areas in the Amazon and Cerrado due to environmental policies (e.g., PPCDAm, Soy Moratorium, the Cattle Agreement) that have successfully limited deforestation in the Amazon (PFAFF; ROBALINO, 2017; RICHARDS et al., 2017; MAGALHÃES et al., 2020; WEST; FEARNSIDE, 2021).

5 CONCLUSIONS

This study presents the preliminary results of a pilot project for monitoring non-forest areas of the Brazilian Amazon, using the DETER methodology adapted to these areas. Results were proximate to the ones obtained by PRODES NF but in a much higher temporal resolution. The data from DETER NF aims to assist the government in its decision-making and law enforcement processes. For instance, our results underscore the necessity of investing in suppression control actions, particularly in the *lavrado* region within Roraima state, a region occupied predominantly by savannas, the currently most affected vegetation type in non-forest areas. Nonetheless, we highlight that DETER NF must not, under any circumstances, be considered an official annual value for the suppression of non-forest original vegetation, which is the aim of PRODES NF. DETER NF has been operational since August 1, 2023, complementing the provision of daily disturbance alerts for the whole Amazon biome, providing important data for 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. The data is publicly accessible on the website http://terrabrasilis.dpi.inpe.br. It is important to emphasize that in the current daily operations, DETER NF

utilizes images from CBERS 4 and CBERS 4A to increase daily revisits and reduce the unmonitored area due to cloud coverage.

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Authors' Contribution

CGM, JKCP, LS, LEPM, and CAA were involved in the coordination of the project and in the article development. VLC, MSR, FCA, LPP, and LHAG contributed to article development, data analysis, and figures. CGM, CBQ, TCL, DCMB, DLCL, and DRVM served as auditors. NAPM, LHAG, VFR, APB, MHHM, GMRA, RCST, MRRN, DRVM, RA, EFMB, ACSA, and EHSC comprised the team of interpretation experts. JJS, LSB, EHSC, DMS, IPC worked on image processing. JKCP, FCP and AC were responsible for project database maintenance. MA, HX, MX, and AAAS acted as external consultants. CGM, MA, HX, and MX participated in fieldwork.

Conflicts of Interest

There is no conflict of interest.

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