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Beyond the reporting of disturbed areas: the use of Deter to analyze the spatiotemporal patterns of forest degradation in the Amazon

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Abstract
The Brazilian Amazon, a critical component of Earth's climate regulation and biodiversity, has been increasingly affected by forest degradation, a process less monitored than deforestation. This study examines the recurrence and spatiotemporal patterns of forest degradation in the Legal Amazon from 2016 to 2024 using data from the Daily Monitoring of Suppression and Degradation of Native Vegetation (Deter) monitoring system. We first review methodological advances in Deter, highlighting its role in near real-time monitoring and enforcement. Subsequently, we applied a pixel-level recurrence analysis to map degradation frequency and analysis of spatiotemporal patterns, allied to statistical tests to assess monotonic trends. Results show that although most affected pixels had only one detection of degradation, critical hotspots, particularly in Pará and Mato Grosso, had up to five detections. Burn scars were the most frequent type of degradation, with a marked surge in 2024 corresponding to a 271% increase in the degradation rate. No significant overall trend was observed across the time series. Spatiotemporal patterns revealed a shift of degradation toward the eastern Amazon forest edge in 2016–2018, a concentration in southern and northern Mato Grosso in 2019–2021, and widespread degradation across the Legal Amazon in 2022–2024, with a pronounced hotspot in southern Pará. These findings emphasize the growing significance of forest degradation in Brazil, highlighting the need for integrated conservation strategies that extend beyond deforestation to include early detection and response. Strengthening monitoring systems such as Deter remains essential to support environmental governance, enforcement, and sustainable land management in the Amazon.

Keywords Deforestation monitoring, Forest degradation, Remote sensing, Amazon rainforest, Environmental governance

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Introduction

The Brazilian Amazon, the world's largest tropical rainforest, faces significant threats from deforestation and fires, driven by logging, agricultural expansion, and illegal land grabbing (Berenguer et al. 2024). These activities not only threaten biodiversity but also contribute substantially to global carbon emissions, impacting climate change (Gatti et al. 2021; Franco et al. 2025). In this context, closer and more effective forest monitoring is essential for addressing the complex challenges posed by fires and deforestation in the region (Flores et al. 2024; Tyukavina et al. 2017).

Enhanced forest monitoring enables early detection of illegal activities, providing timely information to law enforcement agencies and environmental authorities (Jackson and Adam 2020). This is important in combating deforestation, as rapid intervention can prevent the progression of land clearing, reduce damage, and hold perpetrators accountable. Moreover, forest fires, often linked to deforestation (Lima et al. 2024), are exacerbated by the use of fire to clear land for agricultural purposes. Accurate monitoring can help identify fire hotspots and predict areas at high risk, allowing for pre-emptive action to mitigate their impact (Andela et al. 2022; Celis et al. 2023).

Additionally, closer monitoring facilitates better land-use planning and sustainable forest management by providing critical data on ecosystem health and human activities (Jackson and Adam 2020). It supports the policy-making process and assists in ensuring compliance with environmental regulations, such as Brazil's Forest Code and supply-chain agreements for agricultural commodities (Soterroni et al. 2018; Gibbs et al. 2015; Skidmore et al. 2024). In light of the accelerating pace of deforestation and the growing intensity of fires in the Amazon (INPE 2025), a comprehensive approach to forest monitoring is necessary to protect this vital ecosystem (Garrett et al. 2021; Guo et al. 2023). Strengthening monitoring systems can significantly enhance conservation efforts, curbing illegal activities and fostering sustainable development in the region.

Although deforestation has been the primary focus of scientific research on the Amazon biome, forest degradation remains comparatively underexplored (Lapola et al. 2023). Addressing forest degradation is essential for regulating Earth's climate, preserving biodiversity, supporting local well-being and livelihoods, and ultimately sustaining humanity as a whole (Malhi et al. 2014). Analyses of satellite data reveal that degradation and disturbance are significant drivers of tropical carbon emissions, with the tropics experiencing 2.3 million km^2 of forest loss from 2000–2012 (Brinck et al. 2017). Recent findings indicate the problem is even more acute. Bourgoin et al. (2024) showed that the degradation of tropical moist forests is greater than previously estimated, making it a major and often overlooked source of carbon emissions. Furthermore, the high fragmentation of these ecosystems—over 30% of tropical forests are highly fragmented (Sun et al. 2025)—increases their vulnerability to edge effects, degradation, and carbon loss, underscoring the urgent need to protect intact forest landscapes.

Remote sensing-derived data from 2024 reveals a concerning new trend: during the recent drought years (2023–2024), the rise in degraded forest areas has surpassed the declining area of deforestation events (INPE 2025). Exploring the reported total areas of deforestation driven or not by degradation, Mataveli et al. (2025) argue that the impacts of the rising extent of these processes demand solutions that consider forest degradation in conservation policies, which can only be achieved based on adequate information about where and when the forest is being degraded. In this sense, the "Daily Monitoring of Suppression and Degradation of Native Vegetation" (Deter) program, designed and executed by the Brazilian National Institute of Space Research (INPE), stands out as a crucial source of information, due to its capability to generate daily information regarding forest degradation events in the Amazon. In the present study, we expand the analysis of Mataveli et al. (2025) by using Deter data to show how forests are being degraded in time and space in the Amazon. To this end, we first review up-to-date information about this program and discuss its importance in forest preservation. We then show the spatiotemporal patterns of forest degradation in the Amazon from 2016 to 2024. Finally, we draw some conclusions from the study and outline some areas for further work.

Methods

Updated information about the Deter system was collected by reviewing published articles citing Deter. Recent progress and usefulness in the combat and control of anthropogenic forest disturbances are then reported according to this data.

We then analyzed the spatiotemporal patterns of forest degradation in the Brazilian Legal Amazon, using the recurrence of degradation alerts emitted by Deter's publicly available data (INPE 2025). This data set is based on the interpretation of imagery from a combination of optical sensors (CBERS-4, CBERS-4A, Amazonia-1) to deliver alerts in two broad forest disturbance categories: complete suppression and degradation. Complete suppression is further classified as deforestation with exposed soil, deforestation with new vegetation cover, and mining, whereas degradation is composed by burn scars, planned selective logging, unplanned selective logging, and other types of forest degradation.

The spatiotemporal analysis was based on vector data from the Deter program, covering the period between

August 2016 and December 2024. Initially, we selected only Deter polygons corresponding to degradation classes. These data were then filtered by year. For each year, the degradation polygons were converted into 30 m spatial resolution raster files. A binary mask was created in which degradation pixels were assigned a value of 1 regardless of degradation type, and non-degradation pixels were assigned a value of 0. The annual degradation masks were summed to calculate how many times the same pixel experienced degradation during the analyzed period across the Brazilian Legal Amazon. To enhance visualization performance in Geographic Information System (GIS), the final product was spatially aggregated to a 1 km pixel resolution using the modal function and subsequently clipped to the boundaries of the the Brazilian Legal Amazon region.

Annual degradation values were also used to calculate the percentage variation rate of forest degradation detections (Δt) for each year relative to the previous one. This rate was obtained by subtracting the detected degradation area in year $t-1$ from that in year t, dividing the result by the detection area of year $t-1$, and multiplying by 100 to express the value as a percentage.

To assess the presence of monotonic trends (increasing or decreasing) in each forest degradation group over the analyzed period in the Brazilian Legal Amazon, we applied the traditional non-parametric Mann-Kendall test (Hipel and McLeod 1994; Libiseller and Grimvall 2002). This test evaluates the null hypothesis (H_0) of no significant trend against the alternative hypothesis (H_1) of a significant trend in the time series, using the S statistic and Kendall's τ (positive values indicating an increasing trend, negative values a decreasing trend, and zero the absence of a trend). Statistical significance is determined from the p-value, which is obtained by standardizing S into a normal test statistic (Z). In this study, the Mann-Kendall test was applied assuming a 5% significance level, and 95% confidence intervals were also estimated for Kendall's τ to assess the uncertainty of trend magnitude.

We also grouped degradation values in three time intervals (2016–2018, 2019–2021, and 2022–2024), to further analyze how these are distributed in both space and time. We adopted a conservative approach in which the products were reclassified and binarized into three new layers, indicating the presence (value = 1) or absence (value = 0) of forest degradation detections. These rasters were also spatially aggregated to a 1 km pixel size using the modal function and clipped to the boundaries of the study area. To represent spatiotemporal dynamics, the following expression was applied: $(\text{“}2016-2018\text{”}\times 4)+(\text{“}2019-2021\text{”}\times 2)+(\text{“}2022-2024\text{”}\times 1)$ where, for example, $(\text{“}2016--2018\text{”}\times 4)$ means that the raster containing Deter data from 2016 to 2018 was multiplied by four and so forth. The resulting pixel values were assigned specific colors to represent different degradation categories: 0 = no degradation; 1 = degradation only in 2022–2024; 2 = degradation only in 2019–2021; 3 = degradation in both 2019–2021 and 2022–2024; 4 = degradation only in 2016–2018; 5 = degradation in both 2016–2018 and 2022–2024; 6 = degradation in both 2016–2018 and 2019–2021; and 7 = degradation across all periods. All processing steps described in this and the aforementioned analyses were performed in the R programming language, using a suite of packages such as sf, dplyr, lubridate, tidyr, terra, and prettymapr for handling geographical data, and trend and Kendall for statistical analyses.

Recent advancements and effectiveness of Deter

Deter focuses on emitting primary vegetation disturbance alerts for Brazilian inspection and control agencies. Besides its main role in curbing natural vegetation disturbance events, Deter results are also open for public consultation, meaning that this transparent data can be assessed independently and used for projections and as the basis for many types of socio-economic-environmental studies.

Deter's main feature is its capacity to deliver disturbance alerts in near real-time and with high accuracy, meaning that satellite images are processed as soon as they are available. Therefore, Deter is able to report the ongoing suppression and/or degradation of the natural vegetation to be investigated by control agencies. Deter has evolved from a single system proposed under the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) in 2004 (Brasil 2004) to a family of systems focused on different biomes and based on various datasets and methodologies. Currently, the Deter system monitors forested and non-forested areas in the Amazon (Almeida et al. 2022; Messias et al. 2024b), Cerrado and Pantanal (Almeida et al. 2025), with continuous studies to expand Deter's reach using improved methodologies and novel data sets (Soler et al. 2021; Doblas et al. 2024).

In the majority of Deter systems in operation, a team of trained experts visually interprets medium spatial-resolution optical remote sensing images daily and draws the alerts of interest. These are then audited by an independent team of experts and delivered to Brazilian inspection and control agencies. Each system presents interpretation keys and protocols designed for a specific type of vegetation/disturbance process (Almeida et al. 2022). These protocols are constantly evolving based on local experts' feedback and field data (Messias et al. 2024c).

A well-known limitation of systems based on optical remote sensing images is cloud-cover, mainly in tropical regions such as the Brazilian Amazon. As such, Deter has historically presented limitations regarding the limited cloud-free observations from December to March. This limitation had a direct impact on the effectiveness of deforestation monitoring in the Amazon. Assunção et al. (2023), for example, observed that a 10% increase in cloud cover resulted in an approximately 6% decrease in the number of fines issued by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). To solve this problem, two Synthetic Aperture Radar (SAR) systems were included in Deter's family: Deter-R (Doblas et al. 2022), which operated between November 2021 and August 2024, and its successor, Deter-RT (Doblas et al. 2024), which is the object of an ongoing research carried out by the cooperation among INPE, the *Centre National d'Études Spatiales* (CNES), Global Earth Observation (GlobEO), and the *Centre d'Etudes Spatiales de la Biosphére* (CESBIO). Both systems are based on the daily and automatic analysis of Sentinel-1 imagery. Deter-R issued around 1.6 million ha of forest suppression/degradation warnings, with an estimated rate of false positives of 0.26% and a minimum mapped area as low as 0.4 ha (Reis et al. 2023; Doblas et al. 2024). Deter-RT is still in its development phase, but it is expected to operate with the same minimum mapped area and improved detection capabilities (Reis et al. 2025).

Deter also included efforts to integrate the automatic processing of images and/or the use of images with higher spatial resolution, translated into projects such as the automatization of the preprocessing within Deter (interpretation was facilitated by the segmentation of fraction images) and Intense Deter (based on the visual interpretation of higher resolution optical imagery in areas of special interest in the Amazon) (Shimabukuro et al. 2007; Soler et al. 2021). These initiatives are currently discontinued.

As is common with all near real-time systems, there is a trade-off between frequency and accuracy, as well as between commission and omission errors. Deter focuses on detecting events for field actions, meaning that the program prioritizes delivering fast results with very low commission. The availability of adequate remote sensing images throughout the year may also vary. As such, Deter data cannot be used to estimate the suppression/degradation rate of natural vegetation. Neither is it advisable to compare monthly values from different years to estimate rates' progression. Official estimates of forest removal can only be done based on Prodes (Annual Monitoring of Native Vegetation Suppression) data. Prodes is the first Brazilian system to alert primary forest removal events based on satellite imagery in the so-called Brazilian Legal Amazon, with data generated and published as far as 1988. Since 2023, Prodes maps annual natural vegetation loss across the entire Brazilian territory, including areas of non-forest natural vegetation in the Amazon (Messias et al. 2024a; Almeida et al. 2025). An example illustrating Deter's capabilities of deforestation detection compared to Prodes is presented in Fig. 1. Note that, however, Prodes maps the total suppression of natural vegetation, whereas one of the most unique features of Deter is its capability to also alert to degradation events in the Amazon (since 2015) and Pantanal (since 2023) on a daily basis.

So far, Deter has proven to be a valuable tool for curbing deforestation in the Amazon. In Mato Grosso, for example, 38% of IBAMA's fines between 2005 and 2010 were applied to areas detected by Deter (Teures and Castilho 2011). One of the main strategies of the first and second phases of PPCDAm was to prioritize enforcement in large deforestation polygons (> 100 ha). Consequently, the share of these polygons in the total deforested area declined from 44% in 2004 to 17% in 2012 (Brasil 2023). These enforcement actions, combined with legal

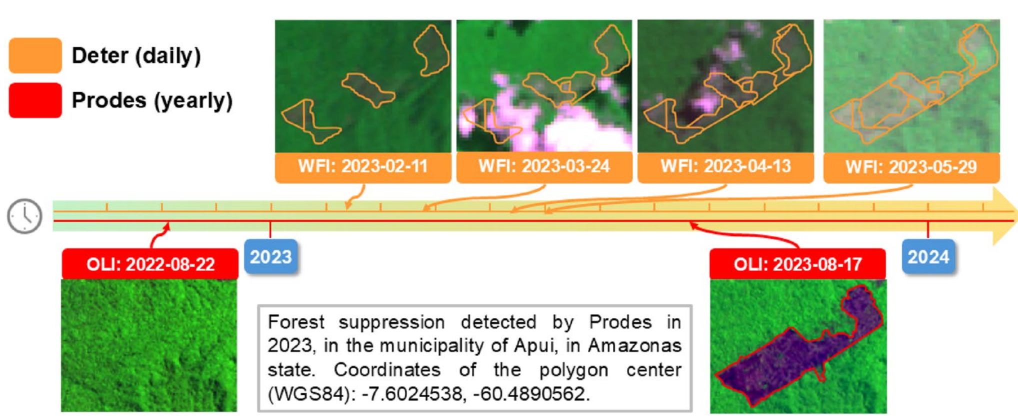

Fig. 1 Examples of Prodes and Deter detections of forest suppression events in 2023. Note that Deter was capable of detecting the first three events in February and has detected the totality of events in this area in May, whereas Prodes was only capable of detecting them in late August. In which WFI (Wide Field Imager) is the sensor onboard CBERS4, CBERS4A, and Amazonia-1, and OLI (Operational Land Imager) is the sensor onboard Landsat 8 and 9

restrictions and lawsuits against companies and landowners, were essential to reducing deforestation (Nolte et al. 2013; Ferreira and Silva 2014; Assunção et al. 2015). However, the weakening of environmental law enforcement, along with other factors, contributed to an increase in the share of large deforestation polygons, reaching 47% in 2022 (Brasil 2023). These numbers show the importance of strengthening public policies based on near-real-time data.

Recurrence and spatiotemporal trends of forest degradation in the Brazilian Legal Amazon

Figure 2 shows the degradation in the Brazilian Legal Amazon from 2016 to 2024, as detected by Deter Amazon data. The resulting forest degradation recurrence map revealed that degradation is sparsely distributed across the region, with a notable concentration in the southern and southeastern sectors (Fig. 2a). Recurrence values ranged from one to five degradation events within the region. Although most pixels were degraded only once (yellow areas) during the period, the map also highlights critical zones where degradation occurred four or even five times. At least two major hotspots with higher degradation recurrence values ($\geq$3) are located in the northeastern and southeastern sectors of the states of Mato Grosso and Pará, respectively.

These patterns align with the spatial trends of deforestation, driven mainly by the expansion of croplands and pasturelands in these areas (Morton et al. 2006; Bonini et al. 2018; Magalhães et al. 2020). Underpinning this land conversion are potent socio-economic factors and government policies. While poverty and unequal land access push small-scale farmers into forests for subsistence, the growth of agribusiness for cattle ranching and soy production drives large-scale clearance (Lapola et al. 2023; Ribeiro et al. 2025). These activities are often indirectly supported by policies that prioritize economic growth over conservation, including land regularization that rewards forest clearing, weak enforcement of environmental laws, and infrastructure projects that open pristine areas to exploitation (Fearnside and Leal Filho 2025). This combination of political and economic pressure and lenient regulations systematically drives the conversion of forest into economic assets, creating a clear link between national policy decisions and escalating environmental damage (Rochedo et al. 2018; Brito et al. 2019).

In terms of the area covered by Deter alerts, we observed a decreasing trend in forest degradation from 2016 (~22,857 km²) to 2018 (~11,083 km²) with a percentage change (Δt) of up to - 40%, followed by fluctuations in degradation data between 2019 and 2023 (Fig. 2b). The year 2024 recorded the highest forest degradation area (~57,621 km²) in the analyzed dataset, with the highest Δt, of 271%. However, the Mann-Kendall test revealed a Kendall's τ value of 0, indicating that the assessed time series did not exhibit any monotonic trend (increasing or decreasing) in forest degradation from

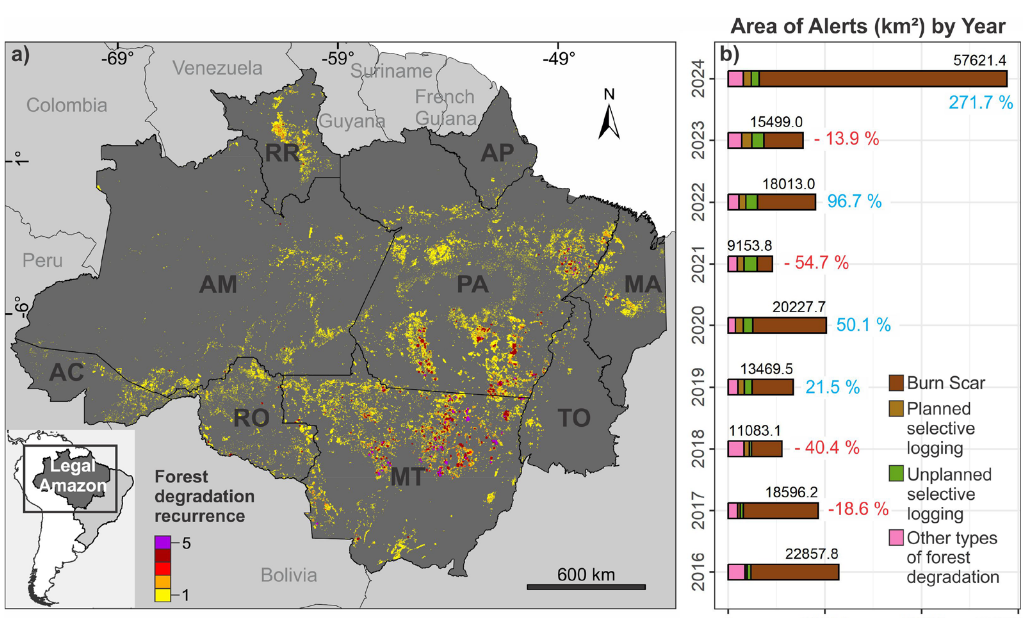

Fig. 2 Forest degradation over time in the Brazilian Legal Amazon. **a** Forest degradation recurrence map (August 2016 to December 2024), based on ~ 1 km pixel size. **b** Area of Deter alerts (km²) by type (burn scar, selective logging, and other types of degradation) for the analyzed period. The percentage variation rates of forest degradation are shown in red (negative) and blue (positive) values. States of the Brazilian Legal Amazon: AC = Acre, RO = Rondônia, MT = Mato Grosso, TO = Tocantins, MA = Maranhão, PA = Pará, AM = Amazonas, AP = Amapá, and RR = Roraima

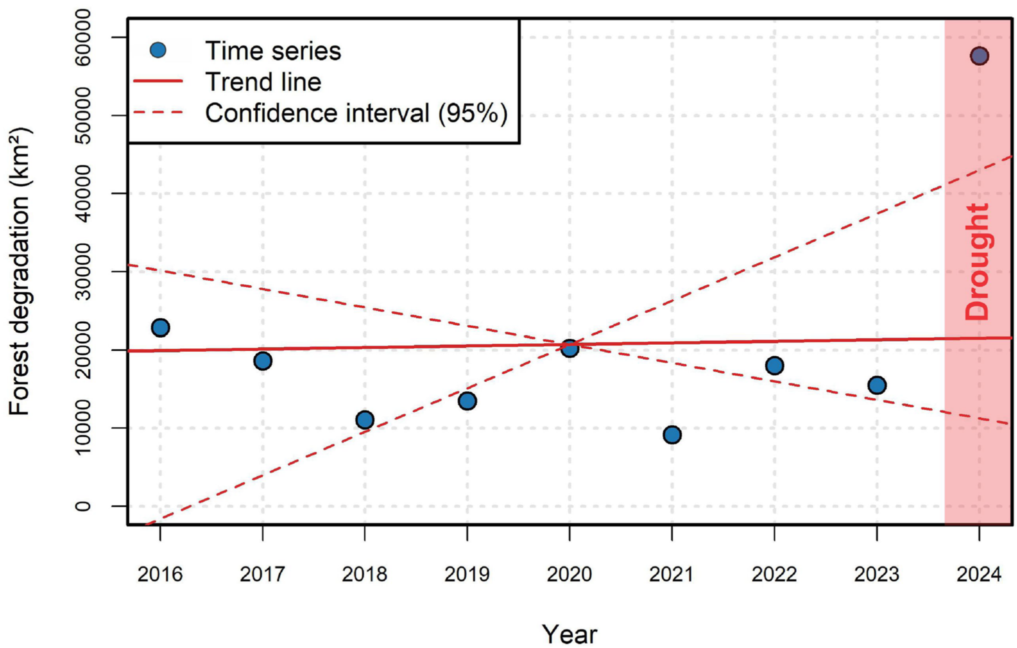

Fig. 3 Trend analysis of forest degradation in the Brazilian Legal Amazon between 2016 and 2024 using the Mann-Kendall test

2016 to 2024 (Fig. 3). The two-sided p-value of 1 confirms that the forest degradation time series is not significant at a 5% significance level, and the wide confidence interval, spanning both negative and positive values, further reinforces the absence of a trend. However, these results should be interpreted with caution, as nine years is a relatively short period for environmental time series, especially for degradation phenomena in the Amazon, which may exhibit strong interannual variability. Additionally, 2024 was an anomalous year, potentially influenced by prolonged droughts in the Brazilian Amazon (Marengo et al. 2024).

An important aspect of the analysis is the local identification of the most frequently occurring forest degradation type. The proportional area of each degradation type from 2016 to 2024 across the Brazilian Legal Amazon is shown in Fig. 2b. Among all types, burn scars were the most frequently observed, followed by other types of forest degradation, unplanned and planned selective logging. These findings are consistent with fire being one of the main drivers of deforestation and forest degradation in the Brazilian Amazon (Lapola et al. 2023). The peak in burn scar area observed in 2024 aligns with recent studies indicating the potential impact of prolonged droughts on the increased occurrence of fires in the Amazon forest during that year (Marengo et al. 2024). This dynamic triggers a critical feedback loop: when these essential carbon sinks are damaged, stored carbon is released through burning, transforming them into major emission sources (Singh 2022). Climate change, in turn, intensifies droughts and fires, accelerating further forest loss and emissions. For Brazil, this loop directly undermines international commitments, as the resulting carbon emissions make Paris Agreement goals impossible to meet (Franco et al. 2025). Consequently, the nation could face significant diplomatic and economic challenges in a world where trade and cooperation are increasingly tied to proven environmental action (Ometto et al. 2011), making forest protection and restoration crucial for both global climate stability and national interest.

The spatiotemporal patterns of forest degradation in the Brazilian Legal Amazon from 2016 to 2024 are shown in Fig. 4. Between 2016 and 2018, a NE–SW trend of forest degradation was observed in Mato Grosso, Tocantins, and Maranhão, particularly along the eastern Amazon forest edge. From 2019 to 2021, degradation was concentrated mainly in the southern and northern sectors of Mato Grosso, associated with the mega fire events that occurred in those years in the Pantanal, especially in 2020 (Pereira et al. 2024), with additional occurrences in Pará. Between 2022 and 2024, forest degradation became widespread across the Brazilian Legal Amazon, with a significant concentration in the southern portion of Pará. Transitions between the three time intervals, as well as throughout the entire analyzed period, were generally recorded as small clusters across the study area, but with notable presence in Pará and Mato Grosso, where forest degradation recurrence is higher (Fig. 2).

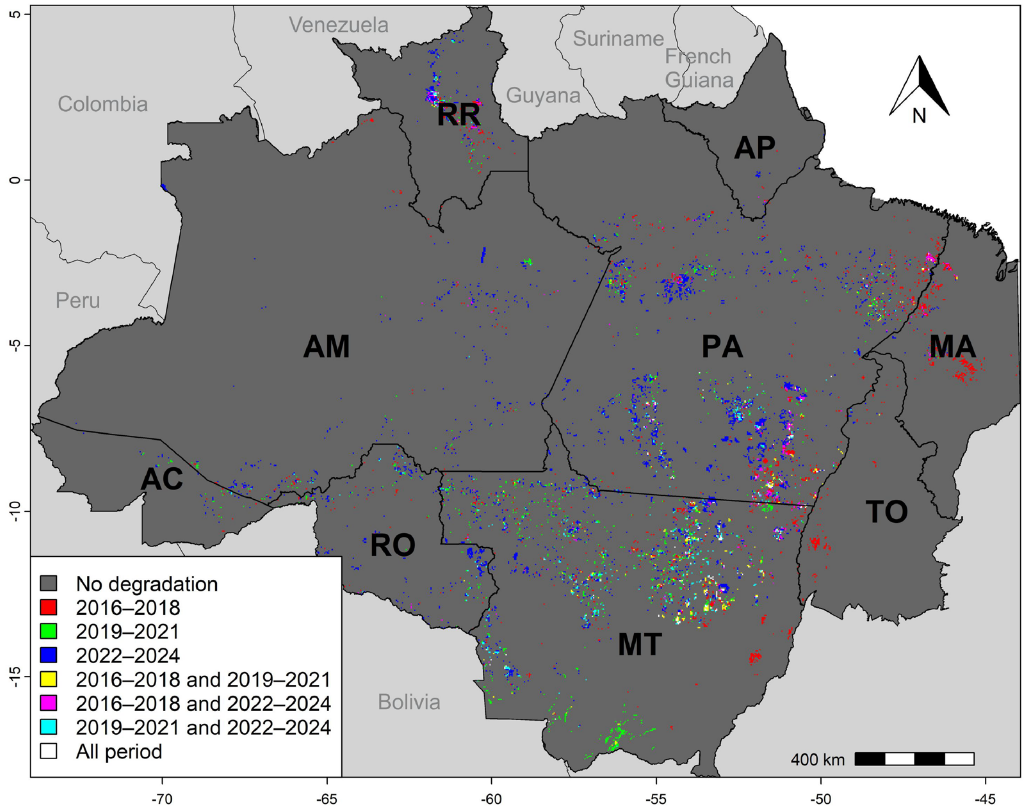

Fig. 4 Spatiotemporal analysis of forest degradation in the Brazilian Legal Amazon between 2016 and 2024. States of the Legal Amazon: AC = Acre, RO = Rondônia, MT = Mato Grosso, TO = Tocantins, MA = Maranhão, PA = Pará, AM = Amazonas, AP = Amapá, and RR = Roraima

Conclusions

Our analysis of Deter data from 2016 to 2024 provides new insights into the spatial and temporal dynamics of forest degradation in the Brazilian Amazon. The recurrence map reveals a heterogeneous pattern, with most areas experiencing only a single degradation event. Spatiotemporal patterns identified critical hotspots, particularly in Mato Grosso and Pará, that were degraded multiple times during the analyzed period. These high-recurrence zones coincide with regions undergoing rapid land-use change, especially due to the expansion of agriculture and pasturelands.

No significant monotonic trend was observed across the entire forest degradation time series. However, annually, there was an initial decline in degradation until 2018, followed by significant variability and culminating in a dramatic increase in 2024, which recorded the highest degraded area in the period. Burn scars were the predominant form of degradation, reinforcing the central role of fire as a major driver of forest degradation in the region.

These findings highlight the persistent and intensifying nature of forest degradation in certain areas of the Brazilian Legal Amazon and underscore the need for targeted monitoring and mitigation strategies. Effective forest conservation in the region requires not only improved enforcement but also comprehensive policies that address the socio-economic drivers of land-use change and strengthen resilience to climate extremes.

By utilizing satellite-based remote sensing technology, Deter provides frequent updates on forest cover changes, enabling authorities to respond swiftly to illegal logging and other destructive activities. Due to the costs of sending monitoring and control teams to the field, it is crucial that Deter commission errors remain extremely low, which may affect the omission rate when compared to other systems. Therefore, the reported degradation rate is probably underestimated in the Deter system, meaning that more subtle degradation events may not have been included in the present analysis. This and other known limitations of the system, such as cloud cover and spatial resolution, are being overcome due to continuous research efforts. Further work is also needed, in respect of evaluating the effectiveness of combining Deter with other tools, and the feasibility of investigating the impacts of forest degradation on long-term changes in land use.

In the meantime, Deter remains a valuable tool for environmental governance and highlights the need for continuous advancement in monitoring technology to ensure the sustainable management of the world´s largest rainforest ecosystem.

Abbreviations

AC	Acre (Brazilian state)
AM	Amazonas (Brazilian state)
AP	Amapá (Brazilian state)
CBERS	China-Brazil Earth Resources Satellite
CESBIO	*Centre d'Etudes Spatiales de la Biosphére*
CNES	*Centre National d'Études Spatiales*
Deter	Daily Monitoring of Suppression and Degradation of Native Vegetation
Deter-R	Deter-Radar
Deter-RT	Deter-Radar-TropiSCO
GIS	Geographic Information System
GlobEO	Global Earth Observation
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
INPE	National Institute for Space Research
MA	Maranhão (Brazilian state)
MT	Mato Grosso (Brazilian state)
OLI	Operational Land Imager
PA	Pará (Brazilian state)
PPCDAm	Action Plan for the Prevention and Control of Deforestation in the Legal Amazon
Prodes	Annual Monitoring of Native Vegetation Suppression
RO	Rondônia (Brazilian state)
RR	Roraima (Brazilian state)
TO	Tocantins (Brazilian state)
WFI	Wide Field Imager

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Author contributions

WLF conceived the study and drafted the initial structure of the manuscript. CGM, VLC, and JBSOAG contributed to the writing, structure, and critical revision of the text. FCA and MSR were responsible for data acquisition, analysis, interpretation, and writing. All authors made substantial contributions to the study's conception, reviewed the content critically, and approved the final version of the manuscript.

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Data availability

The datasets supporting the conclusions of this article are available in the Terrabrasilis repository, accessible through the hyperlink https://terrabrasilis.dpi. inpe.br/downloads/.

Declarations

Competing interests

The authors declare no competing interests.

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