Unaccounted natural vegetation loss in Brazilian Amazon

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Abstract

Deforestation in the Brazilian Amazon has been monitored since 1988 by the Brazilian Amazon Satellite Monitoring Program (PRODES Amazonia), and its data has been pivotal in guiding environmental public policies in the country. While forest formations are officially supported by a monitoring program, a significant portion of the Amazon biome (6.6 % or ~280,000 km²) constituted by non-forest (NF) phytophysiognomies (e.g., savanna, grasslands, flood lands) are still unmonitored. To address this information gap, the PRODES NF system was built and adapted from the well-established and recognized methodology of PRODES Amazonia in Brazil. First findings based on PRODES NF monitoring indicate that the Brazilian Amazon lost 10.46% (~30,000 km²) of NF area, mostly in the last two decades. The states of Mato Grosso, Roraima and Amapá emerged as the primary hotspots of losses, with a growing trend of losses for the last two states. Among the phytophysiognomies, savannas were the most affected (13.3% of their extent). A strong correlation between NF loss and deforestation was revealed in the Amazon biome, with no statistical differences in terms of relative area, suggesting a continuum of vegetation loss along this biome that does not discriminate between forest and non-forest. Finally, PRODES Amazonia and PRODES NF together provide relevant official data that sum up a total of vegetation loss of ~798.000 km² in the Brazilian Amazon (~19% of the entire biome).

Forest loss in Brazilian Amazon have been continuously monitored since 1988 through the Brazilian Amazon Satellite Monitoring Program (PRODES Amazonia)[1]. PRODES data is internationally recognized as a crucial tool to assess and control the extent and rate of deforestation processes, being significant for public policy proposals and enforcement, as well as research on varied topics that include biodiversity, climate change, and human well-being[2]. PRODES Amazonia solely focuses on forest clear-cutting, while companion projects like TerraClass and DETER[3] complement it by providing data on land use and land cover changes in the Brazilian Amazon. This includes information on forest regrowth, primary land use classes, and the detection of smaller deforestation or forest degradation events in near real-time throughout the year. Throughout the PRODES Amazonia data series, however, a considerable challenge persisted in addressing the need to map a consistent historical series of natural non-forest vegetation (NF) loss across an area spanning 279,492.08 km², equivalent to 6.6% of the Amazon biome.

NF stands for natural vegetation other than strictly forest ecosystems and embraces different types of phytophysiognomies. In the Brazilian Amazon, NF occurs as open-like formations such as savannas and grasslands; seasonally flooded areas with sandy soils and sparse trees; ecotones; isolated forest patches with deciduous, semi-deciduous, and even broadleaf characteristics; and natural areas of bare lands[4] (Fig. S3). These landscape features receive names such as pioneer formations, ecological refuges, *lavrados*, *campinas* and *campinaranas* or white-sand ecosystems[4]. Despite the lack of knowledge about their functioning and ecology[5-7], NF ecosystems are important sites for biodiversity conservation with endemic species of different taxa[5,7-10].

Previous mapping attempts[11-13] have shown the expansion of human activities within NF formations, leading to relatively high percentages (~17%) of accumulated deforestation in NF areas up to 2021 in selected Amazonian municipalities[13]. The overall extent of NF losses in the Brazilian Amazon biome and their specific locations were still unknown, which prevented the assessment of the impacts on Amazonian ecosystems and understanding on the drivers behind this destruction.

To tackle this challenge, we have developed PRODES NF, a systematic monitoring system for NF in the Brazilian Amazon. PRODES NF, an adaptation of the PRODES Amazonia forest mapping methodology, utilizes multi-sensor satellite imagery to identify vegetation loss in predominantly open ecosystems. Integrated into the PRODES monitoring system, it ensures continuous mapping of natural vegetation loss throughout the entire Brazilian Amazon biome. This system holds significant potential to support various compliance initiatives, including REDD+, the National Inventory (LULUCF), Trading Forest Certificates (CRA), and corporate commitments to reduce deforestation and ecosystem conversion[14-16]. In this study, we present, for the first time using official data, the spatial and temporal distribution of NF vegetation loss (referred to as NF loss) in the Brazilian Amazon biome, concluding with an overview of the total extent of vegetation loss, encompassing both forests and non-forest ecosystems.

Non-forest loss in the Brazilian Amazon

NF loss hotspots

Accumulated NF losses in the Brazilian Amazon biome until 2000 (baseline map) accounted for 12,934.75 km² (4.63% of the total NF area, Fig. 1) and reached 29,247.44 km² (10.46%) up to 2022, meaning that more than half of the accumulated loss happened in the last two decades. The prevailing pattern of NF loss up to 2022 unfolded from the southern to the northern regions (Fig. 1a), evidencing three main hotspots of NF loss located in the states of Mato Grosso, Roraima, and Amapá. Substantial and earlier losses (pre-2000) were primarily evident in the southwest sector of Mato Grosso (Fig. 1a, blue color), with additional minor occurrences in isolated zones within the central-eastern of Rondônia. The loss of NF persisted in Mato Grosso during 2001-2010 (cyan) and starts to be visible in the southeastern sector of Amapá. Emerging regions of NF loss (Fig. 1a, green color) appeared in the northern and southwestern sectors of Mato Grosso during this period, alongside sporadic patches within Roraima. More recent instances of NF loss (2011-2022) happened across extensive areas in Roraima (denoted by the red color) and localized patches in Rondônia. In summary, Mato Grosso exhibited a higher degree of established and longstanding NF loss, while Rondônia, Roraima, and Amapá showed an escalating contribution and growing relative values for NF losses.

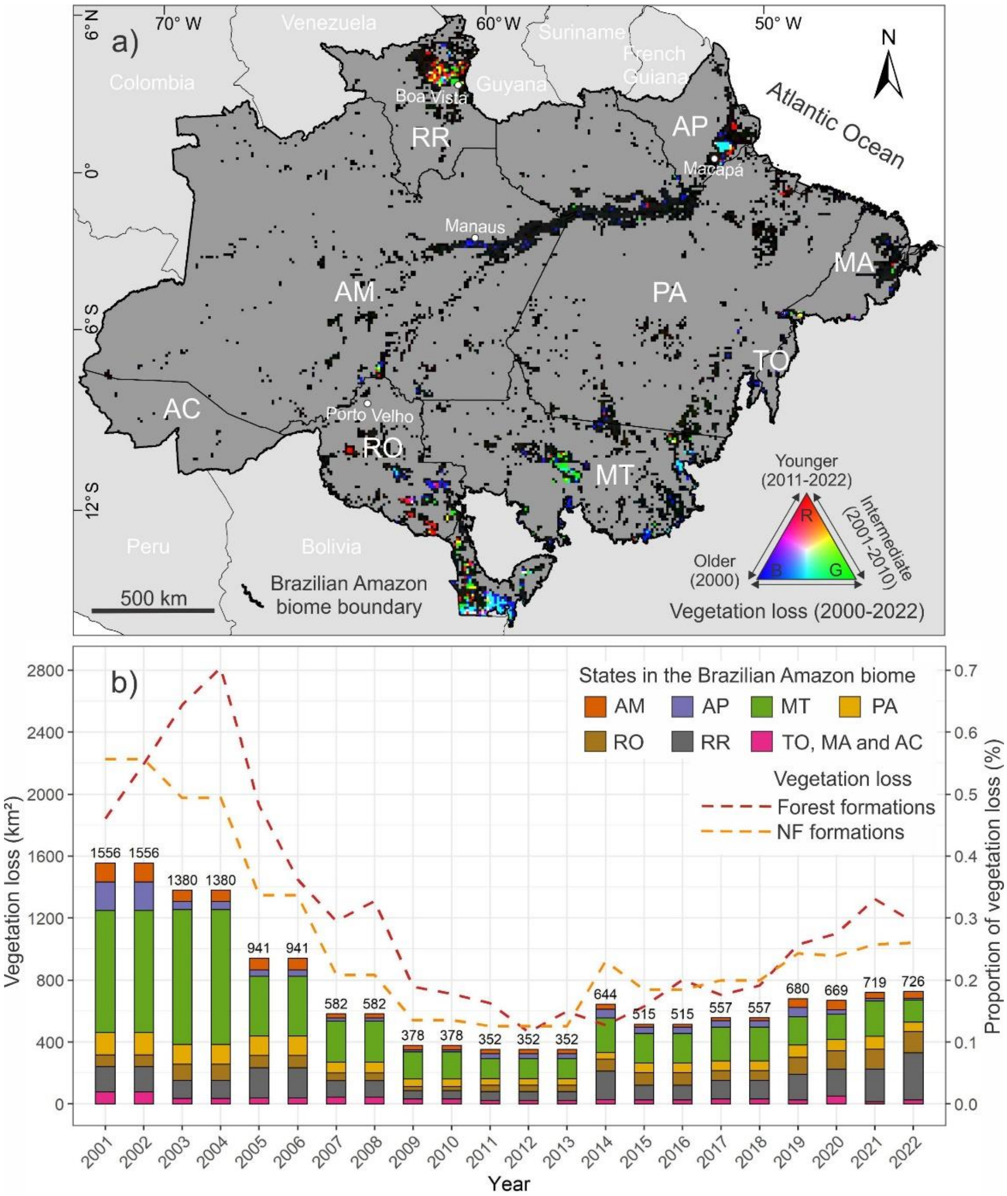

Fig. 1. Spatiotemporal distribution of vegetation loss (NF) in the Brazilian Amazon biome. a) RGB color composite of vegetation loss through time. Primary colors in the RGB system represent older (blue), intermediate (green), and younger loss (red). The secondary colors (cyan, yellow, and magenta) represent continuous loss among the analyzed period. b) Primary y-axis showing annual increments (km²) of vegetation loss. The flatlining effect on NF data is because the data are not available annually. Secondary y-axis showing the percentage of vegetation loss (NF and forest formations) relative to the area of the Brazilian Amazon biome (NF formations) and Brazilian Legal Amazon (forest formations). Historical vegetation loss data simplified from PRODES monitoring program[17].

The state of Mato Grosso had the highest absolute lost area (14,469.20 km²), the second in relative terms (32.1%) (Fig. S2). The State ranks second in area deforested in the Brazilian Amazon[17] and holds the highest cultivated area (75.91% of total) and largest cattle herd in the country (35.68%)[18]. Concentration of land in large properties contributes to mechanized deforestation, along with the expansion of mechanized agriculture[19,20]. The transition region with the Pantanal and Cerrado savannas is highly affected by agricultural expansion in the Amazon[21-23], appearing among the top three hotspots of NF loss (Fig. 1a and Fig. S1). Fig. 1a shows that NF loss in transition areas between biomes is older (up to 2000), with large hotspots appearing in the early 2000s in the central region of Mato Grosso, following the advance of the east-to-west agricultural frontier and the increasing conversion of pastures to soybean fields[20,24].

The states of Roraima and Amapá have been considered the last agricultural frontiers in the Amazon[25,26]. In both States, the influx of capital and technology found in old frontier areas are among the main the causes of NF loss[19]. The expansion of agricultural production was facilitated by various factors, such as highways, technological innovations in seeds, low land prices, and proximity to the capital[7,27,28]. State governments have been playing an important role in attracting farmers from other states to the *lavrado* savannas through economic subsidies and flexibility in state environmental legislation[27-29].

Roraima ranks third in total NF loss, with 3,527.70 km² (Fig. 1b). It hosts the Amazon biome's largest continuous savanna area (~43,000 km²)[28]. NF loss notably intensified from 2001 to 2022, resulting in significant cleared areas. Soybean cultivation saw exponential growth (191% in four years), driven by locally adapted seeds[30]. Roraima's savanna floodplains also favor rice cultivation[31]. This, along with silviculture expansion, regional road projects, and port infrastructure improvements, heightens the risk of savanna loss[5,7,27,29]. In 2014, the region around the state capital, Boa Vista, witnessed a significant fourfold increase in agriculture and other land uses, including forestry and urban development. Urban growth reached 22%[27].

While Amapá initially experienced limited forest and NF loss due to its lack of road connections with other states[5], upcoming projects like the asphalt paving of BR-210 between Boa Vista and Macapá and the establishment of a port at the Amazon River's mouth may heighten pressure on its savannas[5,9]. Compounding this risk is the fact that only 9.2% of the State's savannas are protected, with just 0.3% falling under strict conservation units[32]. In contrast, 72% of the State's primarily forested lands are protected.

The protection gap between savannas and forests implies that land clearing leakage[33,34] into the savannas might be the reason behind the significantly larger area lost (7.3%) compared to deforestation (2.8%)[17], making Amapá the only state with this discrepancy.

Despite not having extensive, continuous areas of NF loss, Rondônia ranks as the third state with the highest relative losses (11.4%). This has resulted in a loss of 2,656.70 km², making it the fourth-largest state in terms of area (Fig. S2a). Over the past decade, there has been a consistent increase in the proportion of NF loss (Fig. S2b). While small hotspots were observed as early as 2000, new focal points have emerged in the last decade (Fig. 1a and Fig. S1). These recent changes may be attributed primarily to the conversion of land to pasture, with a growing portion being allocated for soybean production[11,35,36]. The central region has older conversion areas, aligning with significant deforestation rates experienced in the 1990s, especially near the BR-364 highway[35,37]. It's important to note that most NF areas in Rondônia are located within protected areas and are sparingly distributed across the landscape[38]. This fragmented distribution could explain the presence of isolated hotspots of NF loss (Fig. S1) and the relatively modest ~10% loss in a state that has already experienced a substantial 46.4% reduction in its forest cover[39].

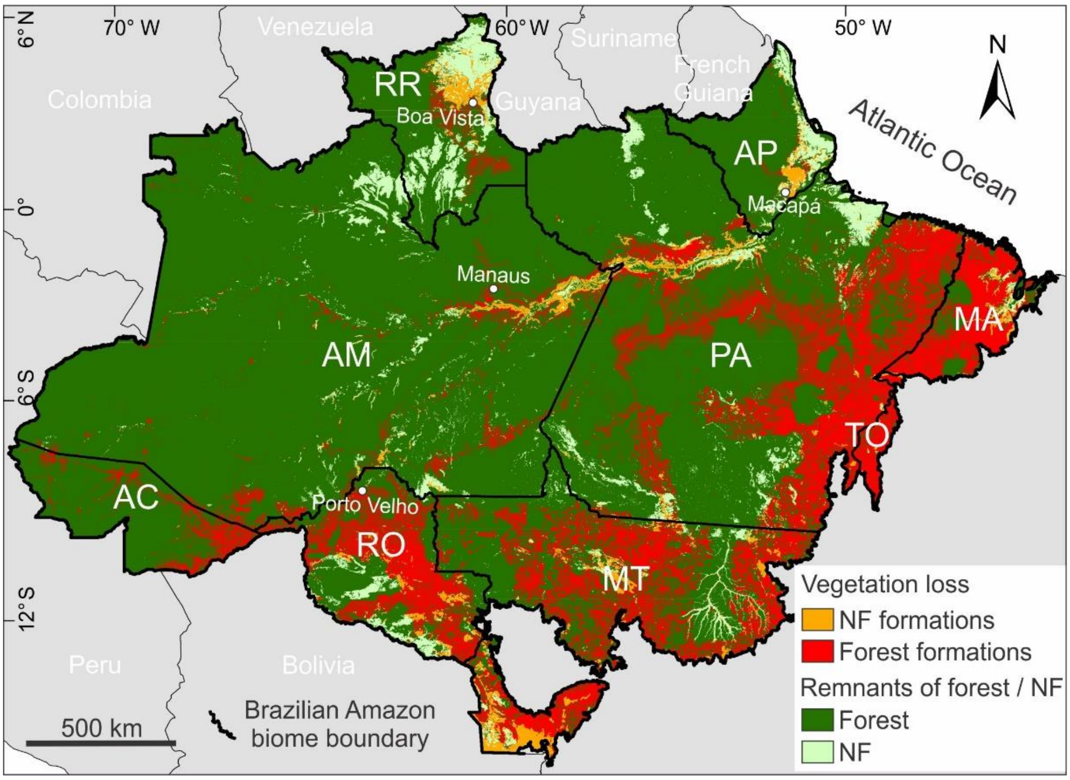

Fig. 2. Geographical distribution of vegetation loss (NF and forest formations) in the Brazilian Amazon biome, with the location of remaining areas of natural NF / forest. NF data are from 2000 to 2022. Vegetation loss data in forest formations are simplified from

the PRODES monitoring program based on the cumulative mask until 2007 and from 2008 to 2022 (http://terrabrasilis.dpi.inpe.br/downloads/).

Temporal trend of NF loss

Examining yearly NF loss spanning from 2001 to 2022 (Fig. 1b) unveils three distinctive: (1) between 2001 and 2008, losses exhibited a noteworthy decline, ranging from 1,555.60 to 581.50 km²; (2) between 2009 and 2013, NF loss was relatively stable, not surpassing 400 km² per year; (3) from 2014 to 2022, yearly NF loss increased, oscillating between 515.00 and 726.50 km². Notably, the highest losses were recorded in 2001-2002 (1,555.60 km²), whereas the lowest values occurred during 2011-2014 (351.90 km²; Fig. 1b). Proportionally to their extents, deforestation (here used only to discriminate forest loss mapped by PRODES Amazonia) almost always showed higher values than that of NF loss during 2003-2013, with an inverted behavior during 2014-2022. In 2014, NF relative loss was almost twice as high as the deforestation (~0.23% and 0.13%, respectively; Fig. 1b). Nonetheless, the relative differences between deforestation and NF loss yielded no significant statistical differences (Student t-test: $t = 0.768$; $df = 40.511$; $p = 0.4464$), while both processes exhibited a robust positive correlation (Spearman's rank correlation: $r = 0.87$; $p < 0.0001$) (Fig. 1b), suggesting that the extent of vegetation loss in forested and non-forested areas did not differ in relative terms and show a continuum at the biome scale.

The strong correlation between deforestation and NF loss suggests a shared response to common factors. The observed decline in deforestation in the Brazilian Amazon, particularly after 2004 (Fig. 1b), can be largely attributed to environmental policies implemented by the Brazilian government in response to high deforestation rates in the Brazilian Amazon. These policies, including: the Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAM); the Amazon Protected Areas Program (ARPA); the prioritization of Amazonian municipalities for preventing, monitoring, and controlling illegal deforestation; the Cattle Agreement; and the soy moratorium, have played a significant role in reducing deforestation rates in the region[24,40-45]. However, it remains unclear to what extent NF loss during the same period responded to these policies, as they were specifically designed and enforced for forested areas only. On the other hand, it is conceivable that the decline in commodity prices during this period, which has been shown to reduce new land clearings in the Amazon[46], could have played a role in the observed decline in NF loss.

In line with the Amazon's deforestation trend, NF loss increased from 2013 onward (Fig. 1b). From 2013 to 2022, both NF loss and deforestation exhibited a rate of 0.21 $km^2.y^{-1}$ (relative to their vegetation extents). Several factors contributed to this rise, including the growing value of soybeans, which led to the conversion of pasture areas in states like Mato Grosso with better logistical infrastructure for soybean production, and the shift of pastures towards the active deforestation frontier[24,47]. Additionally, the increase in the global demand for meat resulted in the expansion of the cattle herd in the Amazon[18]. The discussed environmental policies were identified as drivers of deforestation leakage[33,34] over NF formations by different studies[5,9,22,28,48,49]. Similar events were observed in the biome towards the neighbor Cerrado[22,50,51].

Political decisions have played a significant role in driving natural vegetation loss escalation. Changes to the Forest Code in 2012, including amnesty for pre-2008 deforestation, and other bills aimed at easing environmental licensing, likely incentivized deforestation in anticipation of further legislative changes due to political pressure from the ruralist caucus in the National Congress[52-54]. The political influence on deforestation intensified in the Amazon during the period of 2018-2021, likely influenced by the incentives and discourse by then-president Jair Bolsonaro, coupled with the weakening of command-and-control measures for deforestation in the Brazilian Amazon under his government. Consequently, there was a rapid surge in deforestation and conversion, human-induced fires, and illegal mining activities in various Brazilian biomes, well documented elsewhere[53,55-58]. In addition, NF formations, even in the Amazon Biome, have less protection under the Brazilian Forest Code. A key limitation lies in the lack of differentiation among the various Amazonian phytophysiognomies, which instead results in their protection being generalized across the entire Brazilian Legal Amazon region. For instance, while private properties are required by law to preserve 80% of forest ecosystems in the biome, open ecosystems are less protected, ranging from 35% in *cerrado* areas to 20% in “general” grasslands[59].

Losses by phytophysiognomies

Cross-referencing spatial data on suppression with the official map of Brazilian vegetation coverage[60] allowed us to estimate the losses related to different NF phytophysiognomies (Table 1). The ecotones (see Fig. S3 for phytophysiognomies distribution) had the largest suppressed area (12,388.40 km²). They correspond to mixtures of different vegetation types (e.g., contact of savanna-ombrophilous forest, ombrophilous forest-deciduous forest; see Table S2), where their separation is limited through image interpretation[4,6]. The loss of forest formation within NF areas was significant. During the analyzed period (2000-2022), 5,732.92 km² were cleared, and when considering ecotone areas (Table S2) with other NF formations, this number rises to 17,619.43 km², an average of 590.44 km² (±619.94 km²) lost annually. By normalizing forest loss within the NF mask by its respective area and applying the same approach to deforestation within the PRODES Amazonia mask[17] from 2001 to 2022, both processes displayed a loss rate of 0.04 $km^2.year^{-1}$ per km² of forest. This value signifies an ongoing pattern of vegetation loss extending across forested and NF areas, indicating a consistent continuum of loss.

Table 1. Phytophysiognomies suppression in the Brazilian Amazon inside the non-forest mask. See Table S2 for details regarding the ecotones. Differences in the mapping scales of vegetation and suppression data account for variations in the total suppression values found in this analysis.

NF phytophysiognomies	Total area (km²)	NF Mask (%)	Lost area (km²)	Lost area (%)	Lost area inside NF mask (%)
Ecotones (see table S2)	58,022.82	20.77	12,388.40	21.35	42.28
Savanna	77,428.90	27.72	10,246.55	13.23	34.97
Dense Ombrophilous Forest	44,358.87	15.88	2,987.14	6.73	10.19
Evergreen Seasonal Forest	4,838.88	1.73	1,238.30	25.59	4.23
Open Ombrophilous Forest	10,561.81	3.78	1,193.76	11.30	4.07
Pioneer formations	31,474.98	11.27	546.51	1.74	1.87
Semi-deciduous Seasonal Forest	2,351.38	0.84	309.63	13.17	1.06
Campinarana (white-sand vegetation)	37,040.58	13.26	171.73	0.46	0.59
Savanna-steppe	7,059.11	2.53	6.96	0.10	0.02
Deciduous Seasonal Forest	1,824.67	0.65	4.09	0.22	0.01

Savannas

Savannas, which represent approximately 30% - the largest proportion - of the NF mask, experienced the largest losses (excluding ecotones; Table 1). In the Amazon, these formations are more susceptible to clearing compared to dense forested areas[27]. Considering the combined area of savannas and savanna-steppe, the loss amounted to 10,253.51 km², accounting for approximately 35% of the NF losses and 13.3% of their total extent within the NF mask. If the contact areas of savannas with other formations (ecotones; Table S2) are also included, losses would reach 21,550.58 km². The three main hotspots of NF loss are located precisely within this ecosystem, specifically in the states of Mato Grosso, Roraima, and Amapá (Fig. 1a and Fig. S1).

The main factor driving losses in these states has been linked to the expansion of soybean cultivation, as discussed above. Even when not suppressed, the savannas may be affected by fire and grazing[27,61]. The threats primarily arise from neglect and biases towards these ecosystems, often seen as successional stages of forests with low biodiversity and ecological significance[62-64]. However, the Amazonian savannas are old formations[65] and constitute vegetation islands (Fig. S3) with distinct characteristics from the neighbor Brazilian Cerrado[7,66]. In the states of Roraima and Amapá, the savannas show a great heterogeneity and embraces different phytophysiognomies (e.g., the *lavrados*) with a biodiversity that is still poorly understood and home to endemic species that are threatened in extinction due to limited protection within conservation units[5,7,28,67]. Some studies have highlighted their conservation importance due to their richness, rarity, and endemic species, as well as species adapted to these ecosystems[5,9], low protection (~12% within strictly protected areas[9]), and limited research on their ecology and biodiversity[5,7,32].

Pioneer formations

Pioneer formations within the NF mask have experienced a 1.75% reduction in their extent. These formations consist of pioneering vegetation elements such as grasses, bryophytes, therophytes, cryptophytes, among others, which undergo a continuous succession due to the seasonal instability of the inundated terrain, occurring predominantly in lacustrine and alluvial soils[4]. They constitute a significant portion of the vegetation in the floodplains along the major Amazonian rivers (Fig. S3). These floodplains are periodically inundated and have historically been inhabited by local riverine populations who have relied on the fertile soils for agriculture, extractive activities, and fishing[68,69]. Deforestation in these areas is primarily driven by agriculture and livestock[70]. The floodplains of the Solimões/Amazonas River have experienced moderate NF loss, with higher intensity during the first period (Fig. 1a and Fig. S1), particularly concentrated around the city of Manaus and in the Lower Amazon region between the states of Amazonas and Pará. The central section of the Amazon River channel (ranging from 56°W to 55°W) has been recognized as one of the regions most affected by vegetation loss, encompassing both recent and historical losses, even though certain areas might still maintain up to 70% of their forest cove[70,71].

Campinaranas (white-sand vegetation)

The campinaranas, also known as white-sand ecosystems, and the savanna-steppes were the least affected by NF loss (0.46% and 0.10%, respectively; Table 1). While the latter has the smallest total area within the NF mask among the open phytophysiognomies, the campinaranas rank second in area, behind only the savannas. They encompass a gradient of grassland to forest formations, showing a broad geographic distribution (Fig. S3), and occur as predominant formations in large patches of hundreds of square kilometers in the Negro River basin (ottobasin, level 2) and in border regions with Colombia, as well as exhibiting an island-like distribution pattern throughout the Amazon embedded in other habitats[4,6,10]. Their greater geographical distribution in the northwest of the basin, a region with the lowest anthropogenic pressure in the Brazilian Amazon[72,73], may explain the low levels of losses in this formation. Furthermore, the nutrient-poor, acidic, and water-limited sandy soils[6,10,74] may limit their suitability for agricultural use.

The white-sand ecosystems have lower species richness and diversity of fauna and flora compared to adjacent upland forests, but these are adapted to specific soil conditions and include endemic species[75-79], making them of utmost biological importance and strategically significant for conservation[6,10]. However, like other NF ecosystems in the Amazon, knowledge of biodiversity and even the functioning of these ecosystems are still limited, especially in those island-like areas with patches smaller than 1 km² and immersed within forested areas, which are difficult to map using satellite imagery[6]. Due to the nature of their soils, they are fragile systems and highly sensitive to anthropogenic disturbances[80], and their low protection (< 1 km² within conservation units)[6] makes them extremely vulnerable. Although of low agricultural interest, sand extraction poses a significant threat of white-sand ecosystems in the state of Pará[81].

Final remarks

The strong correlation we identified between NF loss and deforestation (Fig. 1b) suggests a shared response to prevalent factors that contribute to the Amazonian vegetation loss. Conversion to agriculture and pasture has long been recognized as the primary driver of forest loss in the Brazilian Amazon[82] and, as showed here, it is also believed to be the main cause of NF loss, although further investigation is needed. The development of road and port infrastructure in states like Roraima and Amapá, as discussed above, has facilitated the expansion of agricultural lands, reminiscent of past frontiers in the Amazon[83,84]. These states have become emerging agricultural frontiers, driven by the cultivation of crops adapted to the region's soil and climate conditions. Additionally, public policies such as the beef agreement and soy moratorium, which only restrict forest clearing, may have inadvertently led to the encroachment of cattle and soy production into NF ecosystems that were not previously monitored by the PRODES system[5,9,22,28,48,49].

The limited protection of Amazon NF phytophysiognomies is one of the common factors observed in different states where large areas of NF have been lost, accentuated by the low protection in the Brazilian Forest Code, as discussed before. Regarding Amazonian savannas, only 12.3% are within conservation units, reaching 58% if Indigenous Lands are considered[9]. However, a more detailed analysis of the representativeness of different types of NF within protected areas is still lacking, as the protection of each NF phytophysiognomies is uneven[29,32,62,63]. Additionally, political pressures and approval delays/denial of ecological-economic zoning plans have posed a frequent threat to these ecosystems, particularly in states where agricultural expansion is the main proposal for economic development[5,7,11,28].

The join analysis of PRODES Amazonia and PRODES NF has provided the first-ever official quantification of total vegetation loss in the Brazilian Amazon at the biome level. Taking into account the total NF loss (29,247.44 km²) and the total deforestation (768,930.88 km²)[17], overall, the Brazilian Amazon biome has experienced a total loss of 798,178.32 km², representing 18.93% of its original vegetation cover (Fig. 2). The lower proportional loss of NF compared to forests may reflect their island-like spatial distribution, mostly located outside the *deforestation arc* (Fig. S3) and lower agriculture suitability. However, the increasing trend of NF loss observed in the last decade, with rates following deforestation, and the growing threat from the expansion of agribusiness activities over NF formations, combined with inadequate protection and undervaluation, indicates a scenario of significant losses, especially for small island-like NF formations. A more detailed analysis currently underway for each vegetation type may provide further insights into the threats.

We emphasize the recommendations proposed by researchers who have examined the risk faced by NF formations[5,7,9,32,63]. Establishing protected areas, whether for sustainable use or integral protection, both of which have strong evidence of effectively safeguarding local biodiversity and reducing forest loss[85-87], represents a critical measure for strategically planning the conservation of these ecosystems. However, it will require an effort to map the heterogeneity within these ecosystems to effectively protect distinct phytogeographic units of these vegetation types. In this regard, the limited knowledge about the biodiversity and social importance of these vegetation types needs to be overcome to obtain minimal informed decisions regarding the protection and sustainable use of these ecosystems through the suitable, responsible, and participatory ecological-economic zoning.

As assigned by Overbeck et al.[63], savannah conservation often requires different strategies than that of forests (e.g., prescribed fire, grazing). Protecting and sustainably managing these ecosystems will require research to harness their contributions to biodiversity, ecosystem services, and existing uses as already occurring, for example, in the Pampa grasslands[88]. The implementation of monitoring programs, such as the ongoing DETER (Near Real-Time Deforestation Detection System)[3] in NF areas and the continuation of the annual deforestation mapping by PRODES NF are essential actions to enable greater control through enforcement agencies and responsible trade of agricultural products from legally cleared areas.

In this context, extending the soybean moratorium and cattle agreement, or implementing any sectoral or national mechanism with a robust monitoring and verification system to promote deforestation-free agricommodity supply chains, represents significant measures to curb the progression of NF loss[45]. The introduction of PRODES NF provides essential data (i) to allows the monitoring of socioenvironmental compliance of production sites and the use of traceability systems to achieve more sustainable production, and (ii) to plan effective actions to control and combat the conversion of natural vegetation in non-forest areas of the Amazon.

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Author contributions CGM, CAA, DES, LS, and LEM were involved in the coordination of the project and in the article development; VLC, FCA, LJS, and MR contributed to article development, data analysis, and figures; TCL, VR, DLCL, APB, DCMB, and DRVM served as auditors; CBQ to MBS comprised the team of interpretation experts; FCP and AC were responsible for project database maintenance; HX, MX acted as external consultants and participated in fieldwork; APM, LB, EBS, and LGF formed the external validation team for the results; MA analyzed the validation results, conducted a thorough review, and made substantial contributions to the writing of the article.

Data availability The annual NF loss data in the Brazilian Amazon biome for the period from 2000 to 2022 can be downloaded at http://terrabrasilis.dpi.inpe.br/downloads/.

Author Information Reprints and permissions information is available at www.nature.com/reprints and permissions. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to CGM (cassiano.messias@inpe.br) or CAA (claudio.almeida@inpe.br).

Additional Information Supplementary Information is available for this paper.

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Methods

We used a multi-sensor satellite imagery approach with digital image processing and visual image interpretation techniques to map NF vegetation loss within the Brazilian Amazon biome for the period from 2000 to 2022. Images from the Landsat series (MSS, TM, ETM+, OLI sensors) were used to create the baseline map for 2000 and track changes until 2014. From 2016 onwards, Sentinel-2A and 2B images (MSI sensor with a 20-10 m spatial resolution) were utilized due to their improved temporal resolution, allowing for images with less cloud coverage (see Table S2 for details). The number of images per year ranged from 182 to 210 for Landsat and from 546 to 885 for Sentinel (Table S2). Images from the sensor MSS (12 images) were used as auxiliaries to better identify changes in the floodplains of the Amazon and Solimões rivers for the 2000 base map.

The images were processed using scripts in the Google Earth Engine (GEE) cloud computing platform[89]. Selection filters were applied to obtain cloud-free or minimally cloud-covered images. PRODES methodology established an optimal mapping period for each Landsat orbit/point during the dry season, taking into account the region's extensive longitudinal and latitudinal range[1]. Areas with persistent cloud cover were classified as unobserved. Additional preprocessing steps included resampling the red spectral band of Sentinel-2 from 10 m to 20 m resolution for compatibility with other bands, creating mosaics of Sentinel-2 images based on the Landsat grids, and enhancing image contrast through histogram manipulation.

NF loss mapping

NF loss was mapped using the incremental approach in which NF loss of a given year is mapped using a cumulative or exclusion mask of NF loss from previous years, similar to the PRODES approach[1]. This procedure ensures that only newly cleared areas are mapped each year, preventing duplicate mapping of the same area. The year of 2000 was defined as the basemap to create the mask of NF loss. The inclusion of older satellite images (1980s and 1990s) from the Landsat MSS and TM sensors was necessary to create this mask.

Mapping of NF loss occurred biennially from 2000 to 2018 and annually starting in 2019, based on the availability of human resources and higher temporal resolution satellite images. The sole exception was in 2012, when mapping for 2013 took place instead. This deviation was due to the failure of the Landsat-5/TM sensor in November 2011, which disrupted the continuous monitoring of the Earth's surface. Monitoring only resumed in February 2013 with the launch of Landsat-8. For the two-year interval (biennium), we distributed half of the total increment evenly to each year as an approximation for the NF loss amounts in the unmapped year.

NF vegetation was mapped by visual image interpretation techniques using specific elements and interpretation keys to better distinguish between preserved and suppressed vegetation patches. The elements color, shade, texture, shape, and context were used for this purpose. Together with PRODES NF team of interpreters, experts with knowledge in Amazonian NF vegetation also helped to define standard visual interpretation keys (Table S1). NF mapping was performed in the TerraAmazon software[90] at maximum (1:125,000) and minimum (1:75,000) scales based on a same false color composite: shortwave infrared (R), near infrared or near infrared narrow (G) and red (B). For the mapping of NF loss in the floodplains of some large Amazonian rivers, a mask of water bodies was used to avoid mapping of anthropogenic land use on riverbanks and seasonally dry lakes.

Post-processing and audit of NF data

The NF data underwent post-mapping operations to ensure data quality. An independent audit team was established to check and correct any eventual errors (e.g., omission, commission and topology) of NF polygons, using freely available high resolution satellite images when necessary. A spatial filter was applied to remove polygons smaller than one hectare (1 ha), which was the minimum area mapped in this study.

Accuracy assessment

PRODES NF accuracy assessment was implemented using a stratified random sampling by class[91,92]. We sampled 2,100 points (Table S4) and its validation was carried out on the Temporal Visual Inspection (TVI) platform, an open-source tool that simplifies the visualization of points in Landsat images for long time series and allows to perform analyzes quickly, practically and with simultaneous supervision[93]. A time series from 2000 to 2022 was used, with an image in false color composition (RGB / NIR, SWIR, RED) and the mosaic in the composition (RGB / SWIR, NIR, RED). The overall map accuracy was 0.96 and the natural class have 0.99 of user's and producer's accuracy (Tables S4, S5, S6).

Spatiotemporal analysis of NF data

We synthetized the spatiotemporal distribution of NF data in the Brazilian Amazon through maps and graphs, depicting annual state-wise increments and percentages of NF loss as well as the remaining natural NF vegetation. NF maps included the percentage of NF loss for two periods, until 2000 and between 2001 and 2022, based on grids of 10 x 10 km according to previous tests. This strategy was used in order to better represent the spatial distribution of NF loss data in the study area. The grid approach was also derived for three periods (up to 2000, 2002-2010 and 2013-2022) aiming to produce a RGB color composite showing the temporal dynamics of NF loss. The cumulative NF data through time was also compared to deforestation in the Brazilian Amazon. Deforestation data was downloaded from the PRODES digital collections[17].

Phytophysiognomy loss was assessed by overlaying NF loss polygons with official Brazilian vegetation mapping data at a 1:250,000 scale[60]. The calculation presented in Table 1 utilized the Legend_1 attribute from the vegetation data, while the aggregated information of the ecotone features (described in the nm_contat legend) was included in Table S3.

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