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Assessment of deforestation and fire in groups of protected areas of the Amazon

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Abstract - The creation of protected areas was conceived as a global strategy of protecting natural habitats against anthropogenic interventions . This work aimed to evaluate deforestation and fires in protected areas of the Amazon. The groups were: indigenous territories, fully protected conservation units, public sustainable use conservation units, public/private sustainable use conservation units , and non-protected areas. For each group, deforestation and fire density was determined annually in the 2000-2017 period. The most efficient groups to contain deforestation were fully protected conservation units and indigenous territories. The sustainable use conservation units - public/private domain group was ineffective in containing deforestation. Regarding fires, the fully protected conservation units' group was the most efficient in their containment. The only group that was not effective in containing fire was public/private sustainable use conservation units . The correlation between deforestation and fires was low for protected areas, indicating that fire is mainly related to agropastoral management. In order to more efficiently contain deforestation and fires in Amazon, the creation of fully protected conservation units should be prioritized. Alternatively, more indigenous territories and public sustainable use conservation units could be created; although less effective in containing deforestation and fires, they are nevertheless important for preserving Amazonian sociodiversity.

Keywords: Conservation units. Indigenous territories. Environmental preservation. Tropical forest. Geoprocessing.

Avaliação do desflorestamento e das queimadas em grupos de áreas protegidas da Amazônia

Resumo - Uma estratégia global de proteção dos habitats naturais é a criação de áreas protegidas. Este trabalho objetivou avaliar desflorestamento e queimadas em grupos de áreas protegidas da

Amazônia: terras indígenas, unidades de conservação de proteção integral, unidades de conservação de uso sustentável - domínio público, unidades de conservação de uso sustentável - domínio público/privado, e área não protegida. Para cada grupo foi determinado o desflorestamento e a densidade de queimada, anualmente no período 2000-2017. As unidades de conservação de proteção integral e as terras indígenas foram mais eficientes na contenção do desflorestamento, enquanto as unidades de conservação de uso sustentável - domínio público/privado apresentaram pouca eficácia. Com relação às queimadas, as unidades de conservação de proteção integral foram mais eficientes na contenção. As unidades de conservação de uso sustentável - domínio público/privado foram ineficazes. A correlação entre desflorestamento e queimadas foi baixa para as áreas protegidas, indicando que o fogo está relacionado ao manejo agropastoril. Para conter o desflorestamento e as queimadas na Amazônia, deve-se priorizar a criação de unidades de conservação de proteção integral. As terras indígenas e as unidades de conservação de uso sustentável de domínio público podem ser usadas, pois, ainda que menos eficazes, elas são importantes para preservar a sociodiversidade amazônica.

Palavras-chave: Unidades de conservação. Terras indígenas. Preservação ambiental. Floresta tropical. Geoprocessamento.

Evaluación de deforestación y quema en grupos de áreas protegidas en la Amazonía

Resumen - Una estrategia global para la protección de los hábitats naturales es la creación de áreas protegidas. Este estudio tuvo como objetivo evaluar la deforestación y quema en grupos de áreas protegidas en la Amazonía: tierras indígenas, unidades de conservación de protección integral, unidades de conservación de uso sostenible - dominio público, unidades de conservación de uso sostenible - dominio público/privado, y área no protegida. La deforestación y la densidad de quema se determinaron para cada grupo anualmente en el período 2000-2017. Las unidades de conservación de protección integral y las tierras indígenas fueron más eficientes para frenar la deforestación, mientras que las unidades de conservación de uso sostenible (dominios públicos/privados) mostraron poca efectividad. Con respecto a la quema, las unidades de conservación de protección integral fueron más eficientes para contenerlas. Unidades de conservación de uso sostenible - dominio público/privado fueron ineficaces. La correlación entre la deforestación y la quema fue baja para las áreas protegidas, lo que indica que el fuego está relacionado con el manejo agropastoral. Para frenar la deforestación y las quemas en la Amazonía, se debe dar prioridad a la creación de unidades de conservación de protección integral. Las tierras indígenas y las unidades de conservación de uso sostenible de dominio público se pueden utilizar porque, aunque son menos efectivas, son importantes para preservar la sociodiversidad de la Amazonía.

Palabras clave: Unidades de conservación. Tierras indígenas. Preservación del medio ambiente. Bosque tropical. Geoprocesamiento.

Introduction

The tropical forests are essential for maintaining biodiversity (Giam 2017; Symes et al. 2018), regulation of the hydrological cycle and regional climate (Fearnside 2005; Foley et al. 2007; Nobre et al. 2016), and storage of terrestrial carbon (Fearnside 1996; Nogueira et al. 2015). Approximately 60% of the world's remaining tropical forests are located in the Amazon basin (Laurance et al. 2002), 40% in Brazilian territory (Laurance, Albernaz and Costa 2001), which represents the largest continuous area of this type of forest on the planet (Skole and Tucker 1993; Foley et al. 2007).

However, in 20th century deforestation increased in the tropical domain, especially in developing countries (FAO 2016). Tropical forest loss is mainly related to logging and the expansion of areas occupied by agricultural activities and human settlements (Chakravarty et al. 2012; Giam 2017; Doršner 2018; Pereira and Ferreira 2020). At Brazilian Amazon, cattle ranches are the main responsible for deforestation (Margulis 2004; Rivero et al. 2009; FAO 2016). According to Nobre et al. (2016), Amazon rainforest lost almost 20% of its original cover from 1970 to 2015. In the Legal Amazon, Pereira and Ferreira (2020) verified a total deforestation of 20% in 2017.

Deforestation in the Brazilian Amazon, starting out in the 1970s, occurred preferentially along of the highways opened by the federal government in the 1960s and 1970s (Belém - Brasília, Cuiabá - Porto Velho - Rio Branco, Tranzamazônica and Cuiabá - Santarém) (Alves 2001; Prates and Bacha 2011). Practically 90% of deforestation in the 1991-1997 period occurred in areas up to 100 km from the main roads, with the states of Maranhão, Mato Grosso, Rondônia and Pará (east region) responsible for 80% of the total (Alves 2002).

The concentration of deforestation in east, southeast, south and southwest margins of the Amazon region, following the axes of occupation, such as roads (Skole and Tuker 1993; Alves 2002) originated the expression "Arc of Deforestation" (Margulis 2004; Fearnside 2005; Braz et al. 2016; Sathler, Adamo and Lima 2018; Pereira and Ferreira 2020). Studies have also shown a great spatial dependence on deforestation, which occurs predominantly in the vicinity of already deforested areas (Alves 2002; Margulis 2004; Pereira and Ferreira 2020).

To survey the Amazon rainforest loss, National Institute for Space Research (INPE) created the Project for Monitoring Deforestation of Brazilian Amazon Forest by Satellite (PRODES), which since 1988 has produced annual deforestation rates of the Legal Amazon. As a result of all government support in the 1970s and 1980s and market dynamics after 1990 (Becker 2005; Prates and Bacha 2011), deforestation in the Legal Amazon increased from just over 97,600 km² in the early 1970s (INPE 1992) to 788,030 km² in 2017 (INPE 2018b).

Although deforestation is the worst anthropic effect on forests, including edge effect due fragmentation (Skole and Tuker 1993), other human actions that reduce tree cover, such as predatory logging (without management plan) and forest fire, have severe effects on the environmental services provided by forests (Nepstad et al. 1999; Foley et al. 2007; Chakravarty et al. 2012; Alencar et al. 2015; Brandão et al. 2022). Addicionally, according Alencar et al. (2015), the regime of fires in Amazon is influenced by deforestation because the accumulation of ignition sources and forest fragmentation (increasing in forest edges). During predatory exploitation, timber companies in the Amazon region kill or damage 10-40% of the forest live biomass. As a consequence, there is a 14-50% reduction in the canopy cover, which dries out the debris generated by the exploitation, increasing forest flammability (Nepstad et al. 1999).

The burnings are traditionally used in the Amazon region and other tropical regions as an agropastoral management practice (Sá et al. 2007; Piromal et al. 2008; Chakravarty et al. 2012; Alencar et al. 2015; Sales et al. 2019). However, the fire causes serious environmental impacts such as loss of biodiversity and soil impoverishment, in addition to great damage to private properties (Piromal et al. 2008). Fire records in the Amazon region are mainly related with agriculture on a family scale (slash-and-burn agriculture) and burning of pastures infested with invasive plants with the intention of renewing those (Sá et al. 2007).

The fire is also utilized to eliminate the remains of plant materials (trunks, branches, exposed roots and leaves) resulting from the clearing of the primary forest for commercial agriculture implantation (Piromal et al. 2008; Adeney, Christensen Jr and Pimm 2009; Chakravarty et al. 2012; Alencar et al. 2015; Fonseca-Morello et al. 2017; Sales et al. 2019). Nonetheless, the burning can become out of control and reach an adjacent forest, causing forest fire, which in addition to the emission of greenhouse gases (Fearnside 1996; Piromal et al. 2008; Chakravarty et al. 2012), cause death 10-80% of living biomass and increases the vulnerability of these forests to new fire (Nepstad et al. 1999).

INPE's Burnings Program monitors burnings and fire, as well as fire risk, using satellite images. The Burnings Program generates fire records for South and Central America, Africa and Europe, every day since June 1998 (INPE 2019). The fire records are obtained from the hot pixels, indicative of possible active fire, detected using the thermal bands of the sensors AVHRR (NOAA satellites) and MODIS (TERRA and AQUA satellites) (Piromal et al. 2008). The field validation indicated that, for the reference satellites (NOAA and AQUA), a fire front with at least thirty meters in length and one meter in width, will generate a fire record (INPE 2019).

Deforestation peak occurs in May, three months after rainy season peak, while that of the fire (hot pixels) coincides with the months of lower precipitation, August and September (Aragão et al. 2008). In 2004, pressured by an increase in deforestation rate, the Brazilian government initiated the Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAM). PPCDAM played an important role in reducing the deforestation rate from 20,000 km² (1996-2005 period) to 6,400 km², the average value of 2014-2016 (MMA 2018).

The main strategy for natural habitat protection against anthropogenic interventions (deforestation and fire) has been the creation of protected areas, since conversions from original vegetation formations to human activities have been considerably lower in their interior than in the adjacent unprotected areas (Bruner et al. 2001; Ferreira, Venticinque and Almeida 2005; Nepstad et al. 2006; Adeney et al. 2009; Leverington et al. 2010; Gaveau et al. 2012; Nolte et al. 2013; Françoso et al. 2015; Melillo et al. 2015; Braz et al. 2016; Geldmann et al. 2019; Herrera et al. 2019). In definition, protected area is a geographic space whose objective is the conservation of nature over the long term, as well as of ecosystem services and associated cultural values (Day et al. 2012).

In 2019, the protected areas covered about 17% (1/6) of the planet's land surface (Herreraet al. 2019). Protected areas are essential for biodiversity conservation (Bruner et al. 2001; Nepstad et al. 2006; Fearnside 2008; Adeney et al. 2009; Leverington et al. 2010; Nolte et al. 2013; Geldmann et al. 2019), they play a key role in mitigating greenhouse gas emissions and maintaining environmental services (Fearnside 2006, 2008; Foley et al. 2007; Nolte et al. 2013; Melillo et al. 2015) and they are still important for the conservation of sociocultural diversity (Fearnside 2006).

The National System of Nature Conservation Units (SNUC), established in 2000, defined criteria and norms for creation, implementation and management of Brazilian conservation units (Brasil

2000). Defined in line with the categories proposed by the International Union for the Conservation of Nature - IUCN (Dudley 2008), conservation units (CUs) that makes up the SNUC are organized into two categories with different objectives: Fully Protected (FPCU) aims to preserve nature and only admitted indirect use of natural resources; Sustainable Use (SUCU) that seeks to make nature conservation compatible with the sustainable use of part of natural resources (Brasil 2000).

FPCUs can be subdivided into two groups with respect to land ownership: categories composed exclusively of the public lands - Ecological Station, Biological Reserve and National/State Park; and categories where private lands are allowed - Natural Monument and Wildlife Refuge. SUCUs can also be subdivided in relation to land ownership: only public land - Extractive Reserve, Sustainable Development Reserve, National/State Forest and Fauna Reserve; and composed of public and/or private lands - Environmental Protection Area, Area of Relevant Ecological Interest and Private Reserve of Natural Heritage (Brasil 2000).

The Brazilian government, convinced that protected areas are important for the conservation of biological and sociocultural diversity, maintenance of environmental services and sustainable use of natural resources, created in 2006 the National Strategic Plan for Protected Areas - PNAP, which, besides the CUs, also included indigenous territories (ITs) (MMA 2006; Veríssimo et al. 2011). The inclusion of the ITs in the PNAP was due to the recognition that, in addition to the importance for the survival of indigenous peoples, they also contribute to biodiversity conservation and environmental services maintenance, commitments assumed by National Policy for Territorial and Environmental Management of Indigenous Territories - PNGATI (Bavaresco and Menezes 2014).

After overlappings remotion, Pereira and Ferreira (2021) constated that 45.2% of the Legal Amazon territory was inside of some type of protected area: 22.9% in indigenous territory and 22.2% in conservation unities (7.7% in fully protected and 14.5% in sustainable use categories).

Since the protected areas (CUs and ITs) at the Amazon forest are essential for the conservation of biodiversity and sociodiversity, carbon storage and for regulation of the hydrological regime, the assessment of human action on them becomes primordial. Therefore, this study aimed to evaluate deforestation and fire, and the correlation between both, in protected area groups of the Legal Amazon, from 2000 to 2017, so as to verify if there is different behavior of the groups to these threats.

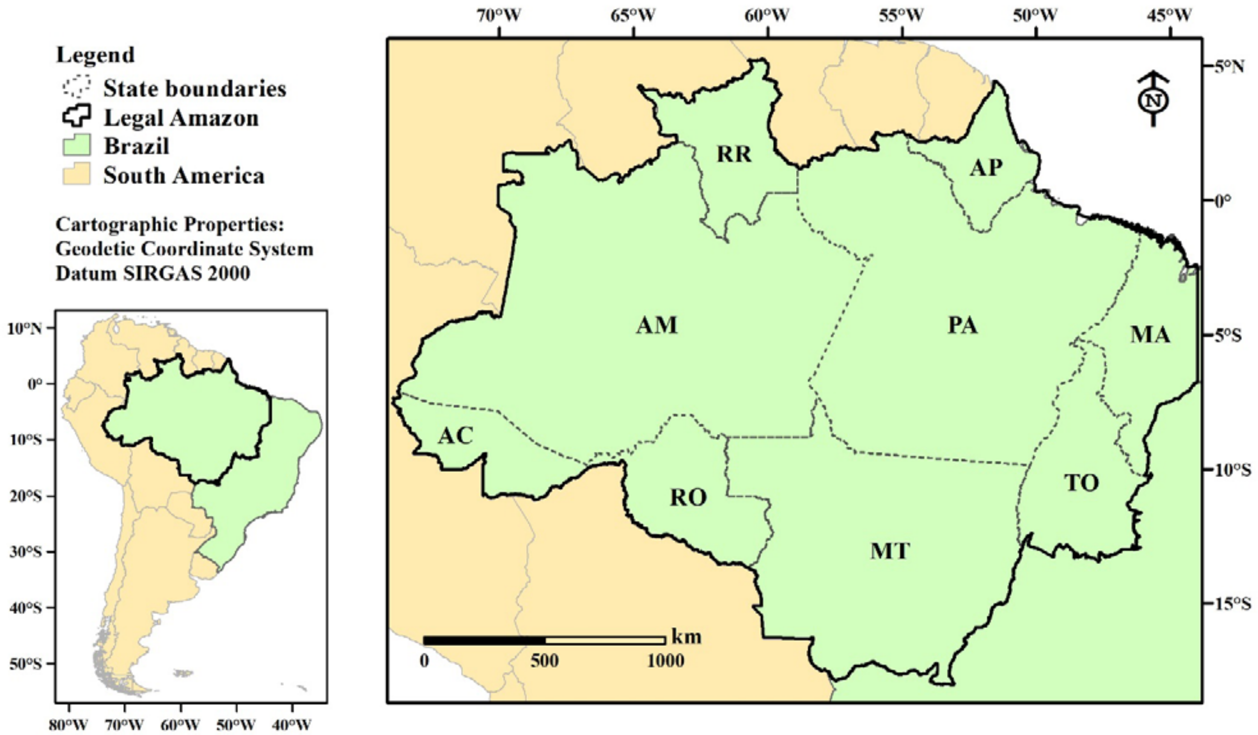
Material and methods

Study area

In this research, only protected areas located in the Legal Amazon were evaluated. This region occupies 5,016,136 km², which represents 59% of the Brazilian territory (Figure 1). It fully covers the states of Amazonas (AM), Pará (PA), Mato Grosso (MT), Rondônia (RO), Acre (AC), Amapá (AP), Roraima (RR), and partially the states of Tocantins (TO, 98%), Maranhão (MA, 79% - west of the meridian 44º) and a small part of the Goiás state (only 0.8%) (IBGE 2011).

The principal biome present in the Legal Amazon is the Amazon biome, which represent 84% of the territory (Pereira and Ferreira 2021). Although there are other phytophysiognomies, in the Amazon biome there is a predominance of rainforest, both dense and opened. These forests are characterized by the densification of tall trees (30 to 50m), which reduces the amount of light inside, especially in the dense forest, limiting the development of shrubs and herbs (IBGE 2012).

Figure 1. Legal Amazon.



Source: IBGE (2021).

The Amazon has a humid tropical climate (A), with predominance of subtypes without a dry season (Af) and monsoon (Am). It has an average temperature close to 25°C, with the average temperature of the coldest month being above 18°C. The maximum annual rainfall is greater than 3,000mm, occurring in the northwest region (dog's head, state of Amazonas), while smaller ones, around 1,100mm, occur in the northeast of the state of Roraima (border with Venezuela) (Nobre et al. 2009; Vale Júnior et al. 2011; Alvares et al. 2013).

Depending on the source material, relief and climate, in general, the soils of the Amazon are poor in nutrients (phosphorus, potassium and calcium), have high acidity and aluminum saturation, and low cation exchange capacity (Vale Júnior et al. 2011). The main soil classes found in the Amazon are: Latosols, Argisols (Ultisols), Plintosols and Spodosols, in which the dystrophic character (low base saturation) predominates (Vale Júnior et al. 2011; IBGE 2015).

Procedures performed

For this study, protected areas were organized into four groups. As a comparison parameter, a selection of areas of the Brazilian Amazon outside the protected areas has been made, which was called non-protected area. The inclusion of non-protected area sample resulted in five groups of analysis:

1. Indigenous Territories: IT (Funai 2021).
2. Fully Protected Conservation Units (all categories): FP (MMA 2019).
3. Sustainable Use Conservation Units - Category I: Public Domain (Extractive Reserve, Sustainable Development Reserve and National/State Forest): SU1 (MMA 2019).

4. Sustainable Use Conservation Units - Category II: Public and/or Private Domain (Environmental Protection Area, Area of Relevant Ecological Interest and Private Reserve of Natural Heritage): SU2 (MMA 2019).
5. Non-Protected Area: NPA. Non-Protected Area are samples of Amazon Legal outside of any category of protected area (indigenous territory or conservation unity) selected for this study.

The work started with the organization of the territorial units (TUs) that compose the protected areas: Conservation Units (MMA 2019) and Indigenous Territories (Funai 2021). Each conservation unit or indigenous territory is considered a territorial unit. If one territorial unit (TU) of protected area (CU or IT) extended beyond the limit of Legal Amazon, only the TU portion inside that was considered (Original No.). Geospatial information was manipulated using the Geographic Information System (GIS) ArcGIS, version 10 (Crosier et al. 2005). Albers projection was adopted, with parameters defined by the IBGE for the Legal Amazon (Braz et al. 2016), to perform metric operations (calculations of perimeters and areas).

The overlaps between the protected areas' TUs have been eliminated by adopting the following order of priority: 1 - Indigenous Territories (IT); 2 - Fully Protected Conservation Units (FP); 3 - Sustainable Use Conservation Units - Category I (SU1); 4 - Sustainable Use Conservation Units - Category II (SU2). Removing all overlays was obtained by converting the file of vector format (original format) to raster format and mosaicking all data, using the priority order cited above. Spatial resolution (pixel size) of 30 by 30 meters was adopted, resolution of PRODES deforestation data for 2017. All raster data generated later adopted this same resolution (30 m). Overlaps removal resulted in the loss of some TUs (No Overlays).

To compare deforestation that occurred within protected areas with deforestation outside them (non-protected area - NPA), lands submitted to the new forest code - Federal Law nº 12.651/2012 (that regulates legal reserves and permanent protection areas), a selection of territorial units outside the protected areas was carried out. For sample preparation, five hexagonal layers with TUs of 500,000, 100,000, 50,000, 10,000 and 5,000 hectares were generated and then selected 20% of each size category, with the aggregation of adjacent hexagons. After removing overlapping areas between layers of the TUs sizes, with priorities for the larger, they were grouped, performing aggregation of contiguous polygons. To finish, a sample of 65% of polygons of this resultant layer was generated. This procedure resulted in a sample composed of 2664 polygons with sizes from 5,000 to 1,200,000 hectares, corresponding to 21.9% of the non-protected area (NPA) in the Legal Amazon. The resulting vector layer was converted to raster format (Original No.).

As the objective was to analyze deforestation and fire in protected areas and in a sample of unprotected area, in a more detailed way, it was necessary to use annual values. Annual deforestation values from 2000 to 2017 was obtained by combining PRODES data for 2014 and 2017: PRODES 2014 - annual deforestation from 2000 to 2007 (INPE 2018a); PRODES 2017 - annual deforestation from 2008 to 2017 (INPE 2018b).

When starting the cross-tabulation between PRODES data and TUs of analyzing groups, it was found that some did not have PRODES classes related to deforestation (forest/cloud and/or deforestation/residue), or even, they had an area less than 6.25 hectares, minimum area mapped by PRODES, having therefore been discarded (PRODES Correct.). As the size of TUs of groups was very variable (IT: lower = 14 ha; higher = 9,547,827 ha), it was decided to analyze deforestation in percentage. In calculating annual percentage deforestation of TUs, the following formula was used:

$$Annual\ deforestation\ (\%) = \frac{Annual\ deforestation}{Forest\ area\ +\ Total\ deforested\ area} \times 100 \qquad (1)$$

Where:
Annual deforestation = deforestation recorded in each year of the 2000-2017 period.
Forest area = sum of forest and cloud classes areas.
Total deforested area = sum of the annual areas of deforestation and residue.

In calculating of the percentage of annual deforestation, the classes of PRODES data that could not be deforested (non-forest and hydrography) were ignored and the clouds computed as forest, once in PRODES data (2014 and 2017) they just occur over forests, and the percentage deforestation 2016-2017 was not very high (≈0.2%).

When examining the annual percentage deforestation of the TUs of the groups, it was found that for some there was 100% deforestation in 2001 (PRODES 2014 data), for example to Quilombo do Frechal Extractive Reserve (SU1) and for some TUs of the NPA group. The TUs with 100% deforestation in 2001 were located at Maranhão state, in a specific scene from the satellite (221/061). Since it is an old occupation region, it is possible that PRODES has considered all scene as deforested. Nevertheless, it is unlikely that an extractive reserve would be created in a place without a forest, even if old secondary one. This characteristic of the PRODES, that not reevaluate an area it has already been deforested before, can create a bias in the analysis, since it is intended to relate deforestation and fire. To minimize this bias, it was decided to remove from analysis all TUs that presented total deforestation in 2017 above 99% (Deforest. 2017).

The fire records for the Legal Amazon (INPE 2019), in the 2000-2017 period, were organized according to the PRODES calendar, which surveys deforestation on August 1st of the prior year until July 31th of the current year. Only the fire records generated by the satellites of reference were used: NOAA-12 - 08/01/1999 to 07/03/2002; AQUA - 07/04/2002 to 07/31/2017. The annual fire density of each TU from each group was determined by dividing the number of fire records for each year by the area in square kilometers (fire km^{-2}).

In order to verify in what type of land cover the fire occurred, the annual records were crossed with the protected areas from which the Group's information was obtained, and with the PRODES data (2014 and 2017) from where information on coverage type was obtained. For fire from 2000 to 2007, information on type coverage was extracted from PRODES 2014; while for fire from 2008 to 2017, PRODES 2017 was used. Three types of cover were considered: Forest, Opened Area and Deforestation. Every fire that has occurred in a non-forest area (PRODES denomination to shrubland or grassland natural vegetation types) or in a deforested area priorly to fire year was considered to have occurred in an "Opened Area". The fire that has occurred in forest or deforested area after fire year were assumed as to have occurred in "Forest". When fire and deforestation both has occurred in the same year, the cover type was called "Deforestation".

Statistical analyzes (normality test, equality of variances, comparison of several values simultaneously) of the values of percentage deforestation and density of fires, as well as the evaluation of the correlation between both values, were carried out using the GraphPad Prism program, version 6, with a confidence level of 95% (GraphPad 2014). To evaluate the values of the correlation coefficient between percentage deforestation and fire density, the intervals proposed by Mukaka (2012) were used (Table 1).

Table 1. Reference values to interpret the correlation coefficient.

Correlation Value	Interpretation
0.90 to 1.00	Very high correlation
0.70 to < 0.90	High correlation
0.50 to < 0.70	Moderate correlation
0.30 to < 0.50	Low correlation
0.00 to < 0.30	Negligible correlation

Results

At the end of initial analysis, 2,760 TUs of the five groups remained (Table 2, Figure 2), which represented 54.14% of the Legal Amazon territory. It was registered a reduction of 18.51% in the original number of TUs, due to overlays. The percentage participation of each group in this study and the percentage participation of each group in relation to the Legal Amazon can still also be observed in Table 2.

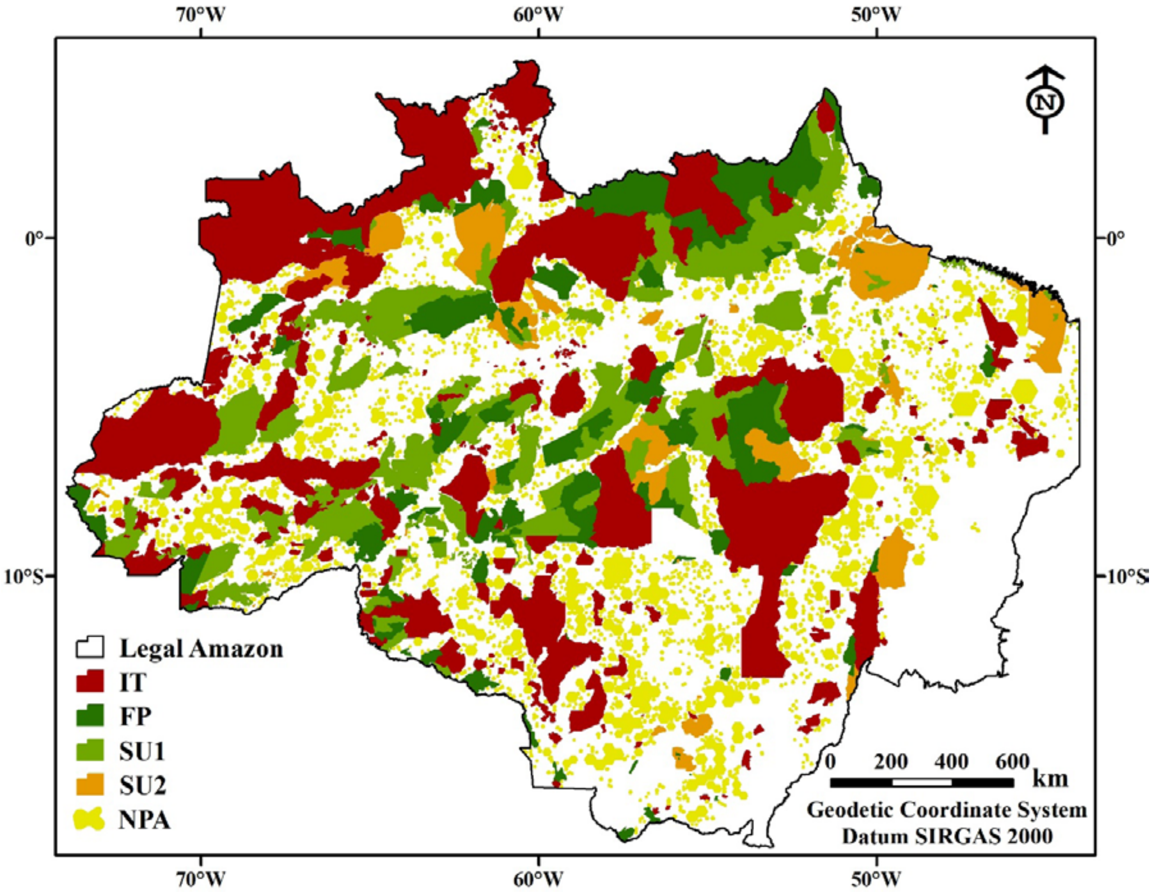
Table 2. Territorial units (TUs) of study groups.

Groups	Original No.	No Overlays	PRODES Correct.	Deforest. 2017	Reduction (%)	Area (km²)	Study (%)	Legal Amazon (%)
IT	383	383	364	359	6.27	1,138,256	41.88	22.68
FP	112	109	93	86	23.21	371,058	13.65	7.39
SU1	156	156	156	154	1.28	514,917	18.95	10.26
SU2	72	71	56	54	25.00	209,228	7.70	4.17
NPA	2,664	2,664	2,174	2,107	20.91	484,200	17.82	9.65
Total	3,387	3,383	2,843	2,760	18.51	2,717,658	100	54.14

The values of percentage deforestation and fire density of the TUs, per year and per group, had a similar characteristic, the predominance of very small values (close to zero), with the group average value, in some cases, being considered an outlier (besides of the stems of the boxplot) (Nepstad et al. 2006). These characteristics of both, it has reflected in the absence of normality (Kolmogorov-Smirnov test, $p < 0.001$) and also in the inequality of the variances (Bartlett test, $p < 0.001$), which made it impossible to compare the values of percentage deforestation and fire density of the groups using analysis of variance (Zar 2010).

Due to these characteristics of the percentage deforestation and the fire density, in addition to an elevated number of outliers, it was decided to compare them simultaneously using the Kruskal-Wallis non-parametric test (Nepstad et al. 2006), which does not assume a normal distribution or equality of variances (Zar 2010). Dunn's test was performed in association with the Kruskal-Wallis test, in order to compare the values of percentage deforestation and fire density of the groups analyzed in pairs, taking care to use the corrected p-value for multiple comparisons (Zar 2010). The comparison of the values of percentage deforestation and fire density was performed considering all records of the groups for the 2000-2017 period simultaneously (Table 3).

Figure 2. Final territorial units of study groups (Indigenous Territories – IT; Fully Protected Conservation Units – FP; Sustainable Use Conservation Units, Category I – SU1; Sustainable Use Conservation Units, Category II – SU2; Non-Protected Area – NPA), after correction for deforestation of 2017 (Table 2).



Sources: Indigenous Territories (Funai 2021); Conservation Units - Fully Protected and Sustainable Use (MMA 2019); Non-Protected Area (this study).

Table 3. Number of records of percentage deforestation and fire density by analysis groups for the 2000-2017 period.

Groups	TUs	Years	Records
IT	359	18	6,462
FP	86	18	1,548
SU1	154	18	2,772
SU2	54	18	972
NPA	2,107	18	37,926

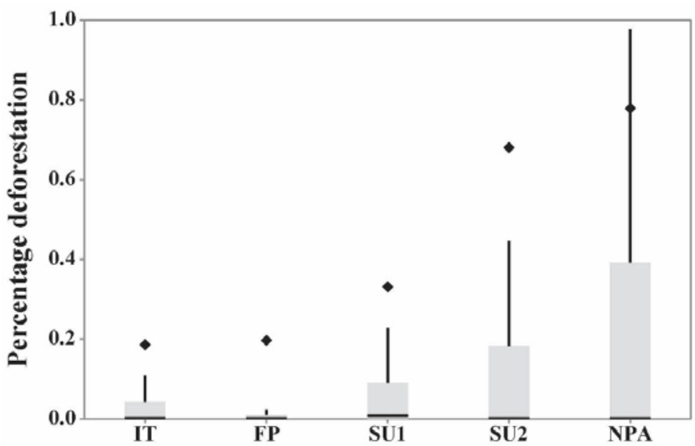
Because of absence of normality and differences between variances, the relationship between percentage deforestation and fire density was assessed using Spearman's rank correlation coefficient (Spearman's ρ), a non-parametric measure (Zar 2010; Mukaka 2012). As well as for analyzing the values of percentage deforestation and fire density, the analysis of the relationship between both was carried out using the total number of records in the 2000-2017 period simultaneously (Table 3).

As in the 2000-2017 period there were many TUs of all groups without deforestation or with very low percentage deforestation, the average percentage deforestation for all groups was below 1%, being lower in the IT group and higher in the NPA group (Table 4, Figure 3). The median values were very low, much lower than average (the representation of the median almost did not appear in Figure 3). However, the average value is not a suitable parameter for the characterization of the percentage deforestation, since for all groups, except the NPA, it would be considered an outlier, because it is located beyond the stems of the boxplot (Figure 3).

Table 4. Percentage deforestation by group for the 2000-2017 period.

Statistics	IT	FP	SU1	SU2	NPA
Minimum	0	0	0	0	0
Maximum	30.05	53.70	33.98	67.24	93.58
Median	0.001	0.000	0.008	0.001	0.000
Average	0.186	0.197	0.331	0.681	0.779
Standard deviation	0.919	1.627	1.543	3.786	2.739
TU - highest average	2.23	4.10	4.47	4.25	5.37

Figure 3. Boxplot for percent deforestation values by group for the 2000-2017 period: diamond represents the average; horizontal black line represents the median and outliers were omitted.



The TUs with highest values of annual percentage deforestation (maximum) by group were: IT Karajá Santana do Araguaia (Santa Maria das Barreiras - PA) in 2001; FP Rangedor Ecological Station (São Luís - MA) in 2001; SU1 Itapetininga Extractive Reserve (Bequimão - MA) in 2001; SU2 Environmental Protection Area of Baixada Maranhense (48 municipalities at north/northwest of Maranhão state) in 2001; and NPA Non-Protected Area 1520 (Piçarra - PA) in 2000 (Table 4).

The TUs with highest average percentage deforestation (TU - highest average) by group for the period were: IT Karajá Santana do Araguaia (Santa Maria das Barreiras - PA); FP Rangedor Ecological Station (São Luís - MA); SU1 Araras Sustained Yield State Forest (Cujubim - RO); SU2 Environmental Protection Area of the Maracanã Region (São Luís - MA); and NPA Non-Protected Area 1520 (Piçarra - PA) (Table 4).

In all protected area groups, the maximum value of deforestation percentage occurred in 2001, suggesting that this year was critical for deforestation in protected areas. For two groups of protected areas (IT and FP), the maximum value and the highest average of percentage deforestation has occurred at the same TU, that evidenced the severe deforestation problem at both: IT Karajá Santana do Araguaia and FP Rangedor Ecological Station.

It was found that at least one of the groups had different values of percentage deforestation in the 2000-2017 period (Kruskal-Wallis test, $p < 0.001$). Based on Dunn test, it was verified yet that the deforestation values of the FP and IT groups were different from all the others. It was also observed that there was no difference in deforestation values between the SU1 and SU2 groups, and also among SU2 and NPA groups (Table 5).

Table 5. Dunn's test (p-value): comparison of the percentage deforestation values.

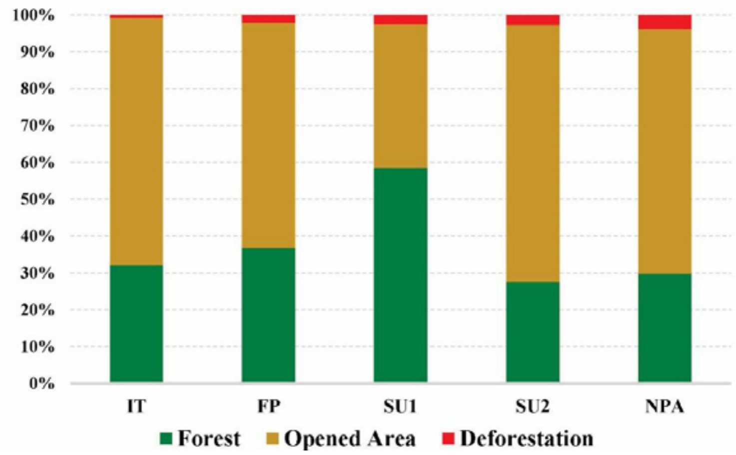
	IT	FP	SU1	SU2
FP	<0.001			
SU1	<0.001	<0.001		
SU2	0.018	<0.001	0.071	
NPA	<0.001	<0.001	<0.001	1.000

In total, 821,727 fire records from 2000 to 2017 (PRODES year) were analyzed, which have occurred in the 2,760 TUs of the study groups. As it is an area of predominantly agropastoral use, the NPA group presented the biggest amount of fire records, with the IT group being in second place, principally due to its large territorial extension. The CUs presented a lower quantity of fire records, with a decreasing behavior in the following order: SU2, SU1 and FP (Table 6, Group%). Almost two thirds of the fires occurred at "Opened Area", and were associated with agricultural management activities. Approximately one third of them represented forest fires ("Forest"), more frequently in the SU1 Group. Finally, only a few ones were related to "Deforestation" (Table 6, Type%; Figure 4).

Table 6. Fire records by study group and coverage type for the 2000-2017 period.

	Forest	Opened Area	Deforestation	Total Group	Group%
IT	54,078	113,278	1,420	168,776	20.5
FP	9,373	15,564	540	25,477	3.1
SU1	33,229	22,173	1,489	56,891	6.9
SU2	26,381	67,122	2,667	96,170	11.7
NPA	140,840	315,434	18,139	474,413	57.7
Total	263,901	533,571	24,255	821,727	100
Type%	32.1	64.9	3.0	100	

Figure 4. Percentage of fire records by coverage type and by group for the 2000-2017 period.

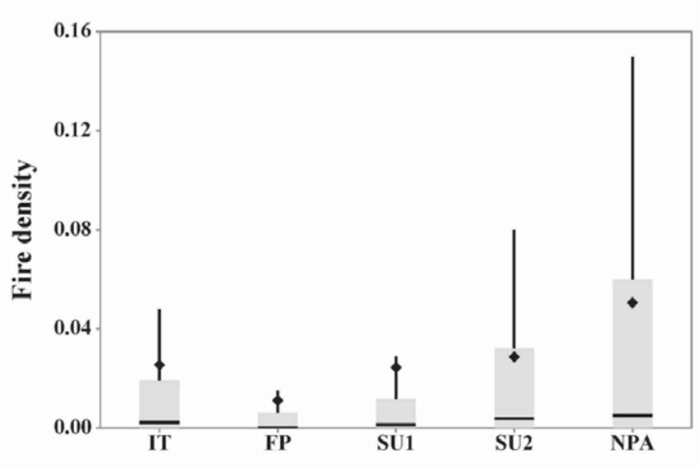


In relation to the values of fire density (fire km−2), in general, the groups presented very low values (in the order of hundredths), since the TUs were large and many of them had no fire in some years in the 2000-2017 period. Similar to percentage deforestation, the median values of fire density were lower than average. The lowest value of average fire density was found in the FP group, while the highest has occurred in the NPA group (Table 7 and Figure 5).

Table 7. Fire density (fire km-2) by group for the 2000-2017 period.

Statistics	IT	FP	SU1	SU2	NPA
Minimum	0	0	0	0	0
Maximum	3.021	0.451	2.290	0.699	1.580
Median	0.002	0.000	0.001	0.004	0.005
Average	0.025	0.011	0.025	0.029	0.051
Standard deviation	0.076	0.034	0.097	0.066	0.098
TU - highest average	0.286	0.097	0.533	0.322	0.438

Figure 5. Boxplot for fire density (fire km-2) values by group for the 2000-2017 period: diamond represents the average; horizontal black line represents the median and outliers were omitted.



The TU with the highest annual values (maximum) of fire density per group were: IT Uty-Xunaty (Vilhena - RO) in 2005; FP Pacaás Novos National Park (seven municipalities at center of Rondônia state) in 2003; SU1 Periquito Sustained Yield State Forest (Cujubim - RO) in 2011; SU2 Area of Relevant Ecological Interest Seringal Nova Esperança (Epitaciolândia - AC) in 2008; and NPA Non-Protected Area 2127 (Itaubal - AP) in 2003 (Table 7).

The TU with the highest average fire density (TU - highest average) were: IT Uty-Xunaty (Vilhena - RO); FP Pacaás Novos National Park (seven municipalities at center of Rondônia state); SU1 Periquito Sustained Yield State Forest (Cujubim - RO); SU2 Area of Relevant Ecological Interest Seringal Nova Esperança (Epitaciolândia - AC); and NPA Non-Protected Area 1225 (Nova Mamoré - RO) (Table 7).

All TUs of protected area groups that had the maximum value of fire density also had the highest average of fire density in the 2000-2017 period, demonstrating that is a chronic problem in these TUs.

Such as deforestation values, at least one of the groups had different fire density values in the 2000-2017 period (Kruskal-Wallis test, $p < 0.001$). The outcomes of the Dunn test allowed verifying that: the fire density value of the FP group was different from all the others; there was no difference in the fire density values among IT, SU1 and SU2 groups; and yet, there was no difference in the values of fire density among SU2 and NPA groups (Table 8).

Table 8. Dunn's test (p-value): comparison of the fire density values.

	IT	FP	SU1	SU2
FP	<0.001			
SU1	0.662	<0.001		
SU2	1.000	<0.001	1.000	
NPA	<0.001	<0.001	<0.001	0.329

In none of the five groups analyzed (IT, FP, SU1, SU2 and NPA) there was coincidence that the same TU had the highest percentage deforestation (absolute and/or average) and the highest fire density (absolute and/or average).

In the integrated analysis for the 2000-2017 period, the values of the correlation coefficient (Spearman's ρ) for the comparison of percentage deforestation and fire density values showed an increasing behavior in the following order: IT, FP, SU1, SU2 and NPA (Table 9).

Table 9. Deforestation vs. Fire: 2000 - 2017 Period.

Statistics	IT	FP	SU1	SU2	NPA
No. of Pairs	6,462	1,548	2,772	972	37,926
Spearman's	0.269	0.391	0.426	0.471	0.587
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Based on the intervals proposed by Mukaka (2012) (Table 1), the correlation coefficient values have permitted to organize the groups into three classes: negligible correlation - indigenous territories

(IT); low correlation - all categories of conservation units (FP, SU1, SU2); and moderate correlation - non-protected areas (NPA) (Table 9). That is, fire on indigenous territories is very few related to deforestation. In all categories of conservation units, just a small amount of fire is related to deforestation, and this relationship increases in the following order: FP, SU1 and SU2. Finally, in non-protected areas, an intermediate quantity of fire would be associated with deforestation.

Discussion

In a general way, studies have demonstrated the importance of protected areas in the preservation of natural environments, without distinguishing between categories (Ferreira et al. 2005; Braz et al. 2016), without observing a significant difference between the protection provided by FPCUs when compared to SUCUs (Gaveau et al. 2012), or demonstrated that the FPCUs are more effective in preserving the original coverage than the SUCUs (Françoso et al. 2015).

The results of this study demonstrated the importance of FP and IT groups in containing deforestation in the Legal Amazon, as they presented lower deforestation values, being statistically different from the SU1 (public areas) and SU2 (public/private areas) groups, as noted by Françoso et al. (2015) for the Cerrado Domain, specifically for FP (Figure 3, Table 5). Although with a lower level of protection than FP and IT groups, SU1 group also contained deforestation, since deforestation was statistically lower than NPA group (Figure 3, Table 5). This outcome seemed to be different from that found by Nepstad et al. (2006) who did not verify an effective protection of extractive reserves, those belonging to the SU1 group of this study, against deforestation. The only group considerate with poor action against deforestation was SU2, because it has presented values without significant statistical difference for the NPA group (Figure 3, Table 5).

Nolte et al. (2013) argue that SUCUs have higher percentages of deforestation, when compared to FPCUs, in part because they are in places of greater pressure for occupation (arc of deforestation). However, Pereira and Ferreira (2020) observed that the argument by Nolte et al. (2013) was valid only for SUCUs in the public and/or private domain (Environmental Protection Area, Area of Relevant Ecological Interest and Private Reserve of Natural Heritage), not being valid for SUCUs in the public domain only (Extractive Reserve, Sustainable Development Reserve and National/State Forest).

Just like for deforestation, studies have also highlighted the role of protected areas in containing fire in the Amazon region (Nepstad et al. 2006; Adeney et al. 2009; Geldmann et al. 2019). Adeney et al. (2009), analyzing three categories of protected areas (FPCUs, SUCUs and ITs), found that the general incidence of fire did not differ between the types of protected areas. Nepstad et al. (2006) evaluating the occurrence of fire in the categories of protected areas ITs, FPCUs, National Forests and Extractive Reserves, they concluded that each of these types of area exercised a similar level of control over fire occurrence.

In disagreement with results obtained by Nepstad et al. (2006) and Adeney et al. (2009), the results of this study demonstrated that the FP group had the lowest fire density values, being statistically different from the SU1, IT and SU2 groups. Even though at a lower level than the FP group, the SU1 and IT groups provided protection against fire, since its values of fire density were statistically lower of than the NPA group. The SU2 group was the only one that did not present important protection against fire, as with as its value of fire density was not statistically different from NPA group (Figure 5, Table 8).

Investigating the relationship between deforestation, fire and precipitation in the Legal Amazon, Aragão et al. (2008) found a strong linear relationship between the annual number of fire and the area deforested annually, from 1998 to 2004 ($r^2 = 0.84$; $r = 0.92$). The authors also demonstrated that fire in deforested areas represented 60% of the total fire records in 2005. Of the remaining, 28% occurred in forests and 12% in areas considered non-forest in the classification of INPE's land cover (PRODES). In this study, the biggest value of correlation between percentage deforestation and fire density, for the 2000-2017 period, was to NPA group (Spearman's $\rho = 0.59$), classified only as moderate (Table 9). It was verified yet that 32.1% of the fire were related to forest fire and 64.9% were mainly burnings, fire associated with agropastoral management practices (Table 6).

That is, considering the 2000-2017 period, a higher percentage of forest fire was observed in this study than Aragão et al. (2008) for 2005, year considered dry (32.1% vs 28%). Only 3% of fire in the analyzed groups were related to recent deforestation (year of the fire coincided with the year of deforestation), which reflected in low values of the correlation between deforestation and fire, being classified as negligible in the IT group, low in all groups of CUs and moderated for non-protected areas (Table 9). Thus, the fire in protected areas are mainly related to the agropastoral management technique.

As well as Aragão et al. (2008), Alencar et al. 2015 found a relationship between an increase in the dry season and an increase in the number of forest fire. Alencar et al. 2015 observed a positive correlation between the total area burned, the number of burn scars and the maximum size of these scars. The authors also found that the ratio between burned and deforested area was much lower in dense forest (35%) than in transitional or open forest (70% and 180%, respectively). According to the authors, this fact is related to the fact that these types of forests are preferentially located on the edge of the Amazon (arc of deforestation), a place of greatest pressure for occupation.

The results obtained by Alencar et al. (2015), associated with those obtained by Pereira and Ferreira (2021) that sustainable use conservation units in the public and/or private domain are being created in large numbers in areas of greater pressure for occupation (arc of deforestation), help to understand the higher incidence of deforestation and fires in the SU2 group.

In the Amazon region, 10 million hectares of pastures (65% of the total deforested area) are abandoned or misused (less than one cow per hectare), that should be used to expand grain and beef production (Fearnside 2008; Greenpeace et al. 2017). Curb the illegal appropriation of public land in the Amazon region is an urgent action, since at least 24% of deforestation in 2016 occurred on public lands yet without a destination. The expansion of a forest economy by way of government programs also is very important. If these two measures were implemented, deforestation would surely have a substantial reduction (Greenpeace et al. 2017).

Among the factors that reduce the effectiveness of public policies in combating forest fire and burnings in the Amazon region, two are more relevant: availability of resources in the first place for combating burnings/forest fire instead of applying them in prevention; little effort in activities that encourage the diffusion of agricultural practices without the use of burnings such as access to credit, specialized technical assistance and the opening of markets for these products (Fonseca-Morello et al. 2017). Between of production and management alternatives that guarantee good levels of productivity without fire use, the following stand out: agroforestry systems, silvopastoral systems, cut-and-grind system, and the system of continuous cultivation of several interrupts crops, through the practice of direct planting (Bragantino system) (Sá et al. 2007; Fearnside 2008; Fonseca-Morello et al. 2017).

Conclusion

Fully protected conservation units demonstrated greater effectiveness in containing deforestation and fire. Indigenous territories and sustainable use conservation units exclusively in public lands (extractive reserve, sustainable development reserve and national/state forest), although less effective, also provided protection against deforestation and fire. Only the sustainable use conservation units that admit public and private lands (environmental protection area, area of relevant ecological interest and private reserve of natural heritage) have not demonstrated effectiveness in containing both deforestation and fire. Thus, as a pillar of the environmental conservation strategy, priority should be given to converting public lands in the Amazon region into fully protected conservation units. However, the creation of sustainable use conservation units in the public domain and indigenous territories would be an alternative option, because in addition to essential for the conservation of sociodiversity, they also offered protection against deforestation and fire.

Burnings are used as a common management practice in the Amazon region. However, when wrongly executed, they can turn into forest fire. In the protected areas of the Legal Amazon, it was found that the greater part of the fire was related to management practices (fire in opened areas). Nevertheless, a considerable part also was associated with forest fire. Only a small part of the fire occurred in areas of deforestation. Thereby, the correlation between deforestation and fire was classified as negligible for indigenous lands and low in all categories of conservation units. Showing, therefore, that fire in protected areas is mainly associated with agropastoral management practices.

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