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Deforestation pattern dynamics in protected areas of the Brazilian Legal Amazon using remote sensing data

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ABSTRACT

Forest fragmentation and deforestation are subjects of great concern in tropical regions, namely in South America and Africa, contributing to a rapid loss of tropical forest area and with serious implications for ecosystem functioning and biodiversity conservation. Despite the decrease in deforestation rates in recent years, the Brazilian Amazon, with the largest continuous region of tropical forest in the world, has suffered the greatest recorded losses, which have been contributing to continuous habitat fragmentation and a reduction in the territory occupied by Amerindian populations. In an attempt to preserve the remaining habitats and forests, Brazil has been adopting land conservation policies, including the implementation of protected areas. Protected areas (PAs) possess the potential to significantly reduce habitat fragmentation by conserving large, contiguous areas of land. In order to examine how effective PAs are at conserving forest area in the Brazilian Legal Amazon, patterns of deforestation are analyzed and compared, inside and outside the PAs, through landscape metrics calculated using the Patch Analyst and V-LATE extensions of a Geographic Information System. Two different sources (the Hansen Global Forest Change Dataset and the Brazilian National Institute for Space Research's (INPE) PRODES project) of annual forest cover-loss data derived from satellite imagery at medium-to-high spatial and temporal resolutions are compared at two-yearly intervals across 2002–2016. Additionally, fragmentation levels associated with deforestation patterns are assessed through an index modeled using a set of uncorrelated landscape metrics, and the associated change factors and trend are discussed. Results show that there is greater fragmentation in some PAs located in Mato Grosso and Pará States, especially those near the "arc of deforestation", and that Yanomami Indigenous Lands (YIL) are tending towards more fragmentation. Although some PAs are in a critical condition, findings show they all actively contribute to improved conservation of the native ecosystem and, in conjunction with sustainable management policies, will continue to help reduce or avoid forest fragmentation and degradation processes.

1. Introduction

Tropical deforestation and forest fragmentation resulting from land-use changes are leading sources of concern in the research community, namely that concerned with estimating the extent of these phenomena and their consequences for both climate change on regional and local scales and the decline in global biodiversity (Arima et al., 2005, 2008; Haddad et al., 2015; Joppa et al., 2008; Tapia-Armijos et al., 2015; Vedovato et al., 2016).

Several authors (Achard et al., 2014; Baccini et al., 2012; FAO, 2005, p. 197; Hansen et al., 2013a) report a reduction in tropical forest on a global scale that is associated with land-use changes and has made a significant contribution to the increase in CO_2 emissions. According to Pan et al. (2011), about 56% of the carbon currently held in biomass is stored in tropical forests, and land-use changes were responsible for 14–20% of global greenhouse gas emissions in 2000–2007 (Arima, Barreto, Araújo, & Soares-Filho, 2014) and 7–14% in 2000–2005 (Henders et al., 2015). Deforestation influences local and regional climates, often leading to an irreversible savannization process (Malhi et al., 2007) and a weakening of the affected regions, which can suffer

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from long periods of drought and reduced water reserves (Lovejoy & Nobre, 2018). Other effects include contributions to species extinctions, loss of ecosystem services and increased habitat vulnerability, with long-term changes in landscape configuration that in turn lead to a fragmentation process (Skole and Tucker, 1993; Tapia-Armijos et al., 2015). One consequence is the appearance of small, non-contiguous fragments, in different years and with varying sizes and levels of isolation, separated by a matrix of human-transformed land cover (Broadbent et al., 2008; Haddad et al., 2015). A new ecological and hydrological cycle therefore begins in each new fragment. All these land-use transformations affect forest-dependent populations, forcing them to change their livelihoods and traditions (Albert, De Robert, Le Tourneau, & Laques, 2011).

Brazil, with the largest continuous region of tropical rain forest in the world, located in the Brazilian Legal Amazon (BLA), is one of the countries with the highest rates of forest loss (Fearnside, 2005; May et al., 2016; Numata & Cochrane, 2012; Skole and Tucker, 1993; Tyukavina et al., 2017; Vedovato et al., 2016). The long history of deforestation in the BLA is closely linked to colonization policies implemented since the early 1960s, investments in infrastructure (i.e. intensive road-building) and fiscal incentives for economic activities, particularly those related with large-scale cattle-ranching and agriculture (Carvalho et al., 2002; Kirby et al., 2006; Moran, 1993). More recently, the Amazonian economy has been oriented by the demands (Nepstad et al., 2006) of the international beef and soy industries, which became important drivers of deforestation in the first half of 2000s and remain so today (Gollnow and Lakes, 2014; Laurance, 2007; Nepstad et al., 2008; Tyukavina et al., 2017).

As part of an effort to monitor and control Amazon deforestation, the Brazilian National Institute for Space Research (INPE) has used satellite data to annually map deforestation in the BLA since 1988, and reports annual deforestation rates as part of the Program for Deforestation Monitoring (PRODES) project (Almeida et al., 2016; INPE, 2017a; Maus, 2014). It also developed the Mapping of Deforested Areas in the Legal Amazon project (TerraClass), whose goal is to map land use and the spatial distribution of land cover in deforested areas identified by the PRODES project (INPE, 2017b).

BLA deforestation rates have varied greatly over the last fifty years, with accelerations in the first halves of both the 1990s and 2000s, peaks in 1995 (29,059 km^2/year) and 2004 (27,772 km^2/year), and then a progressive fall to a historical low of 4571 km^2/year in 2012 (INPE, 2017a). This decline in deforestation rates in the last decade is corroborated by other studies, although absolute values have varied depending on the methodology, type of forest observed and minimum mapping unit adopted (Hansen et al., 2013b; Tyukavina et al., 2017). A reversal trend occurred in 2013, with the highest value for the last eight years recorded in 2016 (7893 km^2/year), although estimates for 2017 (6624 km^2/year) are more encouraging (INPE, 2017a).

In 2010, Brazil passed Decree (a form of legislation) no. 7,390, committing to an 80% reduction in annual Amazon deforestation (to 3925 km^2/year) by 2020, from an average baseline of 19,625 km^2/year in 1996–2005 (Gebara and Thuault, 2013; MMA, 2016). Several measures have been adopted in the light of this goal: stronger enforcement of laws, industry value-chain initiatives, expanded protected-area networking, and a robust forest-monitoring system (Nepstad et al., 2014; Nobre et al., 2016). Some of these strategies are actually deceptive, demonstrating a decrease in illegal deforestation while legalizing new deforestation (Saito and Azevedo, 2017). Simultaneously, different policies based on Protected Areas (PAs) have been implemented to protect tropical forests and preserve the territories of the Amerindian populations.

In general, the efficiency of PAs in the fight against deforestation is consensual, but some authors (Kirby et al., 2006; Vedovato et al., 2016) have referred to their vulnerability to both legal and illegal logging activities, arguing that the influence of nearby roads, agriculture and deforestation contribute to increased degradation by fire, inducing new levels and patterns of forest fragmentation. Effects vary according to edge penetration distances, spatial arrangements and time-of-persistence of fragments (Numata & Cochrane, 2012), and imply biodiversity loss, changes in structure and species composition, increased fire vulnerability and tree mortality, and canopy desiccation (Broadbent et al., 2008; Cochrane & Laurance, 2002, 2008). Numata and Cochrane (2012) analyzed fragmentation for the BLA in seven states, using 2001–2010 PRODES data to calculate landscape metrics. Vedovato et al. (2016) also assessed the status of forest fragmentation in 2014, using a morphological spatial pattern analysis, while Broadbent et al. (2008) quantified rates of forest fragmentation due to deforestation and logging in 2005–2006. In 2010, Soares-Filho et al. used PRODES data to evaluate how efficient PAs were at reducing deforestation in 1997–2008. Focusing on the spatial dimension of land-cover change, Arima, Walker, Perz, and Souza (2016) used field surveys, simulation and remote sensing to identify patterns of fragmentation and their relationship with social processes.

Improving knowledge of fragmentation processes is thus fundamental to the ability to estimate regional impacts and disturbances (Cabral & Costa, 2017; Numata & Cochrane, 2012; Cochrane & Laurance, 2008), which is particularly important in PAs created with a conservationist goal.

The aim of this study is to improve our understanding of how effective PAs have been at protecting forest areas located in the BLA, with reference to two-yearly intervals across 2002–2016, identifying spatial patterns and the associated processes of change. The specific objectives are:

To compare patterns of deforestation inside and outside PAs using derived remote-sensing data from two sources: Annual Forest Cover-Loss data produced by i) Hansen Global Forest Change Dataset (HD), and ii) the Brazilian National Institute for Space Research's (INPE) PRODES project.

To model a fragmentation index using landscape metrics, such as to make it possible to evaluate, for each type of PA and dataset, the level of fragmentation associated with deforestation patterns, without distinguishing natural processes from anthropogenic disturbances.

To identify the main factors of change underlying landscape patterns.

Comparing global and regional datasets allows us to evaluate the advantages and disadvantages of using each type of data in terms of accuracy, work-time consumed and costs, and their usefulness when it comes to developing sustainable policies.

2. Data and methodology

2.1. Brazilian Legal Amazon and protected areas

The study area encompasses all the different types of PAs that are located in the BLA and help protect and conserve native ecosystems (Fig. 1): the various categories of Integral Protection and Sustainable-Use Conservation Units, and Indigenous Lands.

The political-administrative region known as the BLA was created by Decree in 1953 and comprises approximately five million km^2 of Brazilian territory (IBGE, 2017; Matricardi et al., 2013). It includes the states of Acre (AC), Amapá (AP), Amazonas (AM), Pará (PA), Rondônia (RO), Roraima (RR), Mato Grosso (MT) and Tocantins (TO), as well as a part of Maranhão (MA) located west of meridian 44 (Vedovato et al., 2016). Almost the entire area (~65%) is covered by Amazon biome characterized by primary tropical rainforest (ombrophyllous and seasonal forest), while only a small proportion (~15%) is covered by savanna vegetation and transitional forests, where there are grasslands and *campinarana* (Carreiras, Pereira, Campagnolo, & Shimabukuro, 2006; FAO, 2005, p. 197; May et al., 2016). The primary tropical rainforest is located in the central, northern and western areas, whilst the *cerrado* savannas are mostly concentrated along the rims of the southern and eastern areas, although there are also some isolated areas embedded in the tropical rainforest areas (IBGE, 2004).

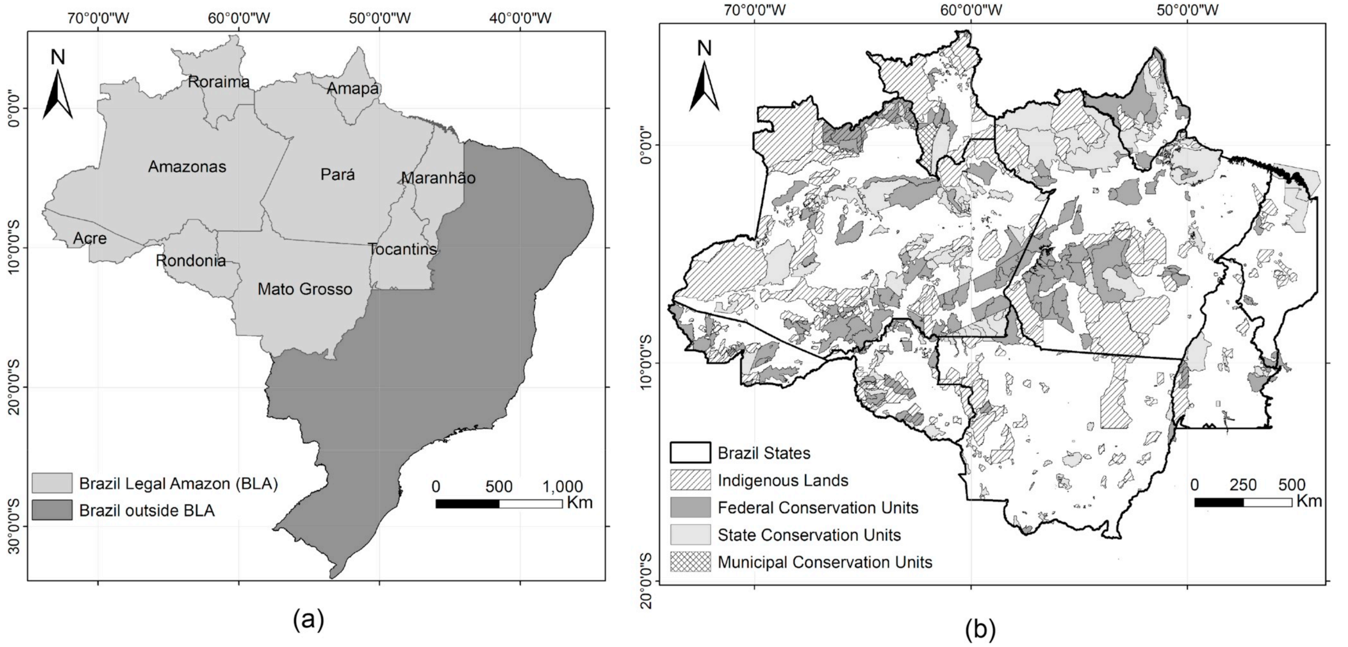

Fig. 1. Location of (a) the Brazilian Legal Amazon in Brazil; (b) Types of Protected Areas by level of government jurisdiction.

Vegetation has suffered severe damage as a result of political and economic decisions. An intensive network of PAs arose in response to these changes, especially after the year 2000 and the implementation of the Brazilian National System of Nature Conservation Units (Law 9985 of 18 July 2000; Decree 4340 of 22 August 2002; Decree 5746 of 5 April 2006) (SNUC, 2011, p. 80; Walker et al., 2009). The purpose of the PAs is to halt the spread of deforestation by delimiting large natural and semi-natural areas, contributing to the protection of species, habitats, territories and Amerindian populations (Nogueira et al., 2018). In 2000, the area under protection represented about 10% of the BLA (Walker et al., 2009). According to Soares-Filho et al. (2010), 54% of the remaining forests were protected by PAs by 2009. Their area increased by 68% in 2004–2012, especially near the agricultural frontiers, and current prospects are for continued growth (Nepstad et al., 2014). Recent data from ISA (2017a,b) show that the actual area has increased to about 48% of the BLA, which suggests that, if correctly managed, they can play an essential role in the reduction of deforestation and forest fragmentation. Under Brazilian law, PAs include two main groups: Conservation Units (CUs), and Indigenous Lands (ILs). The National Nature Conservation Unit System (SNUC, 2011, p. 80) classifies CUs into 12 categories. On the one hand, those with stricter levels of protection are designed solely to preserve biological diversity and do not permit resource exploitation or human occupation; on the other, the sustainable-use units seek to reconcile nature conservation with a sustainable use of natural resources. Conservation units can be subject to either federal, state or municipal jurisdiction. In 2017, 13.15% of the BLA was occupied by federal CUs, with 6.81% under strict protection and 6.34% under sustainable-use protection (ISA, 2017a, b), while state CUs occupied 12.45% of the region, with 2.63% under strict protection and 9.82% under sustainable-use protection (ISA, 2017a, b). However, not all CUs that are created are effectively protected, since some lack agrarian regularization and/or the drawing up and implementation of a management plan (Nogueira et al., 2018). Indigenous Lands created under federal jurisdiction seek to guarantee the land rights of traditional populations and the maintenance of their cultural values (see the so-called “Indian Statute”, Law no. 6001 of 19 December 1973), but on the assumption that those populations and values only have a small impact on natural resources (Nogueira et al., 2018). In 1988, after the Brazilian Constitution had guaranteed the protection of Amerindians, the reserve-demarcation process was speeded up. In 2017, about 374 ILs were demarcated and identified (under the terms of Law no. 1775 of 8 January 1996), occupying about 22.8% of the BLA (ISA, 2017b). Insufficient information on previously defined areas and delays in the recognition process have contributed to overlaps between several CUs and ILs, and between federal and/or state CUs (Imazon, 2011). In the present study, we distinguished between cases in which different PA categories and jurisdictions overlapped, and those with only one category and jurisdiction. In addition, we defined a 10-km buffer zone around each PA, based on Conama (Conselho Nacional do Meio Ambiente, National Environmental Council) Resolution no. 13/1990, to help us analyze whether legally non-compliant activities are taking place there. The legislation has been updated several times since 1990 (Conama Resolutions nos. 428/2010, and 473/2015), but Decree 99,274 of 6 June 1990, under which all activities in the 10-km-radius areas surrounding the CUs that can affect the biota are subject to Conama rules, has remained in force. Actually, each CU can adopt its own buffer zone, but difficulties with conducting the necessary technical studies and securing approval of management plans have meant that a 3-km radius is currently accepted (until 2020) for those CUs without official buffer zones. Notwithstanding this varied legal framework, historically Brazilian policies have adopted 10 km as a reference buffer for environmental studies – a conservative value we have followed in our work, in which the term PA is used to represent all areas under protection as described below.

2.2. Deforestation datasets

Two different sources of annual forest cover-loss data were used, at two-yearly intervals from 2002 to 2016: the Hansen global forest change dataset (HD), and the PRODES project (PD). The global forest dataset developed by Hansen et al. (2013b) entailed application of a decision-tree approach based on the temporal profile of spectral metrics derived from free Landsat imagery to produce several products focused on tree cover dynamics between 2000 and 2016 (GFC, 2018a,b; Hansen et al., b, 2013a; Linke et al., 2017; Han et al., 2017). One of these products – the Forest Cover-Loss, available yearly – quantifies any tree-cover loss (percent tree cover below 25% and trees higher than 5 m) against a baseline of year 2000 forest cover. This means that all losses of any type of forest (i.e. primary tropical rain forest, secondary forest and dry tropical woodland) or deforestation dynamics (silviculture rotations, fire, selective logging, shifting cultivation and natural disturbances) are accounted for (Hamilton and Casey, 2016; Han et al., 2017). Data is available at a spatial resolution of 1 arc-second per pixel, approximately 30 m per pixel at the equator, with no minimum mapping unit defined (Landsat pixel scale) (Beyene, 2014, p. 51; GCF, 2018a, b; Han et al., 2017).

The PRODES project produces annual estimates of the deforestation rate and the spatial extent of deforestation since 1988 at the BLA level. The methodology[1] applies a linear spectral mixing model to Landsat data to obtain the shade, soil and vegetation endmember proportions used to classify the five classes of PRODES classification (Morton & DeFries, 2005): clouds, non-forest, previous deforestation, new deforestation, and forest classes. It only detects large-scale deforestation of disturbed and undisturbed primary forest – old-growth forests of dense humid tropical forest biome – adopts a minimum mapping unit of 6.25 ha, and provides data with a spatial resolution of 60 m.

For each dataset, data were extracted for all types of PA and a 10-km surrounding buffer. In addition, a minimum mapping unit of 1 ha was adopted in accordance with the Brazilian forest definition based on the United Nations Framework Convention on Climate Change (UNFCCC) (Sasaki and Putz, 2009): an area of land greater than 1 ha, with more than 30% canopy cover and a minimum tree height of 5 m. The UNFCCC defines forest as an area of land 0.05–1 ha in size, of which more than 10–30% is covered by tree canopy, but countries participating in the program are free to choose their own forest definition within those ranges (Sasaki and Putz, 2009). As such, sixteen forest-loss maps were obtained for each dataset, eight inside and eight outside PAs. Each PA and the corresponding buffer was labelled with its own attribute to enable analysis. The term “annual forest loss” appears, along the text, since it represents the values of forest cover loss in each year analyzed (2002-2004-2006-2008-2010-2012-2014-2016). In fact we use annual forest cover-loss data at two-yearly intervals across 2002–2016.

2.3. Metric selection for spatial deforestation pattern analysis

Analyzing spatial patterns of deforestation in order to detect and quantify temporal changes requires the collection of information on the composition and configuration of patches (Molina et al., 2015). Our deforestation analysis was based on landscape metrics calculated in the Geographic Information System ArcGIS 10.5.0.6491 (Environmental Systems Research Institute (ESRI), 2016) using the Patch Analyst version 5.2.0.16 (Rempel et al., 2012) and V-LATE version 2.0 beta (Vector-based Landscape Analysis Tools, Lang et al. (2004)) extensions and the datasets described in section 2.2. Each forest-loss map, in raster format, was converted into vectorial format, smoothing edges to ensure that polygons adopted forms near the real, reduce file sizes and facilitate the processing step.

A preliminary evaluation based on field knowledge selected an initial set of four metrics, described in Table 1, as the best measures with which to characterize the fragmentation level (McGarigal et al., 2002). Metrics were calculated at the class level in order to assess the impact of human occupation and land-use dynamics.

Table 1
Description of landscape composition and configuration metrics.

Structural category	Landscape metric	Abbreviation	Description	Units/Value
Area/Density/ Edge	Number of patches	NP	Number of patches	No units; > 1
	Mean patch size	MPS	Average mean surface of the patches	Hectares; > 0
	Edge density	ED	Ratio between the sum of the lengths (m) of all edge segments and the total landscape area (m2), multiplied by 10,000 (convert to hectares)	m/ha; ≥ 0 $= 0$; No edge, consisting of a single patch
Isolation/ Proximity	Mean proximity index	PROX	Sum of the ratio between area and inter-patch distance for all patches within a predefined buffer distance around a patch (a radius of 1000 m was chosen as the buffer)	No units; ≥ 0 $= 0$; patch has no neighbors within the specific search radius; > 0; increases as the neighborhood (defined by the specified search radius) is increasingly occupied by patches of the same type and as those patches become closer and more contiguous (or less fragmented) in distribution

Several studies have focused on the efficiency of using a set of metrics in the landscape fragmentation analysis to avoid data redundancy, rather than using all available metrics (Ghosh et al., 2012; Tian et al., 2011). To ensure that a set of uncorrelated metrics was chosen in this case, we used the Pearson correlation coefficient criteria and a multivariate statistic method based on Principal Component Analysis (PCA).

2.4. Modelling a fragmentation index

Fragmentation levels were evaluated through an index modeled using the landscape metrics and the Principal Component Analysis (PCA) method. First, the four metrics were standardized based on the standard deviation model to make it possible to compare values of different variables. For each dataset, all standardized metric values calculated inside PAs, for all years, were used to model the fragmentation index equation. The purpose was to obtain a single equation per dataset that could represent all fragmentation variations in the period under analysis. The same procedure was followed for buffer areas. Based on Tian et al. (2011) and on Cumming and Vernier (2002), the PCA method was executed, using IBM SPSS software (IBM Corporation Released, 2017), with a varimax rotation criterion, to obtain the eigenvalues (which explain the variance of the metrics), which were used as the weight attributable to each component. The varimax rotation criterion was used to aid in the interpretation of component loadings (the coefficients of individual variables in the principal components) (Cumming & Vernier, 2002) since it attempts to prevent the variables of having high factor loadings for various components (Rossoni et al., 2016).

The variables (metrics) with higher loadings in each component (Table 3) were retained and used to build the fragmentation index. The first two components, with eigenvalues greater than one, always explain the variance above 78.1%, and they represent the characteristics of the four metrics (Table 2). According to Kaiser (1960), principal components are sufficiently reliable if eigenvalues are greater than one. Principal component (PC) 1 always represented the relationships between patches of deforestation (NP and ED), while PC 2 was related with the degree of proximity between patches and their size (MPS and

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[1] http://www.obt.inpe.br/prodesdigital/metodologia.html.

Table 2
Factor loadings before and after the varimax rotation criterion in the PCA method.

Dataset	Factor	Initial eigenvalues			Extraction sums of loadings squared			Rotation sums of loading squared		
		Total	%Variance	%Cumulative	Total	%Variance	%Cumulative	Total	%Variance	%Cumulative
Hansen inside PAs	1	**2.230**	55.746	55.746	2.230	55.746	55.746	2.045	51.120	51.120
	2	**1.066**	26.652	82.399	1.066	26.652	82.399	1.251	31.278	**82.399**
	3	0.670	16.750	99.149						
	4	0.034	0.851	100.000						
Hansen outside PAs	1	**2.039**	50.972	50.972	2.039	50.972	50.972	1.965	49.124	49.124
	2	**1.085**	27.130	78.101	1.085	27.130	78.101	1.159	28.977	**78.101**
	3	0.848	21.192	99.293						
	4	0.028	0.707	100.000						
PRODES inside PAs	1	**2.008**	50.190	50.190	2.008	50.190	50.190	1.926	48.142	48.142
	2	**1.394**	34.838	85.028	1.394	34.838	85.028	1.475	36.887	**85.028**
	3	0.529	13.231	98.260						
	4	0.070	1.740	100.000						
PRODES outside PAs	1	**1.979**	49.470	49.470	1.979	49.470	49.470	1.951	48.776	48.776
	2	**1.239**	30.964	80.434	1.239	30.964	80.434	1.266	31.658	**80.434**
	3	0.740	18.492	98.925						
	4	0.043	1.075	100.00						

In bold are highlighted the eigenvalues higher than 1.

PROX) (Table 3).

The fragmentation index, here designated Spatial Deforestation Fragmentation Index (SDFI), was constructed, based on the eigenvalues of the two principal components (Table 2) and the corresponding loading values of each metric (Table 3), as follows:

$$\mathrm{SDFI}_i = E_{i1} \times (S_1 \times \mathrm{NP}_i + S_2 \times \mathrm{ED}_i) + E_{i2} \times (S_3 \times \mathrm{MPS}_i + S_4 \times \mathrm{PROX}_i)$$

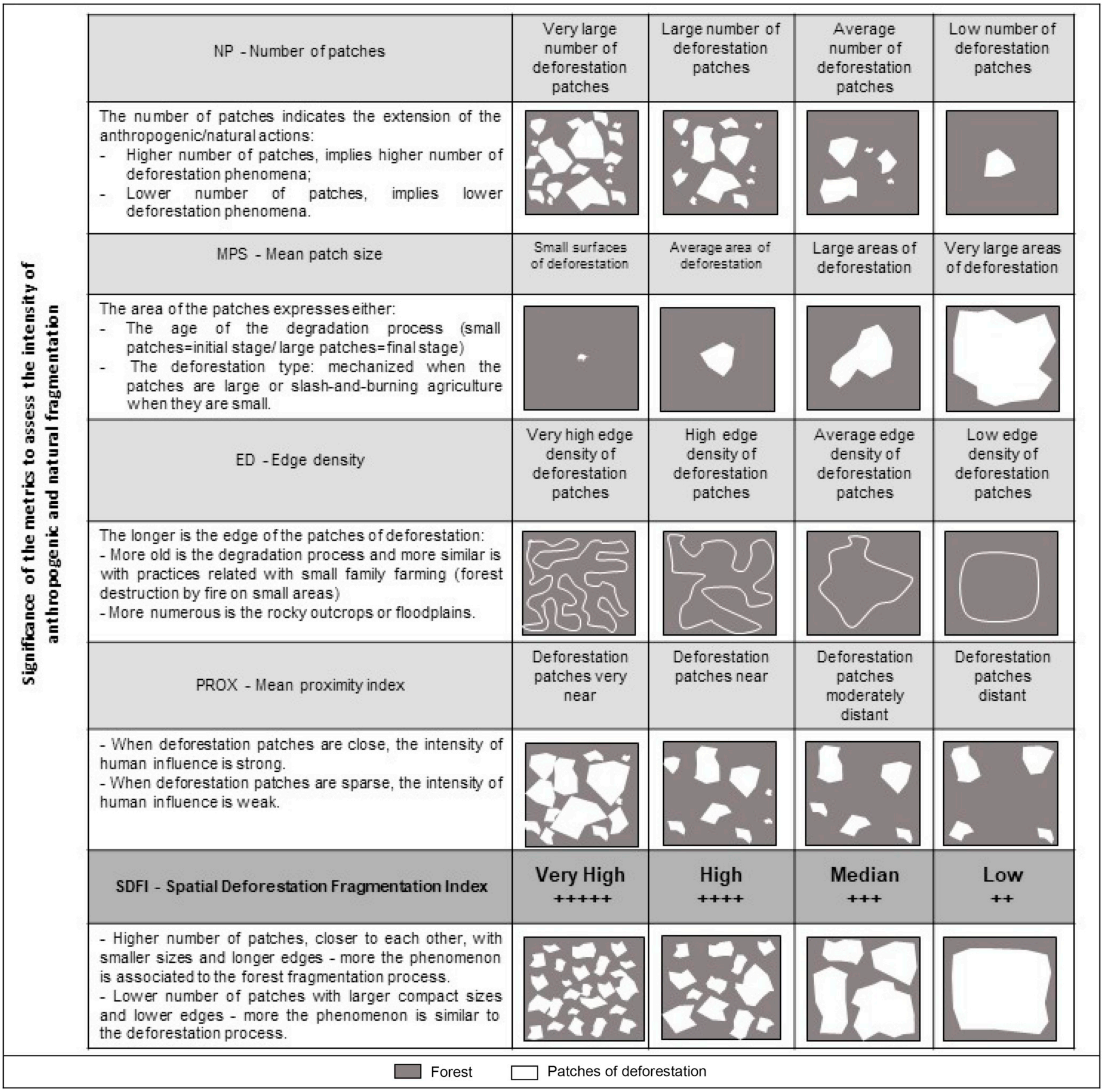
where i is the PA, E_{i1} and E_{i2} are the eigenvalues of the first and second components respectively, S is the loading value of each metric, NP_i is the standardized value of the number of patches, ED_i is the standardized value of the edge density, MPS_i is the standardized value of the mean patch area, and $PROX_i$ is the standardized value of the proximity index.

Considering the different Amazonian landscapes (Dubreuil, Laques, Nédélec, Arvor, & Gurgel, 2008), we visually interpreted all metrics in order to understand how they could be spatially combined to obtain each degree of fragmentation (Fig. 2).

The Jenks natural breaks method was used to divide median index values, inside and outside PAs, into four levels of fragmentation: Low, Median, High, and Very High. Additionally, we analyzed the SDFI trend, based on the slope parameter of the linear regression equation, which was divided into three classes also using Jenks natural breaks: Decrease, Stable, and Increase.

Table 3
Metrics loading on each factor (component) in the PCA method.

Dataset	Metrics	Component	
		1	2
Hansen inside PAs	NP	**0.974**	0.069
	MPS	−0.053	**0.896**
	ED	**0.972**	0.161
	PROX	0.387	**0.647**
Hansen outside PAs	NP	**0.992**	0.035
	MPS	0.003	**0.789**
	ED	**0.983**	0.131
	PROX	0.123	**0.719**
PRODES inside PAs	NP	**0.982**	0.019
	MPS	0.084	**0.853**
	ED	**0.977**	0.103
	PROX	0.022	**0.859**
PRODES outside PAs	NP	**0.989**	−0.02
	MPS	0.028	**0.796**
	ED	**0.985**	0.090
	PROX	0.041	**0.790**



Significance of the metrics to assess the intensity of anthropogenic and natural fragmentation

NP - Number of patches	Very large number of deforestation patches	Large number of deforestation patches	Average number of deforestation patches	Low number of deforestation patches
The number of patches indicates the extension of the anthropogenic/natural actions: - Higher number of patches, implies higher number of deforestation phenomena; - Lower number of patches, implies lower deforestation phenomena.				
MPS - Mean patch size	Small surfaces of deforestation	Average area of deforestation	Large areas of deforestation	Very large areas of deforestation
The area of the patches expresses either: - The age of the degradation process (small patches=initial stage/ large patches=final stage) - The deforestation type: mechanized when the patches are large or slash-and-burning agriculture when they are small.				
ED - Edge density	Very high edge density of deforestation patches	High edge density of deforestation patches	Average edge density of deforestation patches	Low edge density of deforestation patches
The longer is the edge of the patches of deforestation: - More old is the degradation process and more similar is with practices related with small family farming (forest destruction by fire on small areas) - More numerous is the rocky outcrops or floodplains.				
PROX - Mean proximity index	Deforestation patches very near	Deforestation patches near	Deforestation patches moderately distant	Deforestation patches distant
- When deforestation patches are close, the intensity of human influence is strong. - When deforestation patches are sparse, the intensity of human influence is weak.				
SDFI - Spatial Deforestation Fragmentation Index	**Very High** +++++	**High** ++++	**Median** +++	**Low** ++
- Higher number of patches, closer to each other, with smaller sizes and longer edges - more the phenomenon is associated to the forest fragmentation process. - Lower number of patches with larger compact sizes and lower edges - more the phenomenon is similar to the deforestation process.				

▨ Forest ☐ Patches of deforestation

Fig. 2. Spatial relationship between the four landscape metrics and the degree of fragmentation.

3. Results and discussion

3.1. Deforestation dynamic analysis

Time series (2002–2016) of Hansen (H) and PRODES (P) datasets (D) were used to obtain the annual and cumulative forest loss inside and outside PAs (Fig. 3), as well as the annual and cumulative extent of forest loss (Table 4).

The trends in the extent of annual forest loss were different for HD and PD: the former increased from 130,021.9 ha to 707,263.0 ha, and from 479,742.9 ha to 702,947.95 ha, inside and outside PAs respectively, while the latter decreased from 250,057.1 ha to 97,053.3 ha, and 465,762.3 ha to 201,390.6 ha. However, both datasets presented higher forest loss outside PAs.

The cumulative forest loss over the eight years was higher in HD (inside = 0.81%, outside = 2.93%) than in PD (inside = 0.43%, outside = 2.11%), as was the mean annual rate (HD: inside = 0.10%, outside = 0.36%, PD: inside = 0.05%, outside = 0.26%). These values could be due to different forest definitions and methodologies adopted by each dataset, as mentioned in section 2.2.

The higher values estimated by HD may be explained by the fact that it counts losses linked to all forest types and dynamics, whereas PD only considers primary forest. Annual forest loss increased in 2002–2004 (except HD outside), then became relatively stable until 2014, before rising again in 2014–2016. This was the case for both datasets, but values inside PAs were lower than outside. Azevedo and Saito (2013) analyzed the total extent of the deforestation that occurred in Mato Grosso State and was authorized by the Rural Property Environmental Licensing System (SLAPR) in 2000–2007. They found that an increase in authorized deforestation with a high impact on total deforestation area was observed precisely in 2002–2004. 2004 saw the implementation of the Action Plan for the Prevention and Control of

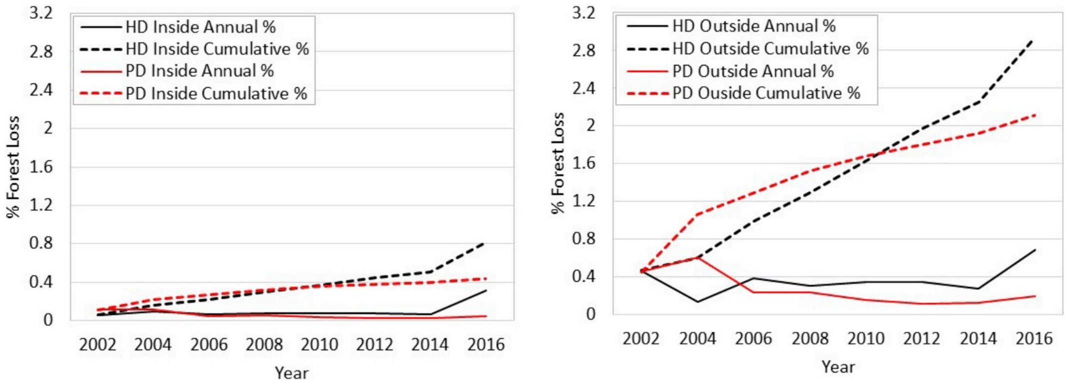


Fig. 3. Annual and cumulative forest loss inside and outside Protected Areas in the Brazilian Legal Amazon for Hansen Global Dataset (HD) and PRODES Dataset (PD).

Deforestation in the Legal Amazon (PPCDAm), which contributed to slow down the deforestation until 2012 (MMA, 2011). The largest reductions were observed in Mato Grosso State, which was the greatest contributor to annual deforestation in the BLA (Azevedo & Pasquis, 2007). Since 2003, the federal government has prioritized the creation of PAs to the south of the River Amazon, as a clear strategy for creating a barrier to the advance of the deforestation boundary in as-yet preserved regions. Two major regions have been considered priority areas: the Porto Velho (RO) – Lábrea (AM) – Rio Branco (AC) triangle, and the region known as “Terra do Meio” (literally “Middle Earth”) in south-central Pará, at the intersection of the Rivers Iriri and Xingu. These two regions together include three ILs and two state and four federal UCs (for a total of 8.4 million ha) and are currently subject to strong social pressure on forests and increases in deforestation around PAs.

The level of protection (Integral Protection (IP), Sustainable-Use Protection (SP), Environmental Protection Area (EPA), or Indigenous Lands (IL)) seems to influence the degree of forest loss (Fig. 4).

Given their high level of degradation and deforestation as noted by Araújo, Barreto, Baima, and Gomes (2017), the EPAs were analyzed separately from the SP units. An increase in cumulative forest loss inside and outside EPAs strongly indicated that this category is incapable of protecting forest. On the contrary, ILs located in regions with high levels of human pressure and a greater increase in forest loss in surrounding areas continued to experience low proportions of forest loss within their perimeters.

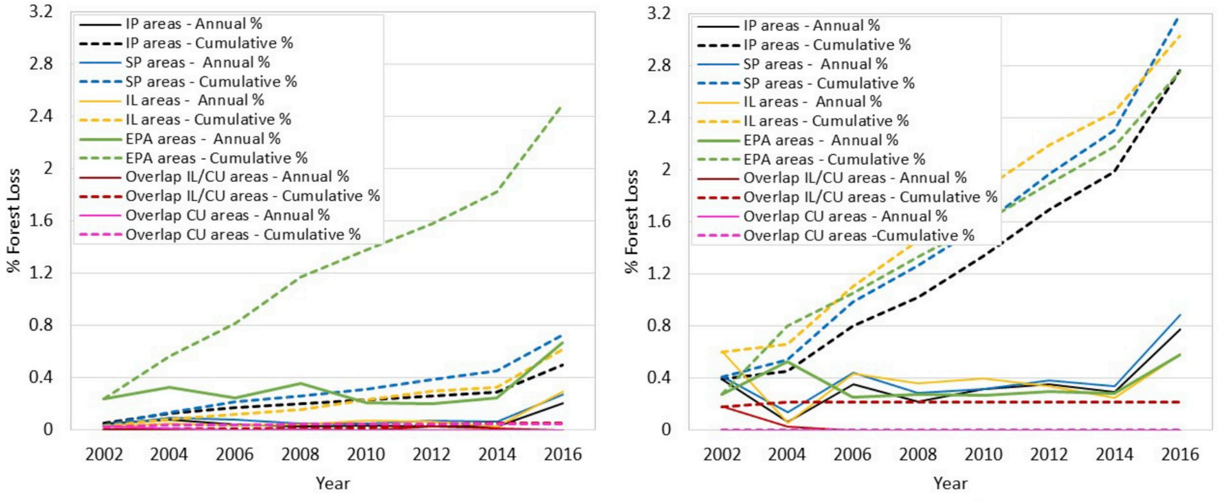
Higher cumulative forest loss was observed, inside PAs, in Pará and Mato Grosso States, and outside PAs, in Acre, Rondônia and Amazonas States, in the priority region referred to above (Table 5 and Fig. 5).

Araújo et al. (2017) highlighted some of these areas as being among the fifty PAs with higher levels of deforestation in the BLA. Although less risk of degradation was observed in Maranhão and Tocantins States, they presented high levels of forest loss in HD, which may suggest higher levels of environmental degradation in the future.

According to Araújo et al. (2017, p. 92), about 87% of the deforestation in the Legal Amazon in 2012–2015 occurred in Pará and Rondônia States, usually near large infrastructures like road networks and hydroelectric installations. ISA (2015) referred the impact the latter factors have had on CUs and ILs and on the definition of new PA boundaries, in the sense that they both promote occupation. In the present study, the SP (Environmental Protection Area (EPA), National Forest (NF), Extractive Reserve (ER)) and IL categories presented higher levels of forest loss, while in the IP category only one PA (National Park – NP) did so. Soares-Filho et al. (2010) said that three categories of PA (Indigenous Lands, Integral Protection, and Sustainable-Use) appeared to have an inhibiting effect on deforestation. In this respect, they especially noted the Xingu, Jarina, Menkragnotí, Baú and Kayapó ILs in central Mato Grosso and Pará States. However, our study indicated the existence of substantial loss of forest in three of these areas – Xingu, Baú and Kayapó. The disturbances in Xingu and Baú are mainly due to anthropic actions, but in Kayapó they are the result of natural

Table 4
Extent of annual and cumulative forest loss inside and outside Protected Areas in the Brazilian Legal Amazon in 2002–2016.

Dataset	Year	Annual forest loss (ha)	Annual forest loss (%)	Cumulative forest loss (ha)	Cumulative forest loss (%)
Hansen inside PAs	2002	130 021.9	0.06	130 021.9	0.06
	2016	707 263.0	0.31	1 868 012.4	0.81
Hansen outside PAs	2002	479 742.9	0.46	479 742.9	0.47
	2016	702 948.0	0.68	3 017 426.8	2.93
PRODES inside PAs	2002	250 057.1	0.11	250 057.1	0.11
	2016	97 053.3	0.04	1 004 493.3	0.43
PRODES outside PAs	2002	465 762.3	0.45	465 762.3	0.45
	2016	201 390.6	0.20	2 174 398.4	2.11



Hansen Dataset Inside

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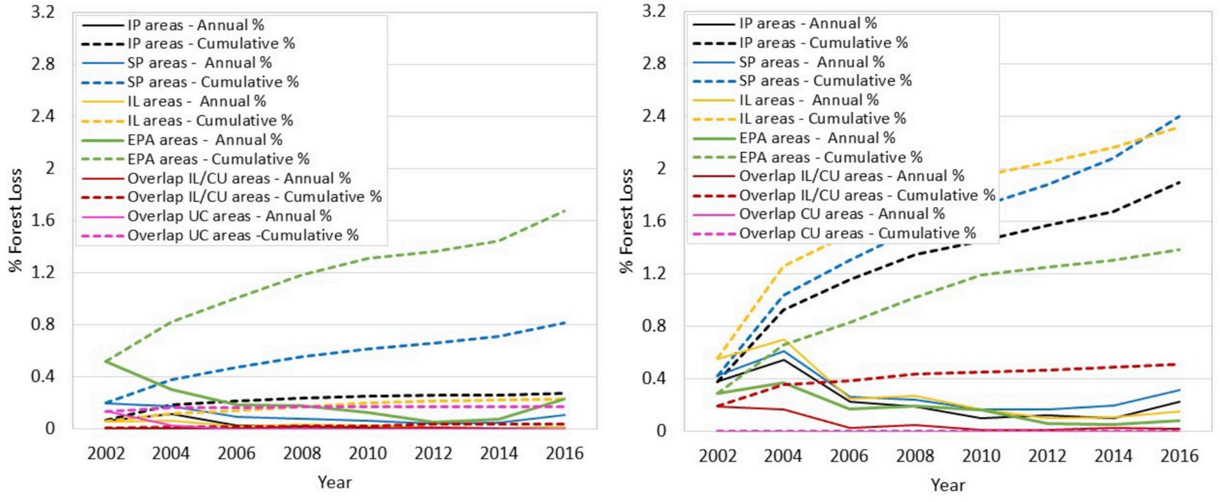


PRODES Dataset Inside

PRODES Dataset Outside

Fig. 4. Annual and cumulative forest loss considering different types of protection area: Conservation Units (CUs) (three groups: IP-Integral Protection, SP-Sustainable-Use Protection, and EPA-Environmental Protection Area), and IL-Indigenous Lands.

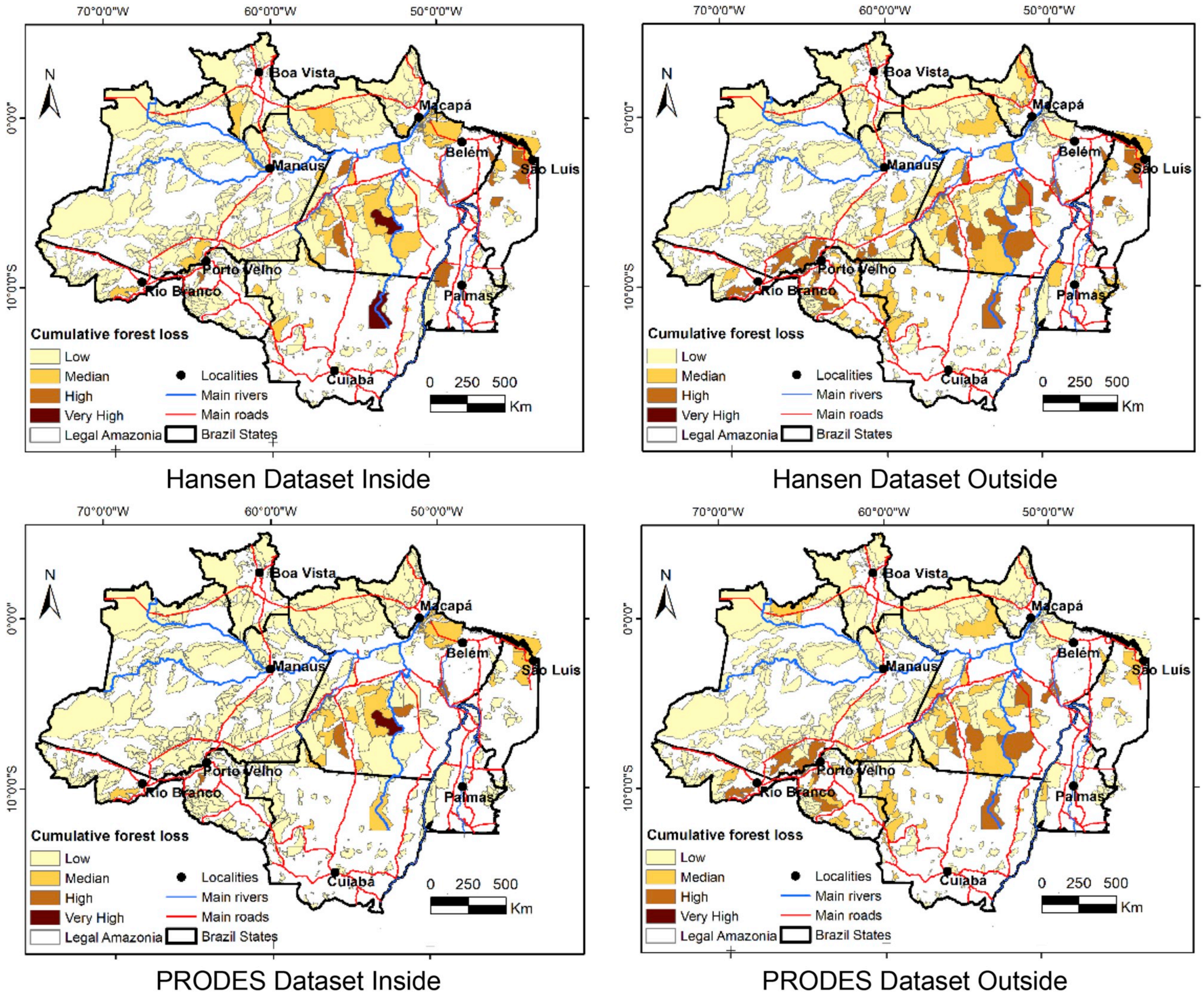
Table 5
Protected Areas with higher forest loss.

Dataset	State	Type of PA	Jurisdiction	Protected Area
Hansen inside PAs	Pará	Environmental Protection Area	State	Triunfo do Xingu
		National Forest	Federal	Jamanxim
		Extractive Reserves	Federal	Tapajós Arapiuns
	Mato Grosso	Indigenous Land	Federal	Xingu Park
	Tocantins	Environmental Protection Area	State	Ilha do Bananal/Cantão
	Maranhão	Environmental Protection Area	State	Baixada Maranhense
		Indigenous Land	Federal	Arariboia
Hansen outside PAs	Pará	Environmental Protection Area	State	Triunfo do Xingu
		Extractive Reserves	Federal	Tapajós Arapiuns
		Indigenous Land	Federal	Kayapó
				Baú
				Trincheira Bacajá
				Apyterewa
	Mato Grosso	Indigenous Land	Federal	Xingu Park
	Maranhão	Environmental Protection Area	State	Baixada Maranhense
		Indigenous Land	Federal	Araribóia
	Rondônia	Indigenous Land	Federal	Eru-Eu-Wau-Wau
	Amazonas	National Forest	Federal	Iquiri
		National Park	Federal	Mapinguari
	Acre	Extractive Reserves	Federal	Chico Mendes
PRODES inside PAs	Pará	Environmental Protection Area	State	Triunfo do Xingu
		National Forest	Federal	Jamanxim
		Indigenous Land	Federal	Apyterewa

(*continued on next page*)

Table 5 (*continued*)

Dataset	State	Type of PA	Jurisdiction	Protected Area
PRODES outside PAs	Pará	National Forest	Federal	Jamanxim
		Indigenous Land	Federal	Baú
				Trincheira Bacajá
				Parakanã
	Mato Grosso	Indigenous Land	Federal	Xingu Park
	Rondônia	Indigenous Land	Federal	Eru-Eu-Wau-Wau
	Acre	Extractive Reserves	Federal	Chico Mendes
	Amazonas	National Forest	Federal	Iquiri
		National Park	Federal	Mapinguari



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PRODES Dataset Inside

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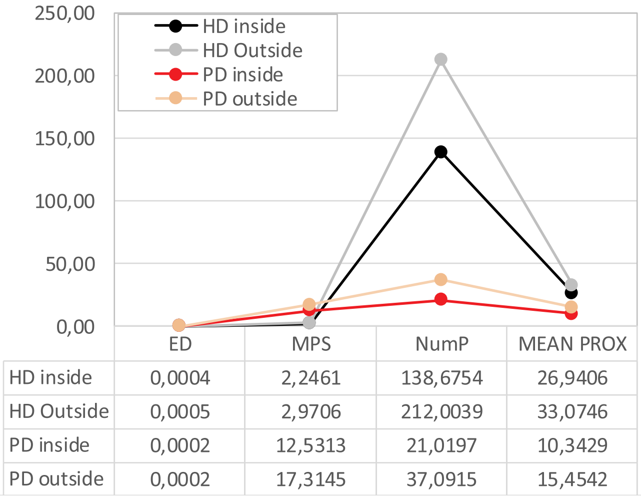
Fig. 5. Cumulative deforestation for 2002–2016. Interval values, in hectares, defined by Jenks natural breaks: Low (0, 7857), Median (7857, 28 724), High (28 724, 81 936) and Very High (81 936, 258 510).

processes, in that the region is characterized by numerous exposed rocky formations.

3.2. *Spatial deforestation patterns and configuration*

The HD presented greater fragmentation than the PD, with a higher number of fragments, lower mean patch size, and greater edge density and proximity, thereby increasing the reported fragmentation process (Fig. 6), as expected given their higher forest loss. In a conservative approach, HD can be useful as a preventive tool, since it can help identify some hotspots that need additional conservative measures; however, by presenting higher values, it can also lead to additional and possibly unnecessary limits on the implementation of policies oriented towards economic development.

The smaller number of fragments (deforested patches) shows that the fragmentation process is smoother within PAs, but in both cases most patches were between 100 and 10,000 ha in size (Figs. 6 and 7).



	ED	MPS	NumP	MEAN PROX
HD inside	0,0004	2,2461	138,6754	26,9406
HD Outside	0,0005	2,9706	212,0039	33,0746
PD inside	0,0002	12,5313	21,0197	10,3429
PD outside	0,0002	17,3145	37,0915	15,4542

Fig. 6. Average class metrics for each Hansen Global dataset (HD) and PRODES dataset (PD) inside and outside Protected Areas.

3.3. Fragmentation index analysis

The index we used was designed to evaluate forest fragmentation in PAs and their surroundings and identify possible critical areas where PA regulations are insufficient to protect forest on their own and additional conservation measures may be needed. Fig. 8 shows the average index values for 2002–2016. Most of the areas presented a low or median risk of fragmentation. Only two PAs located in Pará State (EPA-Triunfo do Xingu and NF-Jamanxim for both HD and PD, and IL-Kayabi for PD only), and one each in Mato Grosso (IL-Xingu Park for HD), Maranhão (EPA-Baixada Maranhense for HD), Tocantins (EPA-Ilha do Bananal/Cantão for HD), and Acre (ER-Chico Mendes for PD) States presented higher levels of risk. Outside PAs, two areas were at risk in Pará State (EPA-Triunfo do Xingu and IL-Parakanã for HD, and IL-Kayapó and Parakanã for PD), along with three in the Porto Velho (RO) – Lábrea (AM) – Rio Branco (AC) (ER-Chico Mendes and NP-Mapinguari, and IL-Eru-Eu-Wau-Wau, respectively for both HD and PD) triangle and just one in Maranhão State (EPA-Baixada Maranhense for HD). According to Mascarenhas et al. (2017), deforestation in ER-Chico Mendes is associated with cattle-ranching, and with forest fires due to extreme drought events. These fires occur not only in regions with greater human pressure, but also in isolated areas without terrestrial access, reflecting the forest's great vulnerability to extreme drought.

Most of the at-risk areas are in the arc of deforestation, which encompasses southeastern Maranhão, northern Tocantins, southern Pará, northern Mato Grosso, Rondônia, southeastern Amazonas, and the southeastern areas of Acre. This is a region where cattle-ranching,

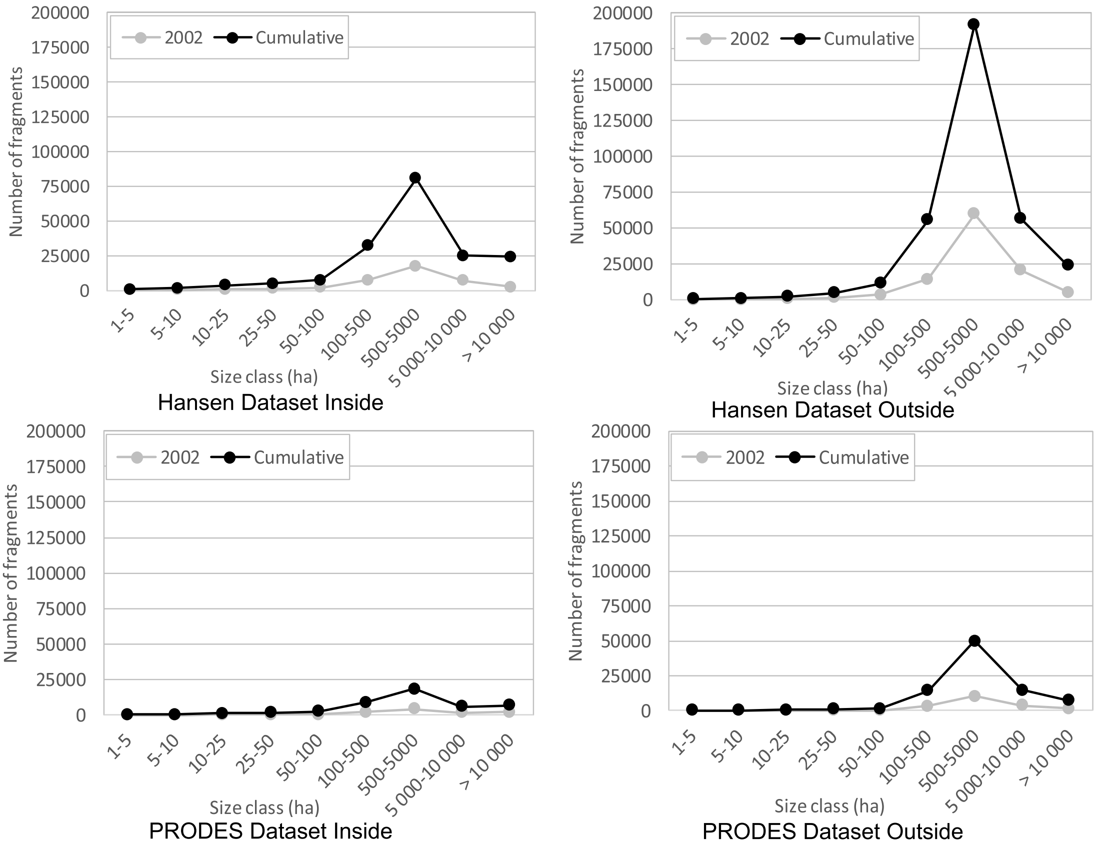
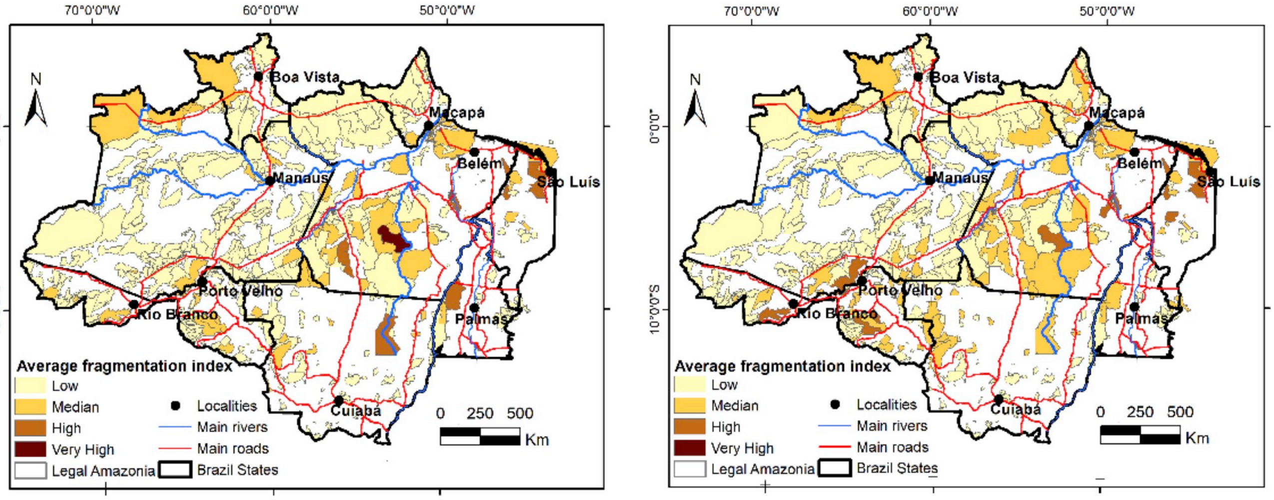


Fig. 7. Number of deforested fragments by size class for the base year 2002 and cumulative years.



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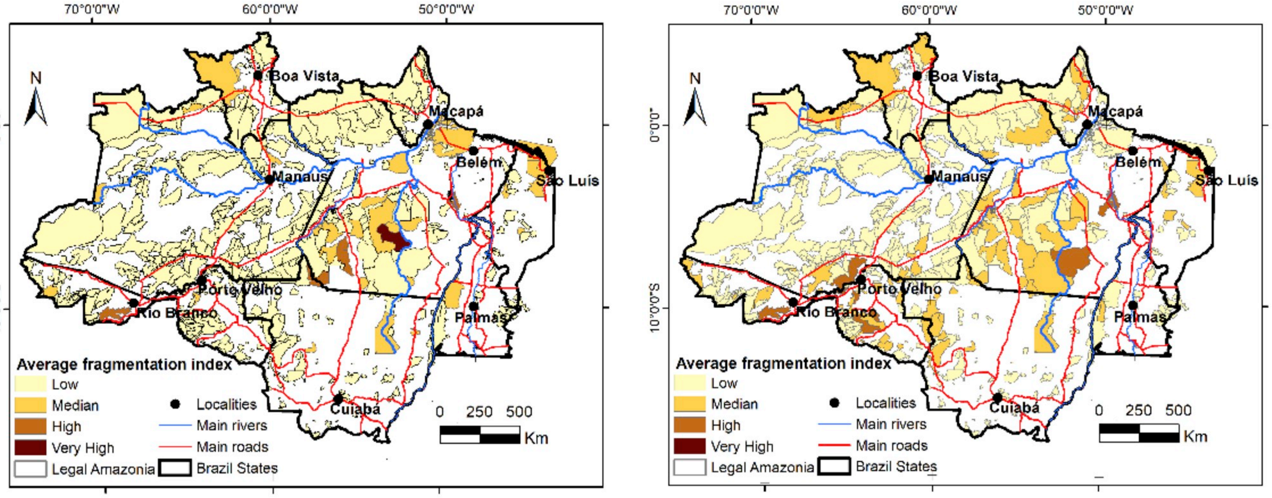

PRODES Dataset Inside

PRODES Dataset Outside

Fig. 8. Average fragmentation index for 2002–2016. Interval values (no units) defined by Jenks natural breaks: Low (−2.37, 1.52), Median (1.52, 10.07), High (10.07, 33.20) and Very High (33.20, 124.39).

small-scale farming and, in the last fifty years, large-scale soy farming have been playing important roles in the clearing of Amazonian forests (Arvor, Meirelles, Dubreuil, Bégué, & Shimabukuro, 2012; Colson, Bogaert, & Ceulemans, 2011). The increase in these activities has contributed to a denser road network, which many authors have suggested is one of the two main factors behind the increase in deforestation, the other being population density (Colson et al., 2011).

As we mentioned earlier, our deforestation analysis showed an increased trend towards fragmentation in EPAs and SPs (Fig. 9).

EPAs (included in the SP group) allow people to live inside PAs, but are considered the weakest category in Brazil's environmental policy when it comes to the enforcement of nature protection. They are usually characterized by larger areas, including urban settlements and even large cities, whereas the SP group, excluding EPAs, is designed to foster the sustainability of traditional communities and their ancestral practices. In general, fragmentation seems to have been stable in the period under analysis (Fig. 10).

Nevertheless, we can see that the apparent stability of the fragmentation process is geographically unequal, suggesting that there are some hotspots in the Northern region (mainly in the Yanomami Indigenous Land (YIL) in Roraima State) and the arc of deforestation where fragmentation is tending to increase. Although the arc is already a well-known deforestation hotspot, the rising rates of forest fragmentation in the YIL confirm an increase in illegal mining activity (Nilsson & Fearnside, 2011), which has been continuously resisted by the local indigenous community and government. These mining activities take place both in water and on land and require the support of light-aircraft landing strips in the forest, which themselves cause additional deforestation and a loss of forest humidity. Nilsson and Fearnside (2011) call goldmining activities the main contributor to forest clearing, especially following the invasion of the YIL by goldminers in 1994–1995, and highlight their impact on Yanomami communities.

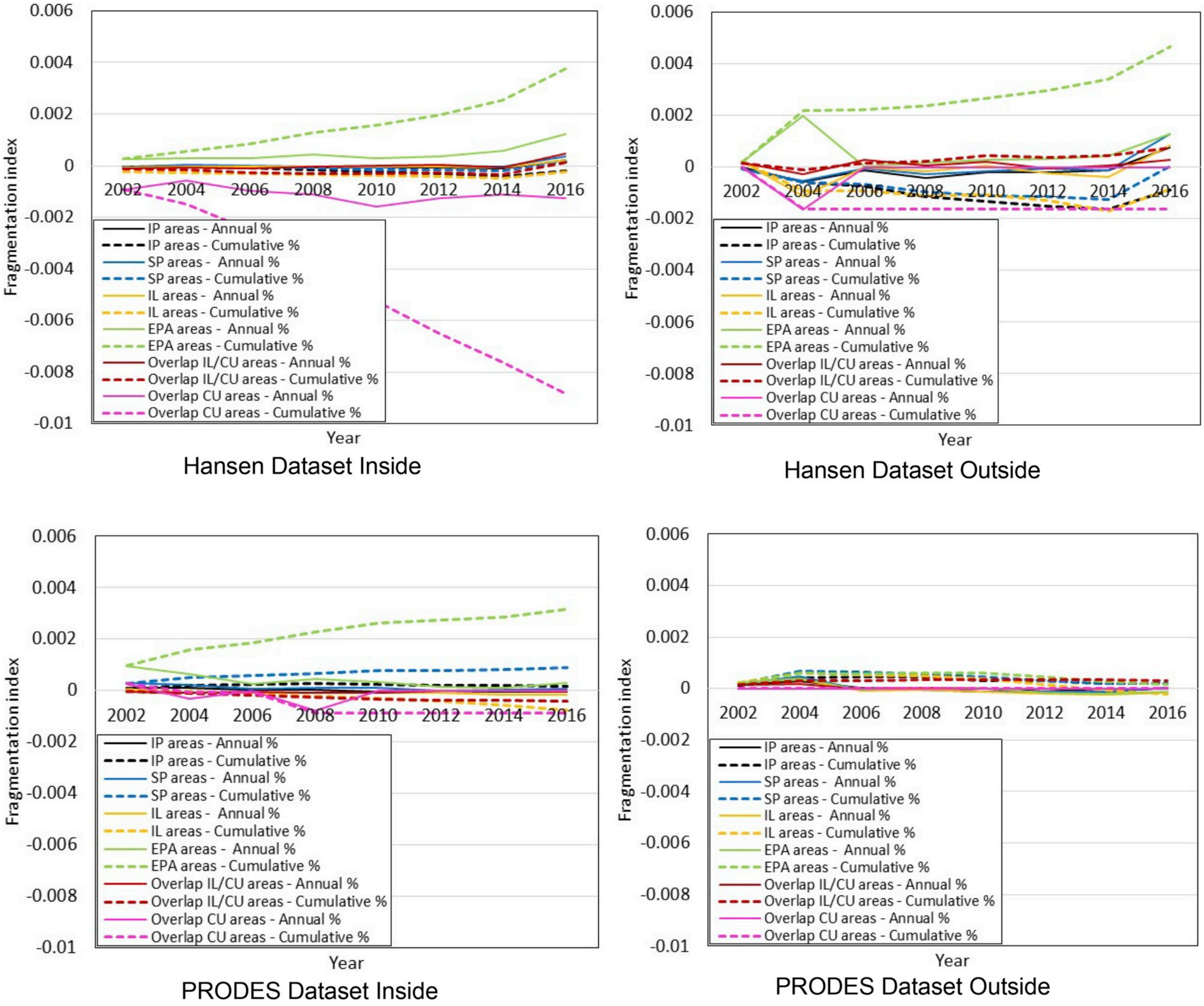

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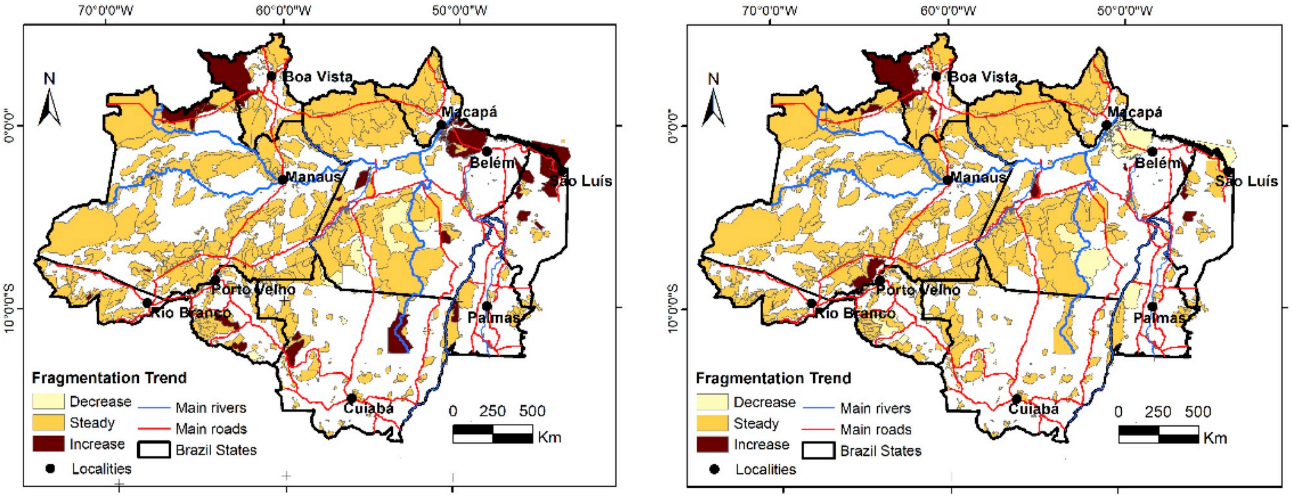
Fig. 9. Annual and cumulative fragmentation index values. Types of protection area: Conservation Units (CUs) (three groups: IP-Integral Protection, SP-Sustainable-Use Protection, and EPA-Environmental Protection Area), IL-Indigenous Lands.



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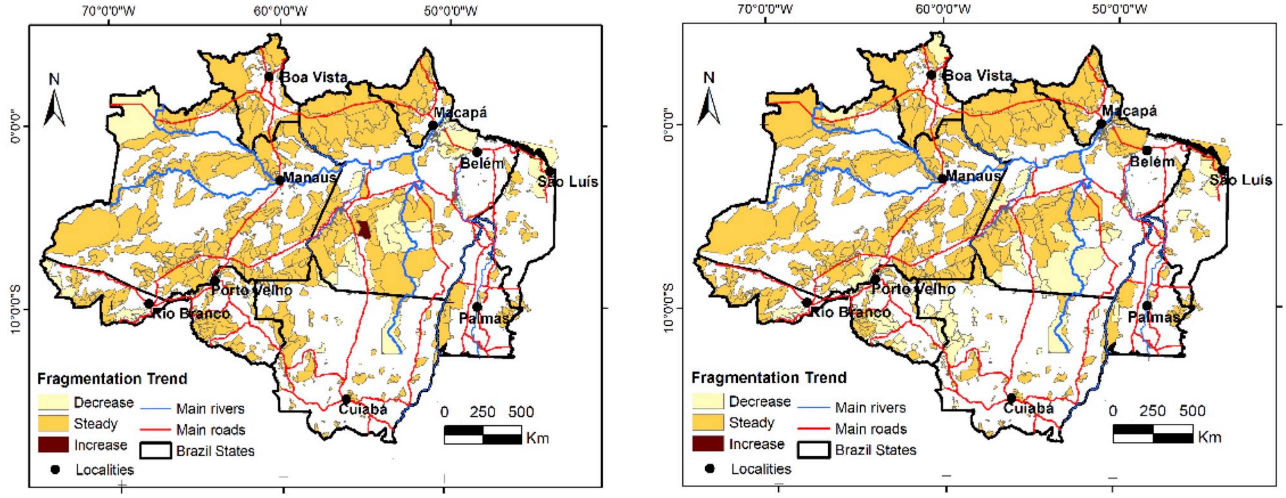

PRODES Dataset Inside

PRODES Dataset Outside

Fig. 10. Fragmentation trends, 2002–2016. Interval values (no units) defined by Jenks natural breaks: Decrease (−2.76, −0.37), Stable (−0.37, 1.03), Increase (1.03, 5.71).

4. Conclusions

Given the increased forest loss in the Brazilian Legal Amazon in the last few decades and the significant impact on the life of people who are dependent on the forest, it is important to obtain information on the past and present states of forests that will help policymakers implement rules which permit sustainable management. Such data make it possible to estimate the effectiveness of the Protected Areas (PAs) that are created with the goal of preserving forest cover. Evaluating changes on a regional scale in the BLA is difficult, expensive and time-consuming, because it implies the analysis of large amounts of data. It is thus important to find new types of data that provide accurate and up-to-date information while minimizing costs. Within this context, a comparative analysis of the most commonly used datasets is useful to an understanding of both limits and possibilities. In the present study, a global dataset produced by automatic methods was compared with a regional dataset developed by the country in question using a specific time-consuming methodology. Instead of resorting to a traditional analysis based on forest patterns, we used forest-loss patterns. Regardless of the data source, deforestation and fragmentation analysis revealed a generally stable trend throughout the BLA except for some hotspots in the arc of deforestation, where the trend is a rising one. A mixed analysis combining deforestation, fragmentation index and trends provides some interesting insights, in that the Yanomami Indigenous Land was highlighted – a result that contrasts with the idea given by deforestation data or fragmentation indices. Fragmentation trends identified this as an area that needs to be carefully considered in more detail, with a new look at the socio-environmental conflicts and hazardous drivers that may be heralding a disaster in the near future. Although global data cannot replace regional information (with its greater accuracy), it does help build a reliable historical profile of the state of forests when no regional data exists.

In addition, our analysis shows that PAs play an important role in the sustainability of the forest ecosystem in the BLA and are a powerful weapon in the fight to reduce deforestation and forest degradation – a conclusion that matches those of a number of authors (Bebber & Butt, 2017; Lee et al., 2007; Nicolle and Leroy, 2017; Soares-Filho et al., 2010). However, care is needed to ensure that local people are not adversely affected by the implementation of conservative measures (Andersen et al., 2017). The real challenge is to achieve two simultaneous compromises: between conservation measures and anti-poverty programs that enable families to increase their incomes; and between a reduction in poverty and the preservation of the forest and respect for the right of Amerindians to use their territory.

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