https://doi.org/10.18406/2316-1817v15n120231739 e-ISSN 2316-1817

Deforestation patterns and stages of the Southern Amazon agricultural frontier

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Received in: 08/07/2022
Accepted in: 06/12/2022

Abstract

From 1980 to 2020, the Paciá River Drainage Basin (BHRP – Bacia Hidrográfica do Rio Paciá), located in the Southern Amazon agricultural frontier, underwent an accelerated process of change in human land use and occupation. This study aimed to identify and analyze deforestation patterns, relating them to landscape metrics and the stages of expansion of the agricultural frontier. The methodology was based on the following phases: 1) organizational structure of GIS (Geographic Information System) modeling; 2) mapping and classification of deforestation patterns; 3) mapping of the expansion stages of the agricultural frontier. Diffuse and geometric patterns represented 72.5% of the polygons analyzed, corresponding to 15.64% of deforestation. However, linear and consolidated patterns, which referred to 12.5% of the polygons, represented 65.5% of the deforested areas in the BHRP. The spatial arrangements of deforestation polygons are associated with two evolutionary stages of the Amazon agricultural frontier: permanent/consolidated, which is located along the Transamazon highway, and pioneer/diffuse, located along the banks of rural roads and the main course of the Paciá River.

Keywords: Land occupation; change; land use; metrics; pioneer.

Introduction

A thousand years ago, tropical forests corresponded to 12% of the Earth's greens areas. However, currently, less than 5% of the planet's surface is covered by moist forests. The largest portion of tropical forest is in the Amazon basin and represents almost 33% of the world's remaining forest cover. Another 20% is located in the Congo basin, West Africa, and hundreds of islands in Indonesia and Malaysia, Southeast Asia. The last 47% are spread in thousands of remaining fragments of tropical forest along the equator (MARTINI, 2002; NUBE, 2013; FAO, 2020).

In 2020, the Amazon rainforest, which has about 284 million hectares (ha) and is distributed in nine countries in South America, experienced in its Brazilian part the largest loss of primary forest, since 1.05 million ha were deforested and transformed into various land use and land cover classes (FERREIRA e SILVA, 2008; INPE, 2022).

In the Legal Amazon, deforestation has been more intense in the municipalities of Caracaraí (RR), Porto Velho (RO), Altamira (PA), Apuí (AM), Lábrea (AM), and Colniza (MT). The replacement of the forest by another type of land use and land cover is concentrated in the rural area of Lábrea, which has a peculiar history of population occupation, regional development, conflict over land ownership, and lack of land regularization (AZEVEDO et al., 2019).

Land cover changes in the rural area of Lábrea can be classified between two types: conversion or modification. Conversion refers to the exchange of one land cover class for another of the same category; for example, converting an area of shifting cultivation or slash-and-burn agriculture into cultivated pasture for extensive beef and dairy cattle farming. Modification involves the total or partial transformation of the structure, function, and floristic land cover composition. Thus, it refers to the change of land use and land cover category; for example, transforming a native forest area into cultivated pasture (BRIASSOULIS,1999).

Considering the deforestation spatial database of the Brazilian Amazon Rainforest Monitoring Program by Satellite (PRODES), many studies have been conducted in the Amazon (ESCADA, 2003; BATISTELLA e MORAN, 2005; SILVA et al., 2008b; SAITO et al., 2011; MAURANO et al., 2019), aiming to analyze typological patterns of deforestation via remote sensing images, relating them to landscape ecology metrics and evolutionary stages of human occupation. These studies agree that the substitution of the open and dense ombrophilous forest in the Amazon is associated with different processes of change in land use and ownership, human occupation of private property in rural areas, and appropriation of natural capital by transnational companies.

Mertens and Lambin (1997) developed the pioneering study on typological patterns of land cover change (geometric, fishbone, diffuse, fragments, and island patterns) and landscape metrics, associated with the evolutionary stage of human land use and occupation. These authors observed, when analyzing deforestation in a deciduous forest in southern Cameroon, Africa, that three typological patterns of land cover change stood out: corridor, associated with spontaneous colonization along roads; diffuse, related to smallholder migratory agriculture; and island, associated with urban area formation.

Escada and Alves (2003) conducted one of the first studies of typological patterns and landscape metrics in the Amazon and found great heterogeneity of spatial patterns of land use and land cover change. From 54 Occupancy Units (UOP – Unidades de Ocupação), they established ten different land use and land cover patterns and grouped them according to some categories, such as form of land ownership, age range of properties in the rural settlement, size of rural establishments, among others. In the UOPs analyzed, the deforestation pattern characterized as fishbone predominates in Rondônia, associated with small rural property, which includes families settled by the National Institute for Colonization and Agrarian Reform (INCRA) in plots of up to 100 ha.

Fearnside and Graça (2009) analyzed typological patterns of deforestation and observed from CBERS-2 images a fishbone pattern (orthogonal) in the district of Santo Antônio do Matupi (AM), which shows that the loss of forest cover extends along the main state, federal, and municipal roads and highways and is mainly concentrated on small family farms of up to 100 ha; in large farms (>1000 ha), it is dispersed and isolated.

Monitoring data on loss of forest cover in the last ten years, aggregated by municipality, show that Lábrea is in the list of Brazilian municipalities with the highest annual deforestation rate. This very region includes 18 Indigenous lands (IL), four conservation units, of which two are of sustainable use and two of integral protection, and one sustainable development settlement (CENAMO et al., 2011).

In the land-use planning of Lábrea, Indigenous lands, conservation units, and sustainable development settlements represent 75.9% of the total area (68,262,680 km^2) and 24.1% are areas for multiple land use, which is similar to the municipalities of Altamira (PA), São Felix do Xingu (PA), and Porto Velho (RO). Although they have a significant integral protection area, these municipalities are at the top of the list of Amazon municipalities with the greatest increase in annual deforestation and carbon dioxide (CO_2) emissions from 2010 to 2020.

This information refers to a singular problem: why do municipalities with extensive integral protection areas have high rates of loss of forest cover? The need for further research on the causes inherent to land cover change in the rural area of Lábrea, especially in the Paciá River Drainage Basin (BHRP), motivated and justifies this study.

Studies show that the patterns of land cover change are related to the different evolutionary stages of the agricultural frontier (MARTINS, 2005; GAVLAK et al., 2011). The heterogeneity of spatial processes and patterns of land use and occupation in the Amazon, identified by satellite image processing, allows the recognition of four evolutionary stages of use and occupation in the agricultural frontier—pioneer, transitional, consolidated, and urbanized—in line with Diniz (2002). Thus, this study aimed to identify and analyze typological patterns of deforestation, relating them to landscape ecology metrics and the evolutionary stages of the expansion of the agricultural frontier in the BHRP.

Material and methods

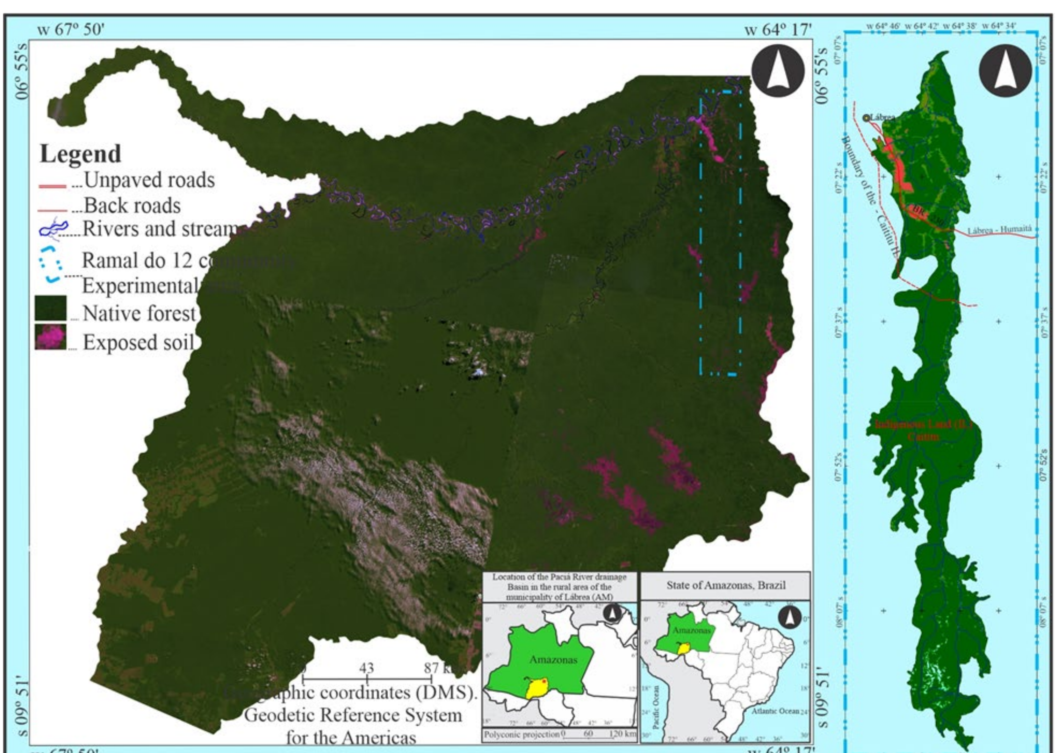
Study site

This study was developed in the Ramal do 12 agricultural colony (CAR-12) in the BHRP. This community is part of the Umari Settlement Project (PA-Umari), located in the middle course of the Paciá River. The BHRP is located between the following geographical coordinates: longitude 64°45'14" and 64°34'21" W and latitude 07°07'16" and 08°07'06" S (Figure 1).

Lábrea is part of the microregion of the middle Purus River and the Legal Amazon. The primary forest cover in this region is classified as lowland open ombrophilous forest with palm trees, alluvial open ombrophilous forest and terraces with palm trees, *campinarana* (without undefined use and cultivated vegetation, originated from shifting or migratory agriculture), cultivated fields (pasture) for extensive beef and dairy cattle farming, and agroforestry system (LINHARES, 2017).

The Paciá River flows by Southern Amazon equatorial forested lowlands, a natural environment where the humid equatorial climate, according to Strahler classification, predominates,

Figure 1. Image charts of the municipality of Lábrea, with the location of the Paciá River drainage basin (AM).



Source: LANDSAT-TM images/scenes 001/65, 001/66, 233-65, and 233-66-RGB. Cartographic base elaborated from the topographic map of the Directorate of Geographic Service (DSG) of the Ministry of the Army; scale 1:100000. Prepared by the authors.

with three dry months (June to August) and high average annual temperatures (24°C and 27°C). Most rainfall occurs from November to March; thus, these months have the highest rainfall rates (from 1310 to 1555 mm). April to October are transition months (SILVA et al., 2008a).

Methodological procedures

The methodology of this study was based on Silva et al. (2008b), Gavlak et al. (2011), and Saito et. al. (2011) and involves a quantitative research of a basic nature with exploratory objectives. To understand the problem, quantitative data from primary and secondary research sources were used. Quantitative data received descriptive and comparative statistical significance treatment of the average of landscape metrics and its main variable was the size of deforestation polygons and the remaining tropical forest in the BHRP. This methodology included three phases: 1) organizational structure of GIS (Geographic Information System) modeling; 2) mapping and classification of typological land cover patterns; 3) mapping of the expansion stages of the agricultural frontier in the BHRP. These phases are detailed below.

Organizational structure of GIS modeling

In this phase, in the main GIS/SPRING 5.0 module, the AMAZ_SUL geographic database and SQLite Manager were chosen to store the study data. Later, the (Umari_AM) project was created. The lat/long map projection system, adjusted to Datum SIRGAS 2000, the international reference system for the Americas, was used. In the SPRING data model interface, categories were defined with their information plans (IP) and attributes: i) image (LANDSAT); ii) theme (Ter_Legal, Rede_hídrica, Rodovias, sede_municipal); iii) object (Assent_rur); iv) registration map (geology, relief, soil, and vegetation) (INPE, 2015).

The selection of polygons with typological patterns of deforestation and landscape metrics, associated with the stages of human land use and occupation, was performed by processing images captured by the TM sensor on board the LANDSAT satellite (scenes 233/065 and 233/066), which had 30-m spatial resolution (pixel) and RGB color composition (B3: red; B4: green; B5: blue).

After image rectification, pre-interpretation was performed using the supervised classification method with the maximum likelihood algorithm, in which five land cover sampling classes were considered: 1) deforestation; 2) primary forest; 3) pasture; 4) exposed soil; and 5) watercourses. Based on this information, thematic land cover maps of the BHRP were produced (MOREIRA, 2001).

Criteria to classify typological land cover patterns in the BHRP

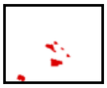
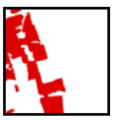
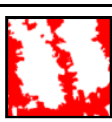
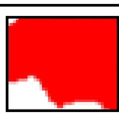
In the first step of this phase, deforestation patterns and land cover changes were classified for 1988 to 1997, 1998 to 2007, and 2008 to 2020, following the typology presented in Table 1.

According to their size in ha, deforested areas were sorted by screen sampling into six deforestation polygons (<10 ha; 11–50 ha; 51–100 ha; 101–200 ha; 201–250 ha; >250 ha).

From a set of landscape metrics, the metric attributes of polygons that discriminated the different areas corresponding to a given change in land cover were analyzed. The metric dimensions of deforestation polygons were associated with each typological pattern of human land use and occupation (Table 1).

Based on the analytical procedures established by Silva et al. (2008b) and Saito et al. (2011), six landscape metrics were considered in the analysis of deforestation polygons: perimeter (PERIM/m), area (AREA/ha), edge density (ED), mean patch size (MPS), mean patch fractal dimension (MPFD), and mean perimeter-area ratio (MPAR).

Table 1. Typology of deforestation patterns and stages of human occupation of the agricultural frontier.

Form of deforestation	Deforestation pattern	Description	Stage of the agricultural frontier
	**Diffuse**	Small, isolated patches; low density; uniform distribution.	**Pioneer use and occupation** Spontaneous popular occupation; small rural producers.
	**Linear**	Elongated and continuous patches; spaced and unidirectional.	**Pioneer use and occupation** Along the roads, eventually planned; small rural producer.
	**Geometric**	Regular geometric shape (symmetrical); low and medium density; medium and large isolated patches.	**Pioneer use and occupation** Popular occupation, planned by the farmer; medium and large farmers.
	**Multidirectional**	Small and medium asymmetrical patches that have joined together; medium to high density.	**Transitional use and occupation** Popular occupation, sometimes spontaneous; concentration of small and medium farmers.
	**Bidirectional**	Small and medium elongated patches with opposite and/or parallel directions.	**Transitional use and occupation** Planned by INCRA; Small farmers.
	**Consolidated**	Large, compact, and continuous patches.	**Permanent public and private use and occupation** Large farmers.

Source: Prepared by the authors, based on Gavlak et al. (2011), Saito et. al. (2011), and Diniz (2002).

In GIS/SPRING, the automatic vector classification routine started by selecting the theme class editing tool from the main menu, which established the association operator and the polygon entity. From the classes and attributes presented in Table 1 (deforestation patterns and stages of land use and occupation), the polygons obtained in the image segmentation and classification phases were classified. Thematic maps were prepared using the GIS/SPRING automatic vector classification tool, following the methodology proposed by Martinelli (2003). Map layouts were defined and adjusted in the SPRING 5.0 SCARTA module.

Mapping of the stages of the agricultural frontier in the BHRP

In the evaluation of the evolutionary stages of the agricultural frontier, materialized by human land use and occupation in the BHRP, criteria were established based on the classification of typological patterns of deforestation. All polygons representing primary forests (continuous primary forest polygon and/or remaining fragments of primary forest) in 1997 with some other type of human land use and occupation in the following years were considered as a path of frontier expansion. Polygons with a diffuse, linear, or geometric land use and occupation pattern from 1998 to 2008 and a multidirectional or consolidated pattern from 2009 to 2020 were considered as a consolidation path. Polygons with a diffuse or consolidated pattern until 1997 with no change in their pattern were classified as diffuse or consolidated. Polygons with linear, bidirectional, and geometric patterns that did not reach the consolidation level were classified as other patterns. These criteria allowed the compatibility of analysis procedures for typological patterns of deforestation, associated with the evolutionary stages of the agricultural frontier described by Diniz (2002) and adapted by Gavlak et al. (2011).

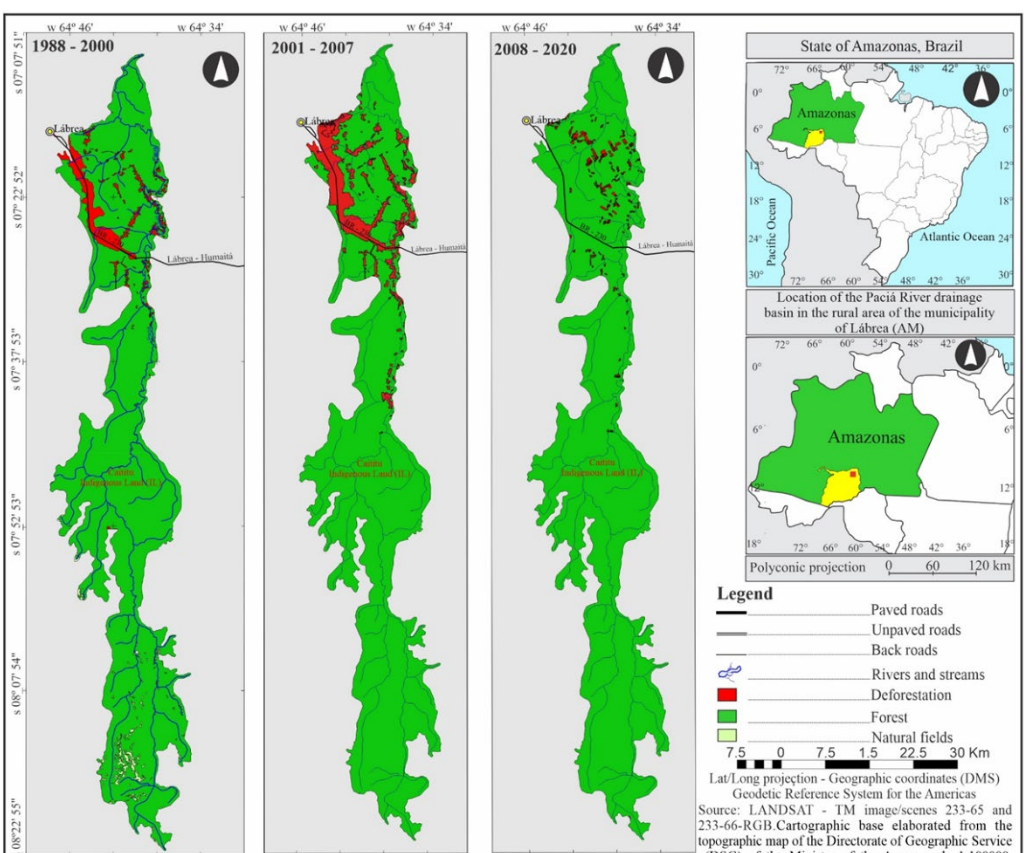
Results and discussion

The deforestation of the open and dense ombrophilous forest in Southern Amazon, especially in the rural area of the municipality of Lábrea, has been occurring on two fronts of expansion of the agricultural frontier. The first is located south of the administrative office of Lábrea, on the limits of the rural settlement projects PA-Monte I and II, along unofficial back roads, starting from BR-317 and BR-364, mainly in Jequitibá, Boi, Baiano, Mendes Junior, Prosam, Proterra, and 1st and 2nd branches. The distance between these rural communities and the capital of Amazonas and the difficulty of logistics of Southern Amazon are undoubtedly the main causes of low governance, which lead the region to concentrate more than 90% of new fires and loss of forest cover in the southern Legal Amazon (CENAMO et al., 2011; REIS and LEAL, 2020).

The second front of expansion of the agricultural frontier is in the BHRP, northern Lábrea, close to the urban area, where, in the mid-1990s, INCRA implemented the settlement projects PA-Paciá and PA-Umari. In this area, deforestation is due to the change in land use by conversion and modification, which represents about 5% of the loss of the remaining primary forest cover.

The evolutionary analysis of deforestation showed an accelerated loss of forest cover along the main and secondary course of the Paciá River. By the 1980s, deforestation in the BHRP extended over 4,273.0 ha (3.02%). In 2001, with an increase of 1.92%, it rose by 4.94%, expanding the size of the deforested area to 6,978 ha (Figure 2).

Figure 2. Evolution of the increase in deforestation in the Paciá River drainage basin (AM).



Source: Prepared by the authors.

The replacement of the open ombrophilous forest, alluvial lowlands, and firm lands by pasture and crops reached 12,382 ha (an increase of 177.43%) in 2010. However, from 2011 to 2020, the accumulated deforestation in the BHRP was 7,055.62 ha. In the last decade, deforestation reduced by 57% in this region.

From 2017 to 2020, the cumulative average deforestation remained at 0.6% per year, which is close to 1.0%. Many factors contribute to the decreasing loss of native forest cover in the study area, especially:

i. Implementing public policies by municipal, state, and federal environmental management institutions, aiming to guide, train, control, and monitor companies and industries that process, improve, and commercialize products and/or by-products derived from forest resources;

ii. Installing and structuring the headquarters of the Chico Mendes Institute for Biodiversity Conservation (ICMBIO) in the municipality of Lábrea;

iii. Implementing the rural production fair, in which small farmers and their families could commercialize the agricultural production of the fortnight directly to the consumer, increasing the value of the regional farm product, as well as their monthly income;

iv. Raising awareness among small farmers to adopt new agricultural production technologies that increase productivity without compromising the environment, in particular the soil ecosystem;

v. Financial incentives granted by the state to rural farmers by the Low-Carbon Agriculture Program (PABC), aimed at the implementation of agricultural production technologies that help reduce environmental impacts caused by traditional agricultural activities; for example, the implementation of the agroforestry system, agroforestry yard, and small sustainable community industries of automatic production of cassava starch and flour;

vi. Demarcating and homologating, in the high course of the BHRP, the Apurinã and Paumari Indigenous lands, which border the integral protection conservation units Ituxi Extractive Reserve (Resex Ituxi) and Mapinguari National Park (PARNA), according to Decree No. 289 of October 30, 1991.

Regarding the creation of environmental protection areas, Vitel et al. (2009) analyzed the effect of state and federal protected areas in Southern and Southwestern Amazon (Ituxi and Médio Purus Extractive Reserves, Iquiri National Forest, Mapinguari National Park, and Balata Tufari) created to prevent deforestation and minimize the environmental impacts related to the recovery, reconstruction, and paving of the road network in Southern Amazon. The authors concluded that federal protected areas are effective in inhibiting the loss of forest cover. However, state sustainable development conservation units are less effective in preventing deforestation in Amazonas compared with federal units.

According to evidence on deforestation and land use change in the Amazon agricultural frontier, cattle farming is the main economic activity in the region and medium and large cattle farmers are responsible for deforestation (MARGULLIS, 2003). Small farmers are labor suppliers or agents. Moreover, the geoenvironmental conditions of Western Amazon—where dense and open ombrophilous forests predominate, with high rainfall indexes—make conventional farming practically unviable. The author reinforces the existence of many sustainable agricultural alternatives, which may include the agroforestry system and the integrated crop-livestock-forest (ICLF) system, which can replace conventional cattle farming, promoting greater social, economic, and environmental benefits.

According to Soares-Filho et al. (2005), the contribution of financial resources to improve infrastructure services in the municipalities along the roads that connect the states of Amazonas, Rondônia, and Acre to other regions of Brazil could accelerate deforestation in the medium and long term. These phenomena would intensify after 2025 and reach its point of stability only around 2045, when agents of deforestation and actions would be concentrated in the vicinity of the municipalities of Apuí, Boca do Acre, and Lábrea, among other federal units located along BR-230, BR-317, BR-319, and BR-364.

Variability of ecological landscape patterns and metrics of deforestation polygons in the BHRP

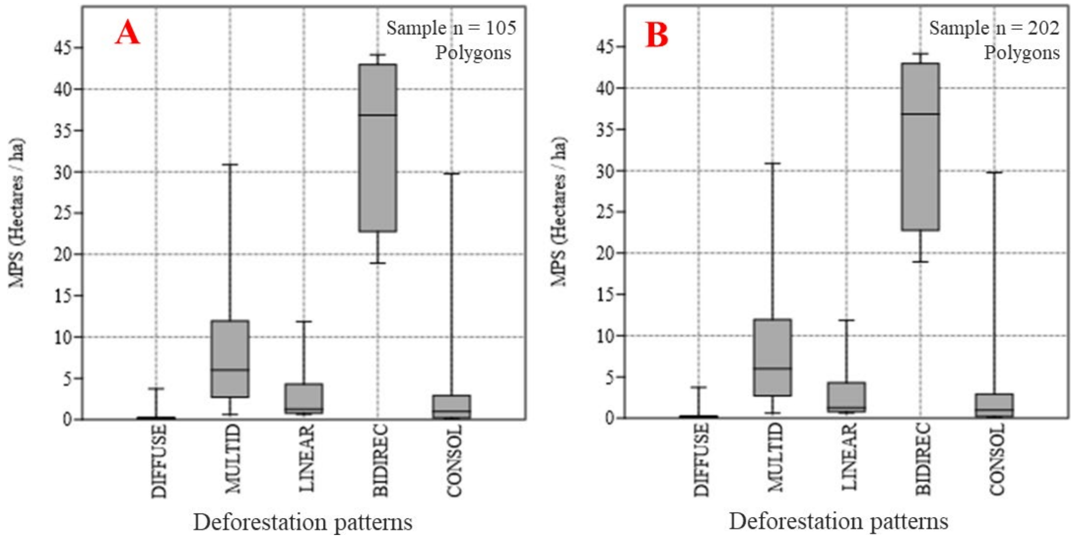
We mapped 307 deforestation polygons, of which 105 were from 1988 to 2007 and 202 from 2008 to 2020. The number of deforestation polygons significantly increased over the last 12 years (2008–2020) in the BHRP. However, the comparative analysis of total polygons versus effectively deforested areas showed a reduction of 59.17% in the increase per deforestation polygon from 2008 to 2020 (2149.41 ha) compared with 2001 to 2007 (3649.26 ha). These results corroborate the clearcutting analyses by PRODES satellite images (INPE, 2017).

Figures 3 to 7 show box plots for each landscape ecology metric analyzed. MPS estimates the average size of deforestation polygons, accumulated and recorded from 2001 to 2007 and 2008 to 2020.

According to Figures 3A and 3B, the bidirectional, multidirectional, and consolidated deforestation patterns had the highest MPS values while the diffuse and linear patterns had the lowest values. The size of the analyzed area may have affected MPS values for the consolidated and geometric patterns. These results are different from a study by Saito et al. (2011) on the effects of scale change on deforestation patterns in the Amazon.

Figures 4A and 4B show that polygons have different median ED values for some deforestation patterns, such as the bidirectional

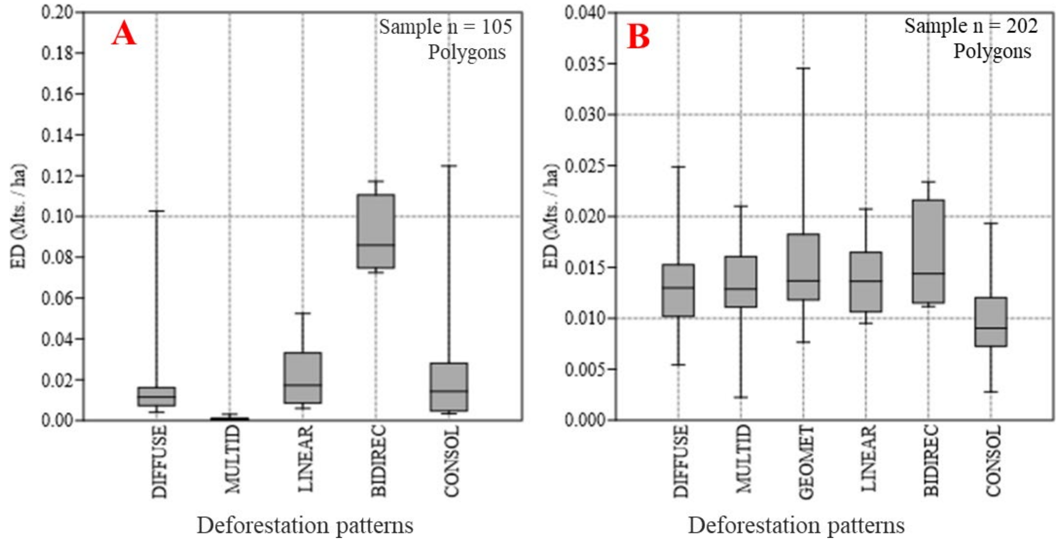
Figure 3. Landscape metrics of deforestation polygons in the BHRP, in the rural area of the municipality of Lábrea, Southern Amazon. **A**. MPS of deforestation from 2001 to 2007. **B**. MPS of deforestation from 2008 to 2020.



Legend: MULTID: multidirectional. GEOMET: geometric. BIDIREC: bidirectional. CONSOL: consolidated. MPS: mean patch size.

Source: Prepared by the authors.

Figure 4. Edge density of deforestation areas in the BHRP, in the rural area of the municipality of Lábrea (AM). **A**. ED of deforestation polygons from 2001 to 2007. **B**. ED of deforestation polygons from 2008 to 2020.



Legend: MULTID: multidirectional. GEOMET: geometric. BIDIREC: bidirectional. CONSOL: consolidated. ED: edge density.

Source: Prepared by the authors.

and multidirectional patterns from 2001 to 2007, and similar values for the diffuse, multidirectional, geometric, linear, and bidirectional patterns from 2008 to 2020.

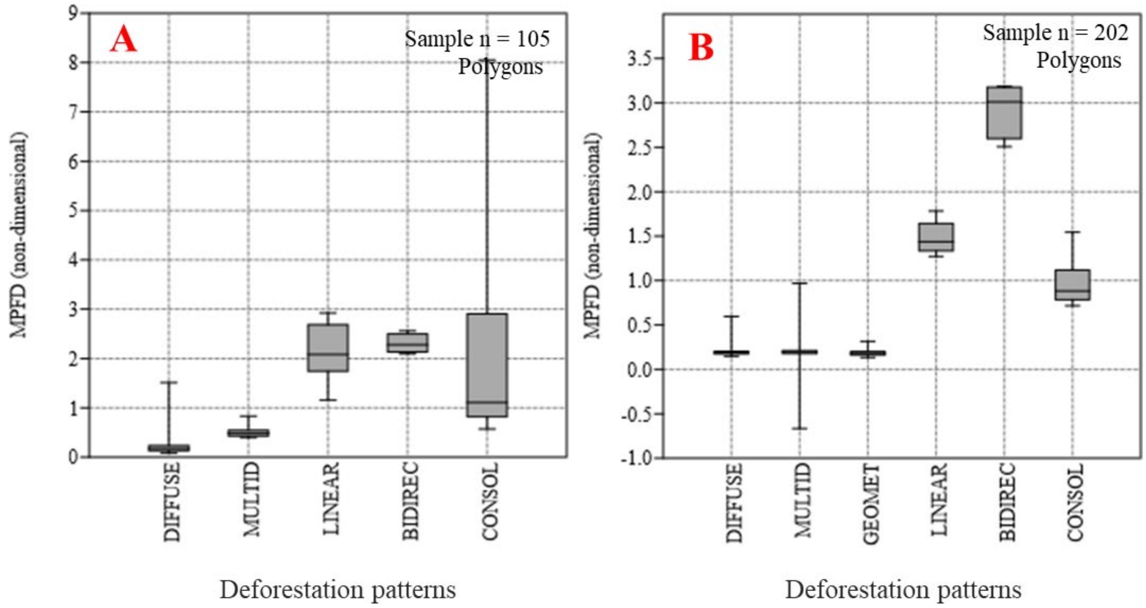
The bidirectional pattern had the highest ED, followed by the linear pattern. Although the number of deforestation patches is small, both had narrow and elongated landscape geometric features and the total deforested area is relatively higher than the sum of the area of deforestation patches of the diffuse pattern. Overall, ED values are not different between deforestation patterns possibly due to the size of the total area of the assessed landscape. For Pirovani et al. (2015), the increase in ED values is due to the gradual growth of deforestation patches and the expansion of productive activities, which represents the formation of new polygons in the landscape. Our results are in line with a study conducted in a rural settlement in the municipality of Vale do Anari, Rondônia, by Silva et al. (2008b).

MPFD values (Figure 5), which show the irregularity and complexity of the form of deforestation patches, were lower for diffuse patterns from 2001 to 2007 and multidirectional and geometric patterns from 2008 to 2020. This result shows that the shape of polygons was close to a rectangle, making them easy to distinguish from other deforestation patterns in the landscape.

For the other patterns, MPFD values remained practically unchanged in relation to the total size of the area analyzed, except for the bidirectional pattern from 2008 to 2020, possibly because each deforestation polygon had a value close to 1, providing homogeneity as to the complexity of forms in all samples.

Much of the increase in deforestation patterns in the medium course of the BHRP is directly related to the expansion of the agricultural frontier, where from 2001, with the demarcation of the PA-Umari, new deforested areas emerged since 2001 from the establishment of small and medium farms, making extensive cattle farming and subsistence agriculture predominant, especially along the rural roads 4, 12, and 24 and on the banks of the main course (midstream to mouth) of the Paciá River. These results are

Figure 5. Weighted mean patch fractal dimension of deforestation patches in the BHRP. **A**. MPFD of deforestation patches from 2001 to 2007. **B**. MPFD of deforestation patches from 2008 to 2020.



Legend: MULTID: multidirectional. GEOMET: geometric. BIDIREC: bidirectional. CONSOL: consolidated. MPFD: weighted mean patch fractal dimension.

Source: Prepared by the authors.

in line with a study performed by Galak et al. (2011) in the Sustainable Forest District in BR-163, western Pará.

MPAR measures the complexity of the shape of polygons. More regular forms have lower values (HUANG et al., 2006; CABACINHA et al., 2010). The linear and bidirectional patterns had the highest values for this metric (Figure 6). As expected, the geometric pattern from 2008 to 2020 had the lowest value, as its polygons were more regular compared with the other patterns. Its value may increase as the size of the analysis area increases, making it more heterogeneous.

The linear pattern had similar median values to the consolidated pattern because, although is polygons were regular, its narrow and elongated area produces high perimeter/area ratio values. From 2001 to 2007, no polygon was geometric. The number of patches was higher in diffuse and multidirectional polygons, which had lower MPAR values and more regular features than the other patterns.

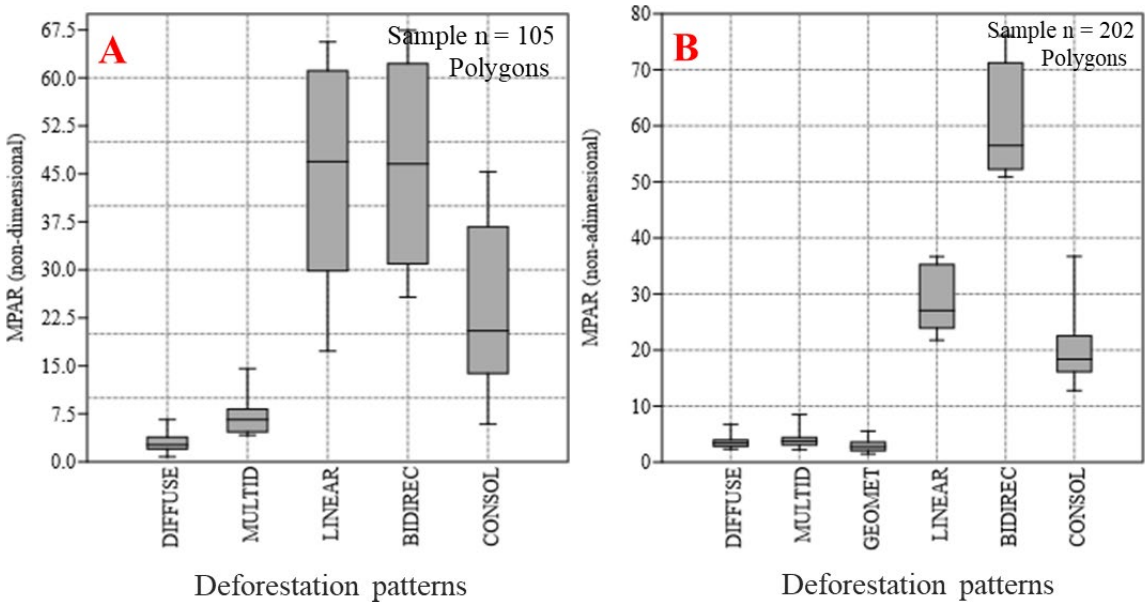
The analyses of typological patterns of deforestation with landscape ecology metrics (PERM, AREA, MPS, ED, MPFD, and MPAR), which are considered the basis for assessing the effects of changing land use and occupation patterns, allowed the discrimination of the quantitative predominance of diffuse and multidirectional deforestation polygons in the BHRP.

These patterns resulted in lower ED, MPS, MPAR, and MPFD values. The analytical results of the typological patterns associated with landscape metrics show that, from 2008 to 2020, the expansion of human land use and occupation stalled in the BHRP.

Variation in typological patterns of deforestation and stages of human occupation in the BHRP

Silva et al. (2008b) and Gavlak et al. (2011) established the identification of typological patterns of deforestation. The different stages of

Figure 6. Mean perimeter-area ratio of deforestation polygons in the BHRP, in the rural area in the municipality of Lábrea (AM). **A**. MPAR of deforestation polygons from 2001 to 2007. **B**. MPAR of deforestation polygons from 2008 to 2020.



Legend: MULTID: multidirectional. GEOMET: geometric. BIDIREC: bidirectional. CONSOL: consolidated. MPAR: mean perimeter-area ratio.

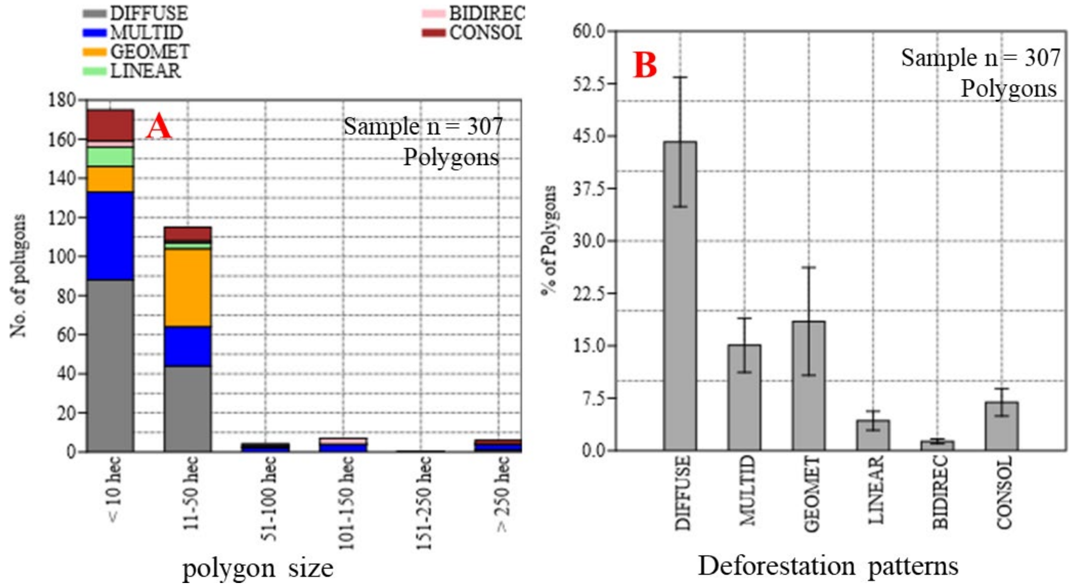
Source: Prepared by the authors.

change in land use and occupation recommended by Diniz (2002) served as the basis for defining the agricultural stage of settlements and spontaneous occupations in the BHRP. The stage that Diniz (2002) classified as pioneer was associated with the diffuse pattern, which slightly changed during the analyzed periods. The transitional stage corresponded to polygons with multidimensional patterns and an increase in the number of deforestation polygons from 1988 to 2020. The consolidated stage was related to polygons with paths of consolidation or stabilization of deforestation and land use and occupation in the analyzed period. Finally, in this study, the urbanized stage corresponded to the consolidated pattern regardless of the size of the urban area.

Figure 7 shows the typological patterns of deforestation associated with the stages of expansion of the Southern Amazon agricultural frontier. The “consolidated” frontier observed in the BHRP is located along the influence area of the Transamazon highway (BR-220) and is characterized by agribusiness—its rural area has excessive land concentration, with large farms and rural properties. More than 7,000 ha belong to a dozen landowners alone in the area from the Paciá River community (Km 35 of BR-230) to the urban perimeter of Lábrea.

The pioneer South Amazon agricultural frontier has three spatial patterns of land use and occupation: geometric, linear, and, above all, diffuse. The association between the pioneer frontier and the diffuse pattern—a process that began at the end of the 19th century with the migration of people from Northeastern Brazil to work in rubber plantations—has been developing along the main course of the Paciá River. Recently, human land use and occupation has intensified in the medium course of the river, increasing diffuse deforestation, especially in the PA-Umari, where the spatial arrangement of rural properties followed the path of the main drainage network (Figure 8).

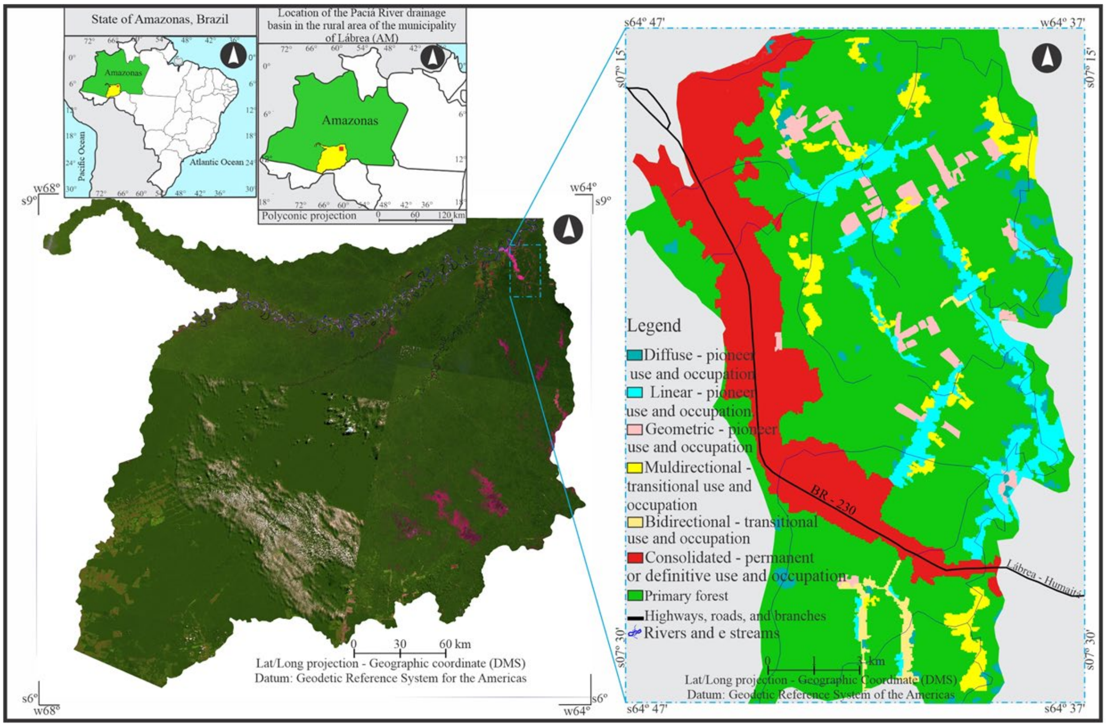
Figure 7. Deforestation patterns associated with polygon size in the BHRP (AM). **A**. Number of polygons sorted by size and deforestation patterns from 2001 to 2020. **B**. Percentage of polygons related to the deforestation pattern from 2001 to 2020.



Legend: MULTID: multidirectional. GEOMET: geometric. BIDIREC: bidirectional. CONSOL: consolidated. MPFD: weighted mean patch fractal dimension.

Source: Prepared by the authors.

Figure 8. Deforestation patterns (2001–2020) associated with the stage of use and occupation of the agricultural frontier in the middle course of the BHRP, in the rural area of the municipality of Lábrea (AM).



Source: LANDSAT-TM images/scenes 001/65, 001/66, 233-65, and 233-66-RGB. Cartographic base elaborated from the topographic map of the Directorate of Geographic Service (DSG) of the Ministry of the Army; scale 1:100000. Prepared by the authors.

In the pioneer frontier associated with the linear pattern, the state organized human land use and occupation, as, in 1997, at the time of the demarcation of the PA-Umari, the CAR-12 emerged with the construction of the road (which starts at BR-230) at Km 12. Along this road, 70 families settled in 50-ha properties. In order to ensure land ownership and due to the lack of capital and reduced work supply, settlers organized an informal network of community work to perform the arduous task of making the land productive. However, a small group of farmers of the CAR-12 has been replacing tuber planting with the cultivation of *Euterpe oleracea* Mart, consorted with other tropical tree species. In these areas, the process of human occupation that originates the pioneering agricultural front presented by Machado (1992) is evident.

Conclusion

Diffuse, geometric, and multidirectional deforestation polygons (222 in total) predominate, corresponding to 15.64% of the loss of primary forest in the BHRP. On the other hand, the linear, consolidated, and bidirectional patterns (83 in total) represent 84.36% of deforestation in the BHRP. Thus, linear, consolidated, and geometric patterns of deforestation come from both the planned land use and occupation, associated with the implementation of road and land infrastructure in the BHRP, and diffuse and multidirectional patterns of land use and spontaneous occupation, in which this use was outside the standards of environmental guidance and government technical assistance.

The gradual change from pioneer (diffuse pattern, linear, and geometric) to transitional (multidirectional) and, later, to permanent occupation (consolidated) results from the expansion of production activities, which forms new deforestation polygons in the landscape and, consequently, increases their ED, MPS, and MPAR values. The increase in these metrics shows greater forest fragmentation and the uniformity and deformity of remaining primary forest fragments in the BHRP.

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