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Amazon deforestation: A dangerous future indicated by patterns and trajectories in a hotspot of forest destruction in Brazil

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ABSTRACT

In recent years, the loss of forest in the Brazilian Amazon has taken on alarming proportions, with 2021 recording the largest increase in 13 years, particularly in the Abunã-Madeira Sustainable Development Reserve (SDR). This has significant environmental, social, and economic repercussions globally and for the local communities reliant on the forest. Analyzing deforestation patterns and trends aids in comprehending the dynamics of occupation and deforestation within a critical Amazon region, enabling the inference of potential occupation pathways. This understanding is crucial for identifying deforestation expansion zones and shaping public policies to curb deforestation. Decisions by the Brazilian government regarding landscape management will have profound environmental implications. We conducted an analysis of deforestation patterns and trends up to 2021 in the municipality (county) of Lábrea, located in the southern portion of Amazonas state. Deforestation processes in this area are likely to spread to the adjacent "Trans-Purus" region in western Amazonas, where Amazonia's largest block of remaining rainforest is at risk from planned highways. Annual deforestation polygons from 2008 to 2021 were categorized based on occupation typologies linked to various actors and processes defined for the region (e.g., diffuse, linear, fishbone, geometric, multidirectional, and consolidated). These patterns were represented through 10 × 10 km grid cells. The findings revealed that Lábrea's territory is predominantly characterized by the diffuse pattern (initial occupation stage), mainly concentrated in protected areas. Advanced occupation patterns (multidirectional and consolidated) were the primary contributors to deforestation during this period. Observed change trajectories included consolidation (30.8%) and expansion (19.6%) in the southern portion of the municipality, particularly along the Boi and Jequitibá secondary roads, providing access to large illegal landholdings. Additionally, non-change trajectories (67%) featured initial occupation patterns near rivers and in protected areas, likely linked to riverine and extractive communities. Tailoring measures to control deforestation based on actor types and considering stages of occupation is crucial. The techniques developed in this study provide a comprehensive approach for Amazonia and other tropical regions.

Keywords – deforestation actors; occupation typologies; cattle-ranching Amazon frontier; land-use change; land grabbing

1. Introduction

1.1. Amazon deforestation's consequences for Brazil and the world

The central role of Amazon deforestation in the global climate and biodiversity crises, as well as its environmental and social impacts in the Amazon region, have made the containment of this destruction a top priority for both the world and for the Amazonian countries (Fearnside, 2021a). With over 40% of the world's remaining tropical forests, Brazil is by far the most important country in terms of potential impacts of tropical deforestation and degradation on global climate (Laurance et al., 2001). This stems not only from the substantial year-to-year carbon emission, but also from the potential emissions of the huge carbon stocks in the remaining forest biomass and in the soil under the forest if released by forest degradation from increasing temperatures, drought severity and forest fires linked to climate change (Barros and Fearnside, 2019; Nogueira et al., 2015). Release of this carbon over a span of a few years would be a key factor in pushing global climate past a tipping point beyond which human countermeasures by cutting emissions would be incapable of stopping the further advance of global warming driven by positive feedbacks in the Earth system (Fearnside, 2022).

The municipality (county) of Lábrea, the focus of our study, is located in the southern portion of Brazil's state of Amazonas and is adjacent to the Trans-Purus region, a vast area that has largely remained undisturbed due to the lack of accessibility by roads. The Trans-Purus region, located in the western portion of the state of Amazonas, has an extensive area of "undesignated public forests," a term referring to government land that has not been assigned to a specific use such as a conservation unit (a protected area for biodiversity), an Indigenous land or a settlement project. These undesignated public forests are the most attractive areas for illegal land occupation by land grabbers, organized landless farmers, loggers, and other groups. The occupation processes occurring in Lábrea are likely to expand to the Trans-Purus region (Fearnside, 2017, 2018; Fearnside et al., 2020). The Trans-Purus region faces deforestation risks from roads planned to branch off the BR-319 (Manaus-Porto Velho) highway. BR-319 highway was initially built in 1972-1973 and abandoned in 1988; it received "maintenance" beginning in 2015 and is now slated for "reconstruction," pending environmental license approval (Figure 1) (Fearnside, 2022; Santos et al., 2023).

If the forest in the Trans-Purus region is lost it would be catastrophic for Brazil, since this area is crucial for recycling the water that is transported to São Paulo and other parts of southeastern and southern Brazil via the winds known as "flying rivers" (Fearnside, 2004, 2015). The prevailing winds in Amazonia blow from east to west because of the effect of the Earth's rotation on the return flow of the Hadley circulation, and these winds bring water that has evaporated from the Atlantic Ocean. Roughly half of the water that falls as rain over Amazon forest is recycled by the trees, which release it as water vapor that, along with the remaining water vapor derived directly from the Atlantic, is carried further by winds (Zemp et al., 2014). South American low-level jet winds are blocked by the Andes mountains and turn to the south and east, transporting water vapor to São Paulo, other parts of southeast and southern Brazil and to neighboring countries (Nicolini et al., 2002; Arraut et al., 2012). This transport is especially strong during December, January and February when the intertropical convergence zone is at its southernmost position and the winds meet the highest part of the Andes. This is rainy season in southeastern South America and is the critical period when the reservoirs that supply the city of São Paulo fill, as well as the many other reservoirs in southeastern and southern Brazil and in neighboring countries. The La Plata River basin, which includes São Paulo, depends on water vapor from Amazonia for 70% of its annual precipitation (van der Ent et al., 2010). A catastrophic drought in 2014 brought São Paulo, the fourth largest city in the world, close to running out of water even for drinking (Nobre et al., 2016; Cunha et al., 2019; Fearnside, 2021b). In 2021 another catastrophic drought struck this part of Brazil (Fernandes et al., 2021; Getirana et al., 2021). These droughts result from changes in ocean temperatures linked to global warming, and they are expected to intensify with projected climate change (Biastoch and Boning, 2013; Coelho et al., 2016). These changes increase the value of maintaining Amazon forest, especially in the Trans-Purus region, as there is no longer any leeway to allow loss of water transported by the "flying rivers."

1.2. Amazon deforestation and the Lábrea hotspot

From 2019 to 2021, annual deforestation in the Amazon biome in Brazil increased by 56.6% when compared to the years from 2016 to 2018, surpassing 10,000 km² per year (INPE, 2021; Alencar et al., 2022). In 2021, the state of Amazonas jumped to second place in the ranking for annual deforestation among the nine states in Brazil's Legal Amazon region (an area the size of western Europe), taking over the historical position previously occupied by Mato Grosso and remaining behind only the state of Pará (InfoAmazonia, 2021).

In recent years, deforestation has been concentrated mainly in eastern Acre, northern Rondônia, and southern Amazonas, which make up the AMACRO integration zone, or the recently renamed Abunã-Madeira Sustainable Development Zone. AMACRO was created in 2021 during the 2019-2022 presidential administration of Jair Bolsonaro with the justification of promoting environmental sustainability through the economic development of the 32 municipalities that make up this region (SUDAM, 2021). However, the prospect of replacing the existing local economy with an agribusiness-based economy aimed at exporting commodities is tied to the intensification of rural violence, as observed in this area (CPT, 2021; IPAM, 2021; IMAZON, 2022). As the potential for large-scale soy plantations and ranching operations increases, there is heightened demand for land and an escalation of land conflicts. These conflicts often manifest as "land grabbing," a term specific to Amazonia, denoting the large-scale, illegal claiming of land, typically on government-owned territories (different from the same term's meaning in Africa and Asia, where it refers to foreign groups purchasing local land) (Agrawal et al., 2019). Government land is invaded both by land grabbers and by small farmers (both organized and individual). The result has been increased deforestation rates (IMAZON, 2022). The occupation process in Lábrea reflects a historical context marked by intense land conflicts related to illegal and disorderly occupation, expansion of cattle ranching, predatory fishing and hunting, illegal logging, and landholdings in protected areas (Tavares and Cordeiro, 2017; CPT, 2021). The term "landholdings" used here refers to self-declared claims in the Rural Environmental Registry (CAR) and does not imply that claimants have ownership or legal title to the areas.

1.3. Typology of deforestation patterns in the Amazon

Addressing escalating deforestation and its profound consequences for humanity is crucial, prompting the need for a comprehensive understanding of this dynamic process. Given the intricate connection between deforestation and changes in land use, it is crucial to comprehend and link the actors and factors involved, forming the basis for targeted policies to mitigate the negative impacts of deforestation on the environment and society (Marinaro et al., 2022). To achieve a thorough understanding of land occupation, a robust approach involves discerning the typology of deforestation patterns and correlating them with actors and different stages of occupation in a region (McGarigal and Marks, 1995; Mertens and Lambin, 1997; Pereira et al., 2007; Silva et al., 2008). This correlation could allow inferences about the evolutionary stage of the occupation and deforestation process in a given area, including likely occupation trajectories (Diniz, 2002; Oliveira and Metzger, 2006; Gavlak et al., 2011).

Previous studies in the Amazon have successfully employed typologies to categorize deforestation patterns, shedding light on the characteristics associated with various stages of occupation. For instance, Silva et al. (2008) identified distinct patterns such as linear, small isolated irregular, small irregular near roads, medium irregular near roads, and large geometric, each linked to specific actors and landholding characteristics. Saito et al. (2011) classified deforestation based on occupation stages, distinguishing between consolidated, diffuse, fishbone, regular geometric, multidirectional disordered, and unidirectional linear patterns. Similarly, Gavlak et al. (2011) defined deforestation patterns and trajectories along a specific highway, providing insights into stages of occupation and associated changes. In a different study, Marinaro et al. (2022) defined the stages and actors of deforestation in a livestock frontier in the Dry Chaco of northern Argentina, contributing to the understanding, organization, and differentiation of various social-ecological processes and perceptions from local-urban inhabitants.

Building upon these insights, the region containing the municipality of Lábrea presents an emergent scenario influenced by a cattle-ranching frontier, consolidating its significance as an important area for comprehending land-occupation dynamics. To gain insight into the recent dynamics of deforestation in the municipality of Lábrea, this study endeavors to understand the patterns and trajectories of land occupation in the region. Focusing on identifying deforestation patterns and trajectories in the municipality of Lábrea from 2008 to 2021 will contribute valuable knowledge to inform policies aimed at mitigating deforestation rates in this critical region.

2. Materials and methods

2.1. *Study Area*

The present study was carried out in the municipality of Lábrea, located in the southern mesoregion of the state of Amazonas near the borders with the states of Rondônia and Acre (Figure 1). The main rivers in the municipality are the Ituxi and Purus, with the Purus River being used as the access route to the municipal seat (the city of Lábrea; 2021 urban population = 24,223) (Tavares and Cordeiro, 2017; IBGE, 2021a). In addition to the river, it is also possible to access the city of Lábrea by the BR-230 (Transamazon) highway, and the southern portion of the municipality can be accessed by secondary roads branching off the BR-364 (Porto Velho-Rio Branco) highway; these secondary roads, built illegally by landgrabbers, have played an important role in the process of occupying this area (Franco, 2011; Tavares and Cordeiro, 2017).

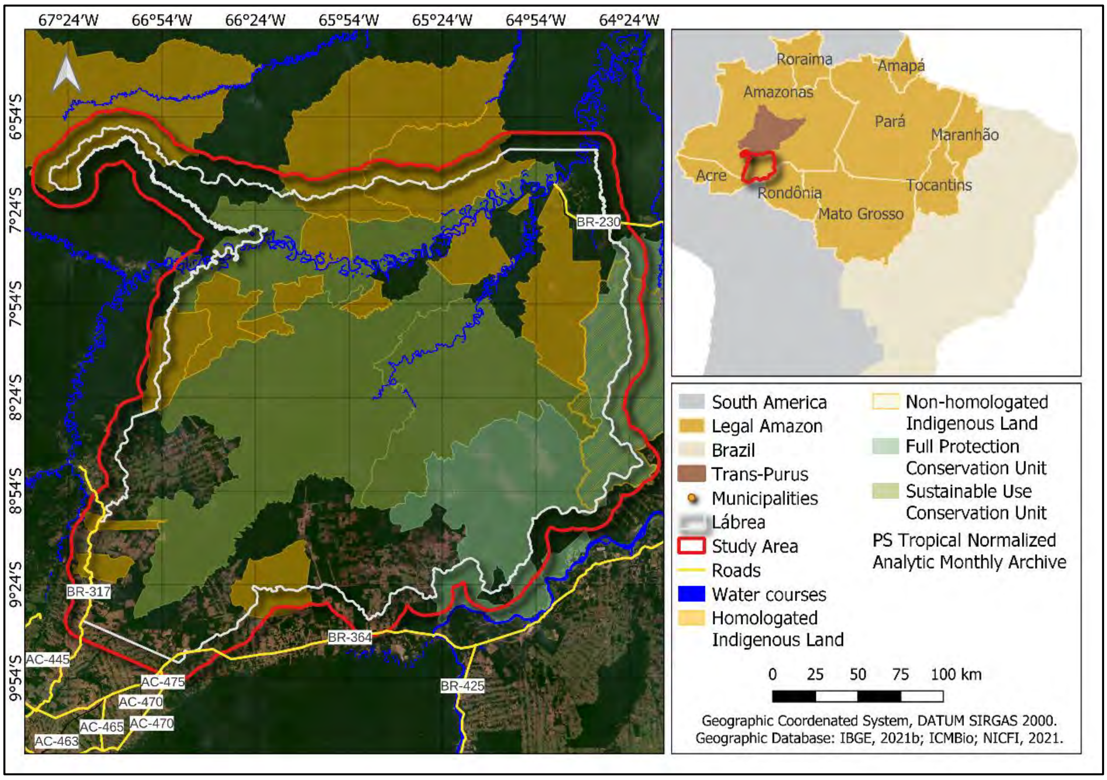


Figure 1. Location map of study area, municipality of Lábrea, Amazonas state.

The study area encompasses 83,900 km² (an area larger than Austria or the Brazilian state of Paraíba). The study area includes a 10-km buffer surrounding the municipality of Lábrea. The buffer was delineated to avoid possible information losses regarding deforestation patterns caused by the neighborhood of the municipality. Around 80% of the study area is in protected areas, divided into 17 Indigenous lands and four conservation units. The vegetation cover in Lábrea is predominantly composed of dense ombrophilous lowland forest (RADAMBRASIL, 1978). The soils are classified as Latosols, Argisols, Plinthosols, and, in areas near the rivers, Gleysols (IBGE, 2020). The relief is formed by depressions and plains, with altitudes ranging from 38 m to 1089 m above mean sea level. The climate is characterized as tropical monsoon (Type Am-i in the Köppen classification system), with short dry periods and a long period with high precipitation (2400 to 2800 mm year^{1}) (Alvares et al., 2013).

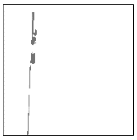
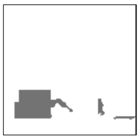
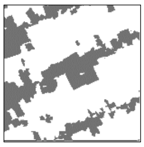
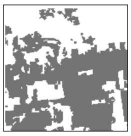
2.2. *Deforestation mapping and definition of occupation typology*

Cumulative deforestation data for 2008, 2013, 2017, and 2021 were obtained from the Project for Monitoring Deforestation in the Legal Amazon by Satellite (PRODES) vector maps (INPE, 2021). The selection of these specific years aimed to analyze the distinct occupation patterns during periods with varying occupation dynamics. PRODES, at the National Institute for Space Research (INPE), estimates annual rates of deforestation by clearcutting based on visual interpretation of satellite images and provides extensive spatial data through the TerraBrasilis digital platform (Assis et al., 2019; INPE, 2021). Widely recognized for its accuracy, PRODES boasts a precision level of 93.5%, establishing its reputation as a reliable deforestation monitoring system (Maurano et al., 2019).

The analysis of deforestation patterns and trajectories using PRODES data proves invaluable in indicating and characterizing diverse processes of forest-cover change associated with agents and types of occupation, enabling a comprehensive understanding of the deforestation and the occupation processes involved. This approach involves creating a typology that establishes and describes the connection between the spatial deforestation patterns in the analyzed area and their semantics. Auxiliary information, such as agribusiness census data, and field information are used in this process. Through exploratory spatial analysis of the arrangement and shape of deforestation polygons and patterns described in the literature, an occupation typology was defined for the Lábrea region based on Azeredo et al. (2016), Gavlak et al. (2011), Saito et al. (2011), and Yanai et al. (2020). The identification and definition of these patterns were also informed by an expedition carried out in the study area in October 2021, revealing different occupation dynamics.

After defining the typology of occupation patterns, the deforestation polygons were analyzed in the context of individual cells. This process involved examining the landscape metrics of the polygons within predetermined cell sizes. Previous studies suggest that the choice of the grid-cell size should consider the dimensions of deforestation patches and their spatial distribution to avoid loss of information or distortion of patterns (Saito, 2010; Gavlak et al., 2011; Saito et al., 2012; Pinheiro et al., 2016; Assis et al., 2021). After preliminary tests and an empirical analysis of the arrangement of deforestation patterns when displayed with different cell sizes, it was found that 10 × 10 km was the most suitable cell size for identifying and describing the patterns proposed in Table 1. Cells where no deforestation patches were observed were classified as "forest."

Table 1. Typology of deforestation patterns associated with human occupation in the municipality of Lábrea (white = forest, gray = deforestation).

Deforestation Pattern	Description
Diffuse 	Small, isolated patches with low to medium density, evenly distributed. This is characteristic of the initial spontaneous occupation distributed along riverbanks, in mining areas, and where small landholders are located.
Linear 	Elongated, continuous patches. This is related to the initial occupation distributed along roads.
Geometric 	Small and medium patches with regular geometry. This represents an initial to intermediate stage of occupation by medium and large landholders.
Fishbone 	Long, branching patches along roads, with an appearance similar to the skeleton of a fish. They represent an intermediate stage of occupation by small and medium landholders, as well as areas intended for settlement projects.
Multidirectional 	Large and medium-sized multidirectional patches with irregular geometry. They represent an intermediate to advanced stage of disorderly occupation.
Consolidated 	Large areas with undefined shape. They have a high density of deforestation with few or almost no forest fragments.

2.3. *Classification of deforestation patterns and trajectories*

Deforestation patterns were classified using spatial data-mining techniques. This procedure was performed using the Geographical Data Mining Analyst (GeoDMA) plugin, a classifier developed by Körting et al. (2008) for TerraView version 5.6.1 software. It combines a set of tools for integrating and analyzing remote-sensing images with data-mining techniques for extracting information and discovering knowledge about large databases (INPE, 2020). This tool allows for the structural classification of objects by extracting a set of landscape metrics that measure and describe the occupation patterns.

The classification process conducted by GeoDMA involved the following steps: 1) extraction of landscape metrics from deforestation polygons within 10 × 10-km cells; 2) compilation of a comprehensive set of training samples for the deforestation class; 3) application of the C5.0 decision tree algorithm to classify and validate the deforestation patterns (Quinlan, 2017), and 4) evaluation of the classification results by analyzing the confusion matrix generated for the training samples.

During the training phase, a single set of samples was constructed for the four analyzed years (i.e., 2008, 2013, 2017, and 2021). This allowed for patterns that are not present in a given year to be included in another period, composing a unique typology that considered deforestation patterns for all years. In total, 383 training samples were collected, of which 60 samples corresponded to diffuse, forest, and geometric patterns, 58 samples were collected for the multidirectional pattern, 55 samples for the consolidated pattern, and 45 samples for the fishbone and linear patterns. Due to the low frequency of some deforestation patterns in the study area, such as the linear and fishbone patterns, different numbers of samples were selected for each class.

Once the training samples were collected, we used the C5.0 algorithm with its "boosting" feature, which generates a predefined number of trees where the final classification of each segment is the one that was assigned by the majority of the decision trees (Quinlan, 2017). GeoDMA automatically separated 66% (254 samples) of the collected samples to classify the patterns (i.e., decision-tree generation), and 34% (129 samples) for validation.

As a result of using the boosting tool, a predetermined set of 30 decision trees was generated, where the categorical attributes (i.e., deforestation patterns) were classified from the non-categorical attributes (i.e., values of landscape metrics). In total, 17 landscape metrics were used, of which three were in over 90% of the classifications, namely: Class Area (CA), Landscape Shape Index (LSI), and Patch Richness (PR). The following metrics also had a certain degree of importance (i.e., utilization values above 60%): Area-Weighted Mean Patch Fractal Dimension (AWMPFD), Total Area of the Biggest Object (TABO), Patch Density (PD), Biggest Intersection Area (BIA), and Area-Weighted Mean Shape Index (AWMSI). These metrics, by quantifying the spatial structure and composition of landscapes, provide insights into the characteristics of deforestation polygons in the grid, facilitating the identification of patterns, changes, and trends over time. For a comprehensive understanding of these metrics, refer to the Supplementary Material (Table S.1).

In the final step, two confusion matrices were generated to evaluate the result of combining decision trees regarding the classification of training and validation samples (Table 2). For the evaluation samples the total accuracy was 92% and the Kappa coefficient was 91%, these values being in the range considered to be quite satisfactory (Hudson and Ramm, 1987).

Table 2. Confusion matrix of validation samples used in the classification of deforestation patterns for the study area for the four analyzed years (2008, 2013, 2017, and 2021) *

	CON.	**DI.**	**FISH.**	**FO.**	**GE.**	**LI.**	**MUL.**	**P (%)**
CON.	14							100
DI.		20				3		87
FISH.			15				1	94
FO.				20				100
GE.					24		1	96
LI.		1	2		1	13		76
MUL.			1				13	93
U (%)	100	95	83	100	96	81	87	
OA								**0.92**

* The analyses use 129 validation samples. Con.= Consolidated; Dif. = Diffuse; Fish. = Fishbone; Fo. = Forest; Ge. = Geometric; Li. = Linear; Mul. = Multidirectional; P = Producer's Accuracy; U = User's Accuracy; OA: = Overall Accuracy.

Deforestation trajectories between 2008 and 2021 were obtained from the results of the pattern classification. These trajectories were divided into "changing" and "non-changing," as proposed by Gavlak (2011). Change in trajectories refers to cells whose patterns were altered over the years, divided into "expansion" and “consolidated.” The "expansion" trajectory is characterized by the cells initially having no deforestation (i.e., they were forest), but in the following years they were classified with patterns with initial to intermediate deforestation levels (i.e., diffuse, linear, geometric and fishbone). "Consolidation" is represented by all cells that in the first year presented an initial or intermediate occupation and by the last year had advanced to a multidirectional or a consolidated pattern (Figure 2). Cells that maintained the same pattern as in 2008 in the final year were classified as one of the "non-changing" trajectories according to the observed deforestation pattern, namely: diffuse, consolidated, and "others" (which encompasses the multidirectional, fishbone, geometric and linear patterns).

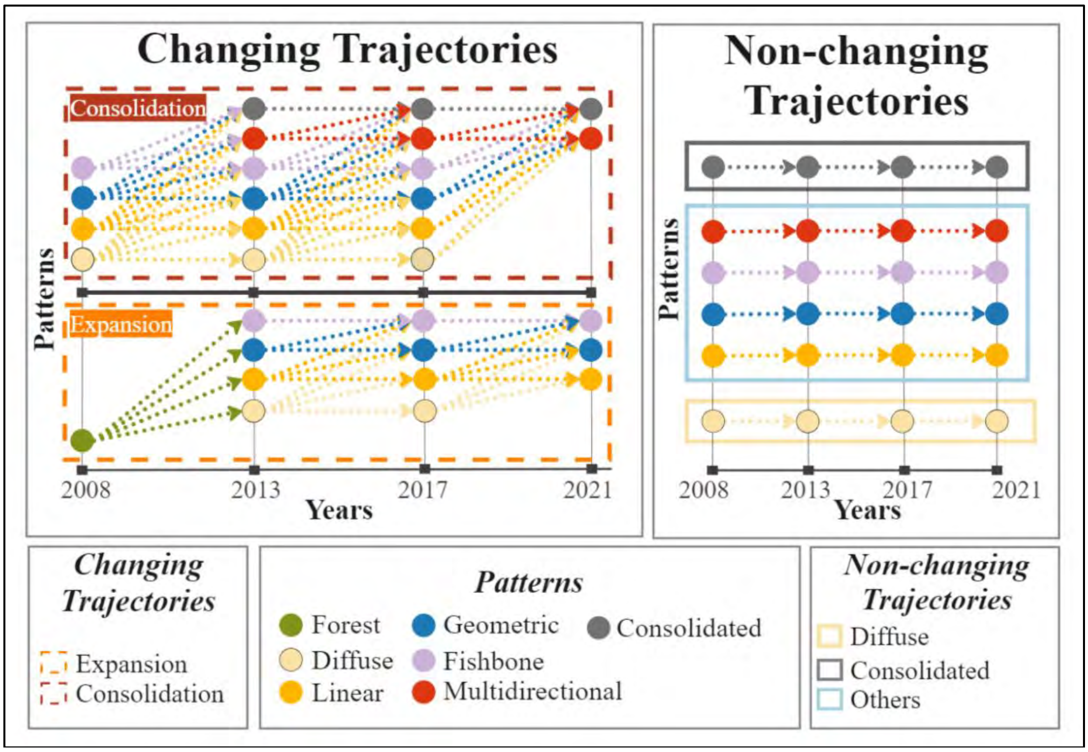


Figure 2. Trajectories of change: consolidation and expansion, and non-changing trajectories: diffuse, consolidated and others (Adapted from Gavlak, 2011).

These trajectories were obtained both for change between the initial and final maps (i.e., from 2008 to 2021), and in the three-time intervals between 2008 and 2021 (i.e., from 2008 to 2013, from 2013 to 2017, and from 2017 to 2021). The first analysis made it possible to capture the differences in patterns for the entire period from 2008 to 2021, resulting in a single final map of occupation trajectories, while the second allowed understanding the evolution of trajectories over the periods analyzed.

In this study the dataset does not allow for the identification of areas that have reverted to forest once classified as deforested. This limitation reflects the relatively short time frame of the analysis, which is insufficient to observe complete forest regeneration.

2. Results

3.1. *Deforestation patterns*

The evolution of deforestation patterns from 2008 to 2021 is presented in the maps in Figure 3. In general, it is possible to observe that the diffuse pattern (i.e., initial occupation) was predominant and concentrated mostly in areas near rivers and in areas that may indicate new deforestation fronts. Although the deforested area in cells classified as diffuse increased over the years, from 12.7 to 14.6 thousand hectares from 2008 to 2021, as exemplified in Table 3, this amount observed in 2021 represented only 1.5% of the total deforested area, considering all patterns (Figure 4).

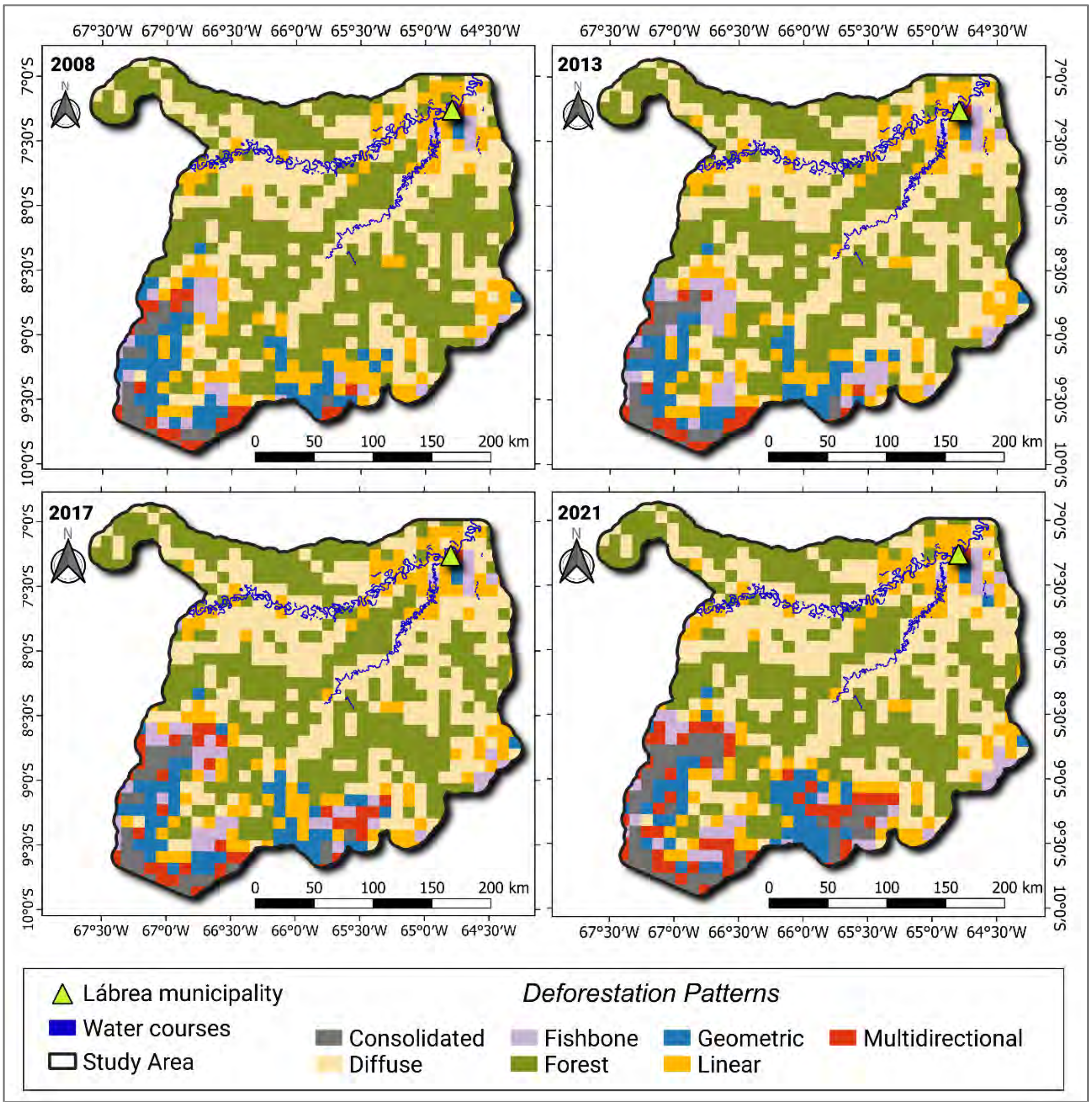


Figure 3. Classification maps of occupancy patterns for the years 2008, 2013, 2017, and 2021 for the study area (i.e., municipality of Lábrea + 10-km buffer).

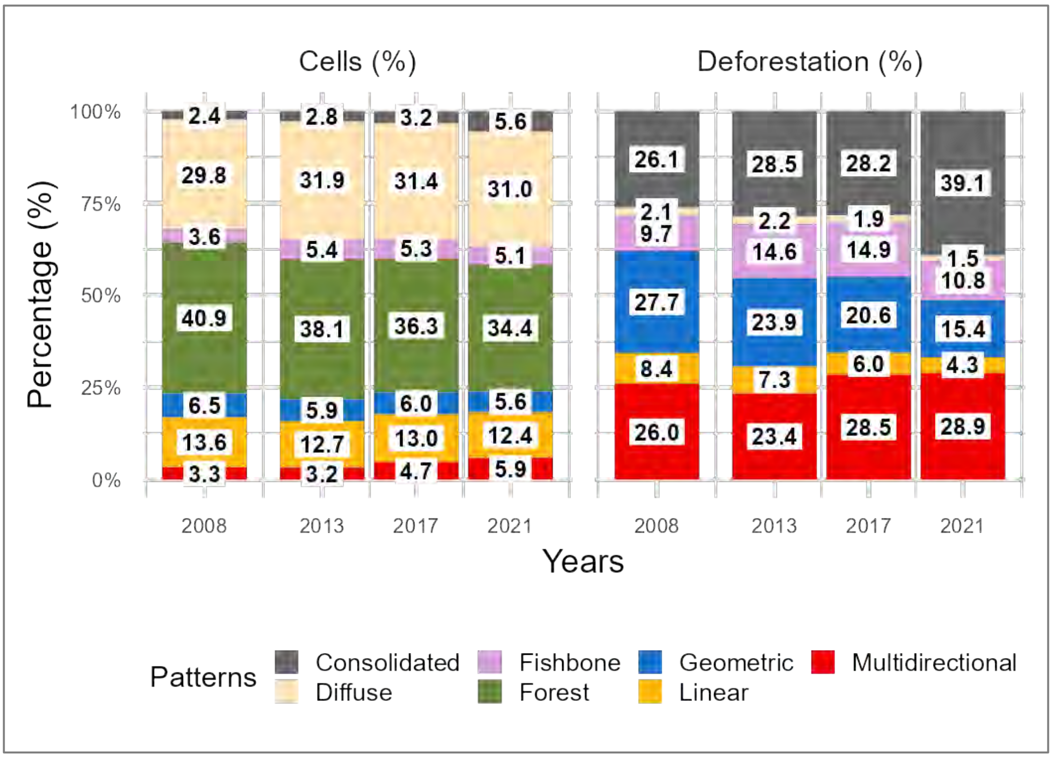


Figure 4. Evolution of the quantities of classified cells (%) and proportion of cumulative deforested area (%) for each type of deforestation pattern for the years 2008, 2013, 2017, and 2021.

Table 3. Evolution of cumulative deforested area, in hectares, for each deforestation pattern in the study area in 2008, 2013, 2017, and 2021.

Deforestation patterns	**Cumulative deforested area (ha)**			
	2008	*2013*	*2017*	*2021*
Consolidated	157,806.70	187,416.65	219,142.62	382,057.48
Diffuse	12,711.50	14,539.63	14,519.02	14,640.14
Fishbone	58,620.54	95,940.64	115,762.75	105,107.86
Geometric	167,178.21	157,325.14	159,579.75	150,823.57
Linear	50,554.12	48,251.45	46,211.81	41,737.13
Multidirectional	156,867.13	153,508.96	221,137.62	282,859.86
Total	603,738.19	656,982.46	776,353.58	977,226.04

The multidirectional and consolidated patterns, which represent advanced stages of occupation, occurred mainly in the southern portion of the municipality of Lábrea. Although these patterns had lower percentages of cells compared to the diffuse pattern, they together represented 52.1%, 51.9%, 56.7%, and 68.0% of the deforested area for the years 2008, 2013, 2017, and 2021, respectively (Figures 3 and 4). An analysis of the deforested areas within these cells revealed a greater percentage increase in deforestation for the consolidated pattern between 2017 and 2021. Over the course of four years, the deforested area in consolidated cells increased by 162.9 thousand hectares, whereas the multidirectional pattern showed an increase of only 61.7 thousand hectares during the same period, and 67.6 thousand hectares from 2013 to 2017 (Table 3).

The linear and geometric patterns showed similar dynamics over the years regarding the number of cells, with a reduction in area when comparing the years 2008 and 2021, reflecting a gradual reduction in cells classified as linear and geometric (Figure 4). Since these patterns are related to the initial and intermediate stages of occupation, respectively, the increase in deforested area in the cells implies a transition to patterns in more advanced stages. Thus, over the years, a linear pattern cell changed to the geometric or fishbone pattern, and the geometric pattern, in turn, progressed to the multidirectional or consolidated pattern. Note that the fishbone pattern showed a significant increase from 2008 to 2017.

3.2. *Temporal evolution of deforestation trajectories*

The temporal evolution of trajectories during the three intervals between 2008 and 2021 (i.e., from 2008 to 2013, from 2013 to 2017, and from 2017 to 2021) are illustrated in Figure S1. The change trajectories (i.e., “consolidation” and “expansion”) and the "consolidated" no-change trajectory (i.e., cells that maintained the consolidated pattern) presented similar frequencies with a slight increase over the years for the consolidation and expansion trajectories but remained lower than the number of cells with the diffuse and “others” trajectories (i.e., cells that maintained fishbone, linear, or multidirectional patterns in the analyzed periods).

Both cells with the "consolidation" trajectory and cells with the "expansion" trajectory showed increases in deforestation, and the cumulative deforested areas in both classes increased over the years (Table 4). However, the contribution to deforestation in Lábrea from areas undergoing consolidation was higher than in the expansion areas for all three periods. The greatest increase in deforested area for both trajectories ("consolidation" and "expansion") occurred between the last two periods (i.e., between 2013 and 2017, and 2017 and 2021), with the cumulative deforestation from consolidation increasing 2.7 times between 2013 and 2017, and 2.4 times from 2017 to 2021. The expansion trajectory had growth similar to these between 2013 and 2017 (increasing 2 times) and from 2017 to 2021 (increasing 1.6 times). This indicates that the speed at which areas are undergoing consolidation is similar to areas undergoing expansion.

Table 4. Evolution of the cumulative deforested area, in hectares, for each deforestation trajectory and for the patterns that compose the "others" trajectories in the study area in the years 2013, 2017 and 2021.

Deforestation trajectory	Cumulative deforested area (ha)			Deforested area (%)		
	2013	*2017*	*2021*	*2013*	*2017*	*2021*
Consolidation	39,295.58	107,891.84	264,575.66	6.0%	13.9%	27.1%
Expansion	19,053.60	37,977.85	60,841.33	2.9%	4.9%	6.2%
Consolidated	160,245.84	192,254.68	229,299.02	24.4%	24.8%	23.5%
Diffuse	13,581.70	13,900.60	14,355.63	2.1%	1.8%	1.5%
Others						
Fishbone	82,004.08	95,643.96	90,573.58	-	-	-
Geometric	154,571.61	149,130.81	116,948.83	-	-	-
Linear	46,845.87	39,420.12	38,084.78	-	-	-
Multidirectional	141,384.17	140,133.72	162,547.21	-	-	-
Subtotal	424,805.73	424,328.62	408,154.40	64.6%	54.6%	41.7%
TOTAL	**656,982.46**	**776,353.58**	**977,226.04**	**100%**	**100%**	**100%**

The non-changing trajectories classified as diffuse and "others" showed similar behaviors in relation to cell frequency and the percentage of deforestation, decreasing from the initial value of 64.6% in 2013 to 41.7% in 2021 (Table 4). However, the relationship between the proportion of cells and the proportion of deforestation differed between these classes. Cells with the "others" trajectory accounted for the most deforestation in Lábrea (Table 4).

The frequencies of patterns with their respective proportions of deforestation in cells classified in the "others" trajectory (i.e., proportion of non-change in the fishbone, geometric, linear and multidirectional patterns) are given in Figure 5. The geometric and multidirectional patterns had the highest contributions to the observed deforestation in this trajectory, so that the geometric pattern decreased while the percentage of cells and deforested area in the multidirectional pattern increased. This may indicate that deforestation increased in cells with the geometric pattern, causing them to no longer be part of the non-changing trajectory and changing to patterns of deforestation in more-advanced stages of occupation (i.e., there was an increase of deforestation in cells with geometric patterns that changed to multidirectional or consolidated patterns, noting that in the next analyzed period there was a smaller number of cells with the geometric pattern and a lower percentage of the deforestation represented by them).

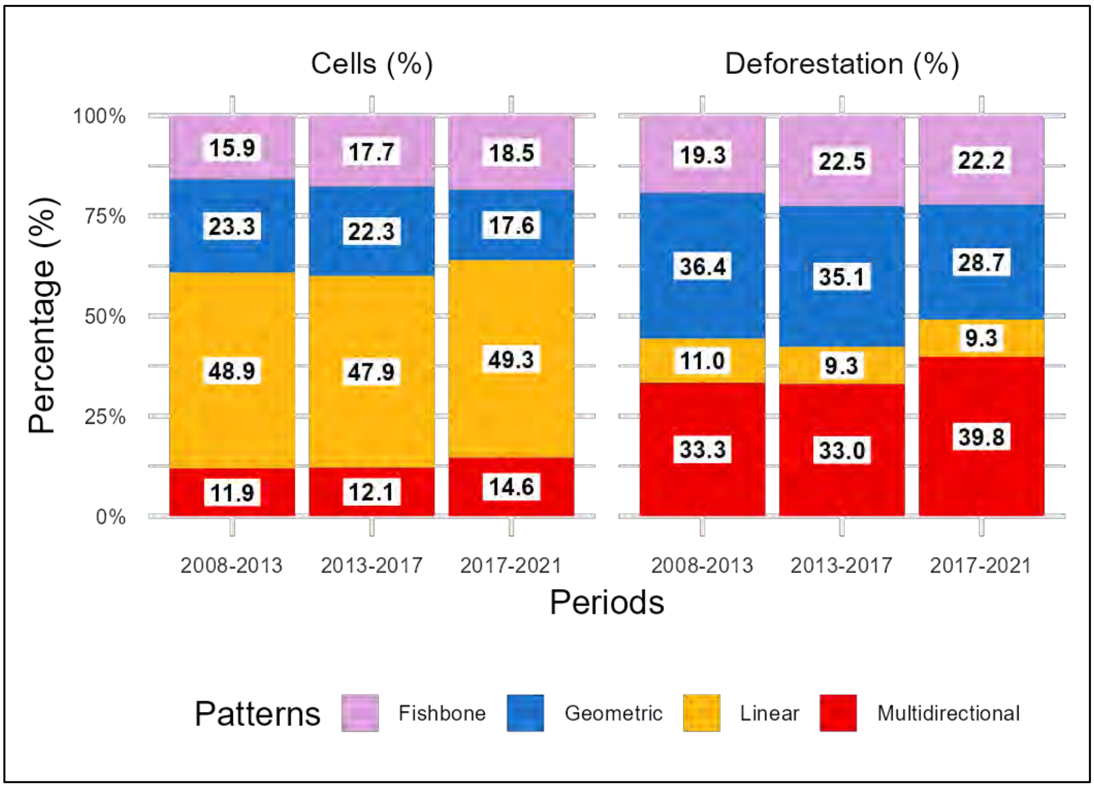


Figure 5. Evolution of the occupation patterns that make up the non-change trajectories (i.e., “others”) in the study area in the periods from 2008 to 2013, 2013 to 2017, and 2017 to 2021.

For the linear and fishbone patterns, the proportions of deforested area varied from 9.3 to 22.5%, with distinct dynamics over time (Figure 5). An increase in deforested area was observed for the fishbone pattern, representing 22.2% of the total deforested area in the last period, which corresponds to 90.6 thousand hectares (Table 4). Cells that maintained the linear pattern, despite having a higher frequency than the previous pattern, had a reduction in deforested area over the years (Table 4). Both patterns are mainly related to early and intermediate stages of occupation, with changes to more advanced patterns being frequent over the years.

3.2. *Deforestation trajectories*

The final trajectory of deforestation for Lábrea (i.e., between the years 2008 and 2021), obtained from the analysis of pattern changes in different stages of occupation, is represented in Figure 6. Cells that presented change trajectories (i.e., "consolidation" and "expansion") are mainly located in the southern portion of Lábrea, and, despite their low frequency compared to the others (29.4%), they represented 50.4% of deforestation in 2021 (Table S.2 in Supplementary material). The deforested area in cells undergoing consolidation and expansion is equivalent to 302,000 and 190,000 ha, respectively. Cells in expansion near rivers and in non-change trajectories with the diffuse pattern are mainly related to early occupations, as observed in Figures 3 and 4, and have smaller deforested areas.

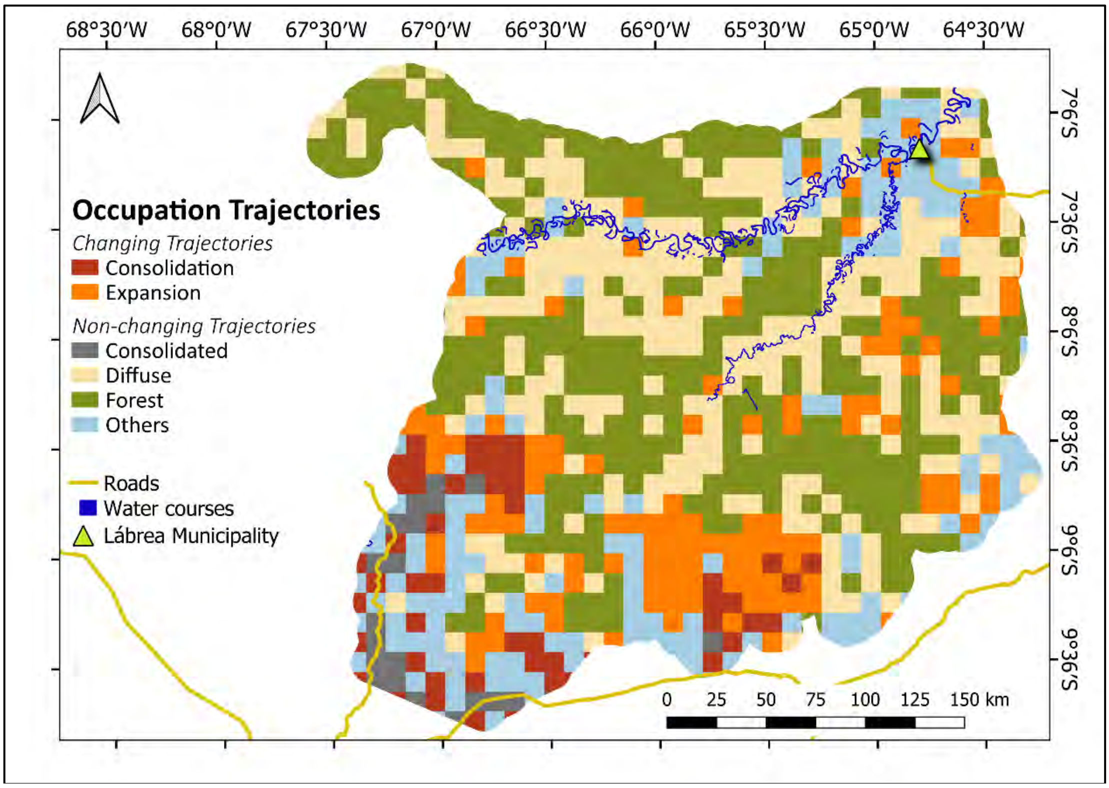


Figure 6. Final map of deforestation trajectories from 2008 to 2021 for the study area (i.e., the municipality of Lábrea + 10-km buffer). The “others” non-change trajectory is represented by the fishbone, geometric, linear, and multidirectional patterns.

The non-change trajectories are portrayed by cells that maintained their pattern, namely "consolidated", "diffuse", and "others" (i.e., cells that maintained linear, geometric, fishbone, and multidirectional patterns throughout the analysis period). The "consolidated" non-change trajectory had the lowest percentage of cells (3.6%), but the deforested area was 17.4% (Table S.2). These cells refer to areas where there was intense deforestation prior to 2008 and were therefore already consolidated due to the observed amount of deforestation. The total deforested area in these cells up to 2021 was 170,000 ha.

The highest frequencies observed belong to the diffuse and “others” non-change trajectories (Figure 6). Cells that maintained the diffuse pattern (without change) over the years had the highest frequency, representing 41.2% of Lábrea's total cells. However, as previously mentioned, the diffuse pattern is characterized by areas of initial occupation by riverine and extractivist communities with limited dynamics, so the proportion of deforested area was only 1.4%, or 13,600 ha (Table S.2).

Cells classified as "others" comprised 25.8% of the study area (Table S.2). This non-change trajectory was responsible for 30.8% of deforestation in Lábrea and corresponded to an estimated area of 300,000 ha in 2021. Of the total cells classified as "others," an area of 113,000 ha (11.6%) had the geometric deforestation pattern, and 96,000 ha (9.9%) had the multidirectional pattern.

4. Discussion

The patterns and trajectories of deforestation in Lábrea identified by the present study have similarities in some respects to the occupation dynamics observed for this region in previous studies. This is the case when comparing the results to a recent study that used cellular grids with a resolution of 50 × 50 km for the entire Legal Amazon region (Maurano et al., 2019). Similarities can be observed, such as intermediate and advanced deforestation patterns (i.e., geometric and multidirectional, respectively) concentrated in the southern portion of our study area, as well as the presence of the diffuse pattern distributed throughout our study area. However, Maurano et al. (2019) did not detect the consolidated pattern in Lábrea, indicating the loss of certain patterns at coarser scales and, therefore, the importance of analyzing deforestation patterns and trajectories at the municipal level to better understand local dynamics and how deforestation frontiers advance in deforestation hotspots like Lábrea (Saito et al., 2011).

The "expansion" and "consolidation" trajectories were concentrated in the southern portion of Lábrea, more specifically in two areas that were also reported by Tomasi (2018): a portion near the Vista Alegre do Abunã district, which is crossed by the secondary roads known as “Boi” and “Jequitibá,” and another area near the municipal seat of Boca do Acre, where the Monte Settlement Project (PA) is located (Figures S.2-1 and S.2-2 in Supplementary material). In addition to these two areas, small areas of expansion and consolidation were observed in our analysis near the Mendes Junior secondary road (Figure S.2-3), located where the states of Amazonas, Acre, and Rondônia meet. The intensification of this trajectory occurred mainly in the last four years (2018-2021). The temporal evolution of deforestation patterns and trajectories showed two important features: a large increase in the multidirectional and geometric patterns (classified as an expansion trajectory in Figure 4) near the Boi and Jequitibá secondary roads in 2021, and the presence of cells in consolidation where deforestation is concentrated, followed by cells in expansion in the same area.

The dynamics observed in the study area underscore the role of roads as vectors for the expansion of new deforested areas (Fearnside et al., 2009; Souza et al., 2017; dos Santos Junior et al., 2018). Additionally, given the study area's proximity to the Tran-Purus region, it is essential to highlight a few key insights. While the observed evolution of patterns do not directly extend to the Tran-Purus region, it can still have notable impacts (Figures 1 and 4). As is well known, the presence of protected areas acts as the primary driver in reducing the advancement of deforestation into the northern portion of the study area (Tomasi, 2018). However, this situation could change with the degazetting of protected areas, environmental degradation, or the construction of new roads leading to an escalating occupation process (Fearnside et al., 2009; Pack et al., 2016). This last aspect is reinforced by three proposed projects presented by the National Department of Transport Infrastructure (DNIT in Portuguese): the construction of a state highway (AM-175) and two federal highways (BR-230 and BR-317) (DNIT, 2021a, 2021b; Figure S.3 in Supplementary material).

The geometric deforestation pattern is located near areas with advanced stages of land occupation (i.e., multidirectional and consolidated) and is characteristic of occupations by medium and large landholders, whose main activity is cattle ranching (Gavlak et al., 2011; Saito et al., 2011). The regions in which these patterns are located also coincide with the presence of claims in the Rural Environmental Registry (CAR) that overlap with undesignated public lands (Figure S.4 in Supplementary material). This type of overlap is an indication of land grabbing (Azevedo-Ramos et al., 2020; IPAM, 2021; Moutinho, 2022).

Despite the presence of patterns that indicate intermediate and advanced stages of occupation, the diffused deforestation pattern was predominant in Lábrea and was concentrated mainly in the central part of the municipality, near the Purus and Ituxi Rivers. In these areas, the presence of small landholdings and riverside populations with low-impact agro-extractive practices is common, which characterizes the small deforested polygons of the diffuse pattern (Schubart, 1983). Similar patterns were also found by Gavlak (2011) in the Sustainable Forest District (DFS) of Highway BR-163 in western Pará, and by Saito et al. (2011) in parts of the states of Pará, Mato Grosso, and the southern edge of Amazonas.

In 2008, the federal government created four conservation units in the northern portion of Lábrea, two extractive reserves (Resex Médio Purus and Ituxi), a national park (PARNA Mapinguari) and a national forest (FLONA do Iquiri) (Figure 1). These were created in the context of the proposed reconstruction of BR-319 connecting Porto Velho to Manaus (Franco, 2011). Since there were no significant changes in the frequency of the diffuse deforestation pattern over time, as well as the proportion of the deforested area that this pattern represented, it is assumed that most of the deforestation observed in the diffuse cells occurred before 2008. This underscores the impact of protected areas in mitigating deforestation, even when they have a sustainable-use designation, such as extractive reserves (areas designated for extraction of rubber, Brazil nuts and other non-timber products), which inherently allow for more permissive activities compared to areas under full protection. Despite this distinction, protected areas play a crucial role in thwarting the progression of patterns associated with early-stage occupations, preventing them from advancing into more advanced stages of occupation and deforestation (Vitel et al., 2009; Soares-Filho et al., 2010; Walker et al., 2020).

The linear pattern is associated with early stages of occupation mainly in the vicinity of secondary roads. Depending on the region where they are located, cells with this pattern can easily evolve into more advanced stages of deforestation, acting as a vector for forest loss in previously inaccessible areas. In this study, the proportion of cells classified as linear was small compared to other patterns. These cells were distributed in areas near the municipal headquarters of Lábrea and in settlement projects. It is important to note that the confusion matrices for the analyzed years indicated classification errors between the linear pattern and the fishbone and geometric patterns. These errors were also found by Gavlak (2011) due to the low frequency of this pattern in his study area.

Although studies have related the fishbone pattern to the evolution of linear patterns in some areas in the early stages of road construction, such as BR-319 and BR-364 (Sampaio and Costa, 2009; Saito, 2010), this behavior was not so evident in the present study. This may be associated with the stage of occupation in Lábrea, which, in the analyzed years, presented more advanced occupation patterns (i.e., multidirectional and consolidated). In addition, deforestation expansion from secondary roads connected to main roads in the southern portion of the municipality occurred before 2008, with a large portion of the trajectories observed being of the non-change type.

The evolution of patterns in existing settlement projects indicates that, until 2017, the Monte settlement project (located near the municipal seat of Boca do Acre) displayed a fishbone pattern. By overlaying cells representing deforestation patterns onto settlement boundaries, it became evident that the Gedeão Sustainable Development Project (PDS) also exhibits fishbone patterns, despite being categorized as an "environmentally differentiated" settlement project where actors and deforestation patterns are expected to differ from a traditional settlement project (PA) (Yanai et al., 2017). The presence of fishbone patterns in the initial analysis periods is linked to the more intense occupation process in these settlement projects, particularly in the 2000s (Tomasi, 2018).

Our findings reveal a significant intensification of deforestation in recent years in the southern portion of Lábrea, specifically near the Boi and Jequitibá secondary roads. This contrasts with the northern portion of the municipality, where the city of

Lábrea is located. The drivers behind the consolidation and expansion of deforestation in this region are diverse, encompassing factors such as the dismantling of environmental policies, increased conflicts in rural areas, weakened environmental enforcement, land grabbing, illegal logging, and proximity to highways (Brito et al., 2019; Ferrante and Fearnside, 2019; Azevedo-Ramos et al., 2020; Vale et al., 2021; Wenzel, 2023).

Studies that identify the relationships between occupation dynamics and economic, social, and environmental variables are crucial for defining strategic actions to curb the deforestation that is advancing into forest areas in the municipality of Lábrea. A recent study applying Bayesian techniques has shown that effectiveness of past measures to slow Amazon deforestation depended heavily on the measures being tailored to the types of actors present and to each area's degree of consolidation (Brandão et al., 2023). Future studies should explore the relationship between the observed deforestation patterns and fire occurrence, given their close association (Silva et al., 2021; Dutra et al., 2023). Finally, the current study in the municipality of Lábrea illustrates that these key variables and their trajectories can be quantified through remote sensing. The application of these techniques could contribute to the understanding of deforestation patterns, providing valuable insights for informing political actions aimed at reducing deforestation rates not only within the eight-nation PanAmazonian region, but also in other tropical forest areas globally.

5. Conclusions

The dynamics of deforestation in cattle-ranching frontier areas in the municipality of Lábrea show that processes of occupancy and deforestation frontier expansion do not occur uniformly. Identifying different trajectories of change is essential for the development of actions to contain new illegal land occupations and the increase in patterns that contribute most to deforestation, such as the multidirectional and consolidated patterns that indicate advanced stages of occupation. It is also important to focus efforts on areas with the consolidation trajectory, which, despite its lower frequency, accounted for the largest deforested area in the municipality of Lábrea.

The areas bordering Lábrea in the neighboring the states of Rondônia and Acre consisted mostly of areas with the consolidation trajectory, which had the highest increase in forest loss over the 2017-2021 period. The growth of this trajectory is mainly related to the increase in the multidirectional pattern (i.e., advanced stage of occupancy). Next to these trajectories, expansion zones were identified that advance from the southern part of Amazonas state into new areas to the north. This is particularly concerning for the vast Trans-Purus region, located to the north and west if Lábrea.

The patterns and trajectories of land-use change indicate how and where deforestation occurs and allow identifying the types of actors responsible for this dynamic. This technique can contribute to the development of public policies focused on forest conservation and protection throughout Amazonia and in other tropical regions. It is necessary to strengthen protected areas, which were observed to play an important role in controlling deforestation. Effective measures to control deforestation require tailoring them to the types of actors and to the degree of consolidation of occupation. The techniques developed in this study can facilitate quantifying these factors over wide areas in Amazonia and elsewhere in the tropics.

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Supplementary Material

Amazon deforestation: A dangerous future indicated by patterns and trajectories in a hotspot of forest destruction in Brazil

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Table S.1. Explanation of Landscape Metrics-Based features. (Adapted from McGarigal and Marks, 1995)

Name	**Description**	**Formula**
AWMSI	The Area-Weighted Mean Shape Index (AWMSI) is the ratio of the perimeter to the square root of the area, weighted by the patch area, so that larger patches carry more weight than smaller ones, with AWMSI ≥1. AWMSI = 1 if all patches are circular or rectangular. This index increases as the complexity of polygons rises, meaning that it increases as shapes become more irregular.	$AWMSI = \sum_{j=1}^{n} \left[\frac{p_j}{2\sqrt{\pi \times a_j}} \times \frac{a_j}{\sum_{j=1}^{n} a_j} \right]$
AWMPDF	Area-Weighted Mean Patch Fractal (AWMPFDF) stands for the fractal dimension of the patch, weighted by the patch area in the landscape. 1 ≤ AWMPFD ≤ 2, measures the irregularity or complexity of the patch shape. AWMPFD approaches 1 for patches with simpler shapes, such as circles or rectangles, and approaches 2 when patches have a more complex shape.	$AWMPFD = \sum_{j=1}^{n} [\frac{2 \times \ln p_j}{\ln a_j} \times \frac{a_j}{\sum_{j=1}^{n} a_{ij}}]$
BIA	BIA stands for Biggest Intersection Area of the class in the landscape.	-
CA	Class Area (CA) is a measure of landscape composition represented by the sum of the areas of all fragments of a specific class in hectares (ha). CA > 0. The CA value approaches 0 when there are few patches of the class in the landscape.	$CA = \sum_{j=1}^{n} a_j$

LSI	The Landscape Shape Index (LSI) measures the shape complexity of patches, with LSI ≥ 1, with no set limit. LSI = 1 when the landscape consists of a single patch with a circular or rectangular shape.	$LSI = \frac{\sum_{j=1}^{n} e_j}{2\sqrt{\pi \times A}}$
PD	PD stands for Patch Density, which equals the number of patches in the landscape divided by total landscape area (m²), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, PD does not include background patches or patches in the landscape border, if present. However, total landscape area (A) includes any internal background present.	$PD = \frac{n}{A} \times 10000 \times 100$
PR	PR stands for Patch Richness, which equals the number of different patch types (classes) present within the landscape boundary.	$PR = m$
TABO	TABO stands for the Total Area of the Biggest Object that intersects the landscape.	-

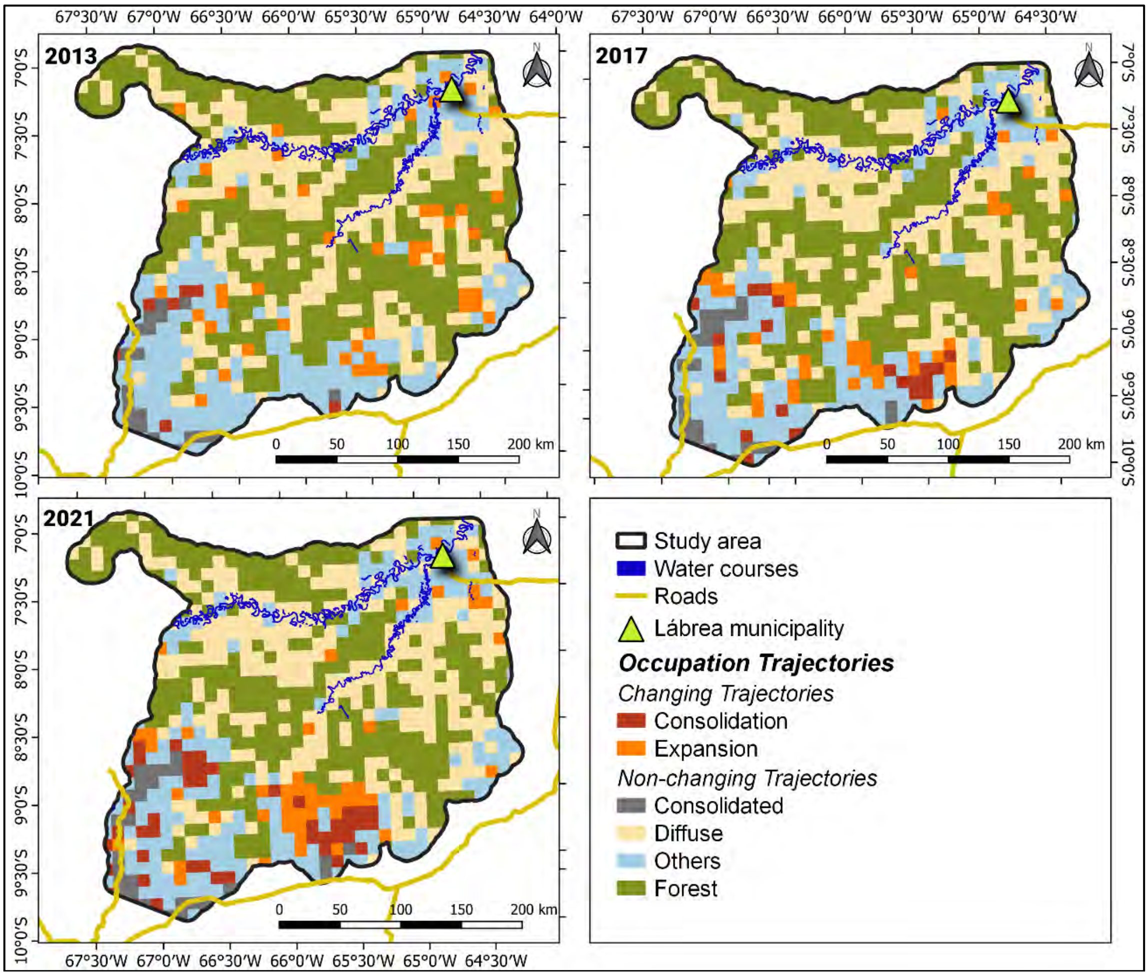

Figure S.1. Maps of the evolution of occupation trajectories in the study area for the periods 2008 to 2013, 2013 to 2017, and 2017 to 2021.

Table S.2. Percentage of deforested cells and total deforested area (in hectares) for each deforestation trajectory from 2008 to 2021 in the study area.

Deforestation trajectory	**Percentage of cells (%)**	**Deforested area (ha)**	**Percentage of total deforested area (%)**
Consolidation	8.2%	302,297.19	30.8%
Expansion	21.2%	190,824.69	19.6%
Consolidated	3.6%	170,081.82	17.4%
Diffuse	41.2%	13,609.84	1.4%
Others			
Fishbone	3.8%	59,238.17	6.0%
Geometric	5.6%	113,078.94	11.6%
Linear	13.6%	31,718.55	3.3%
Multidirectional	2.8%	96,376.84	9.9%
Subtotal	25.8%	300,412.50	30.8%
TOTAL	**100%**	**977,226.04**	**100%**

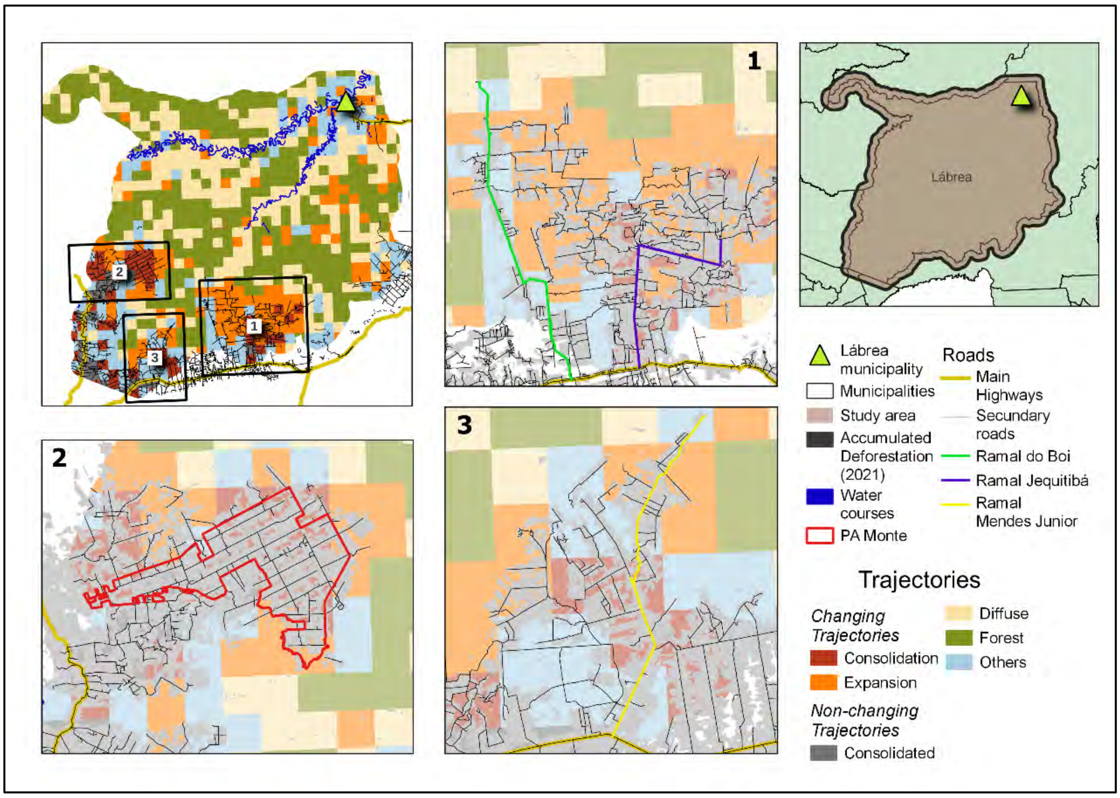

Figure S.2. Areas with advance of the "consolidation" and "expansion" change trajectories for the study area (i.e., the municipality of Lábrea + 10-km buffer) from 2008 to 2021.

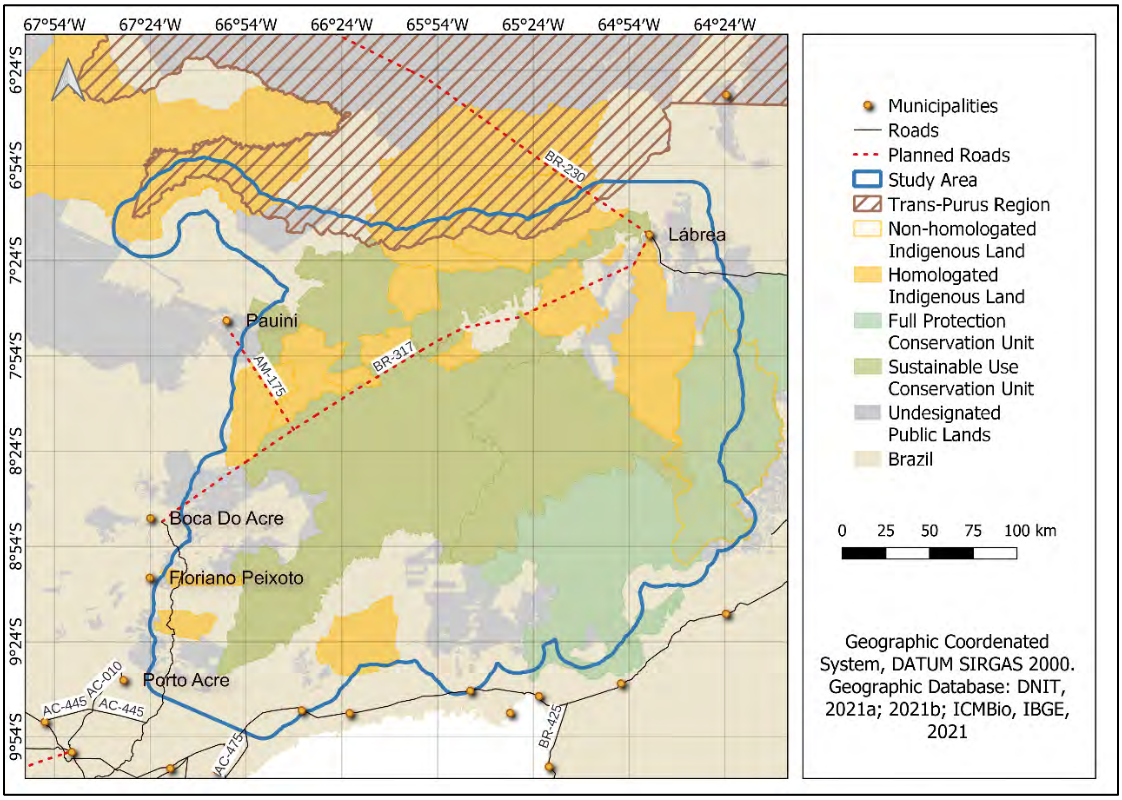

Figure S.3. Map of planned state and federal highways for the municipality of Lábrea, Amazonas.

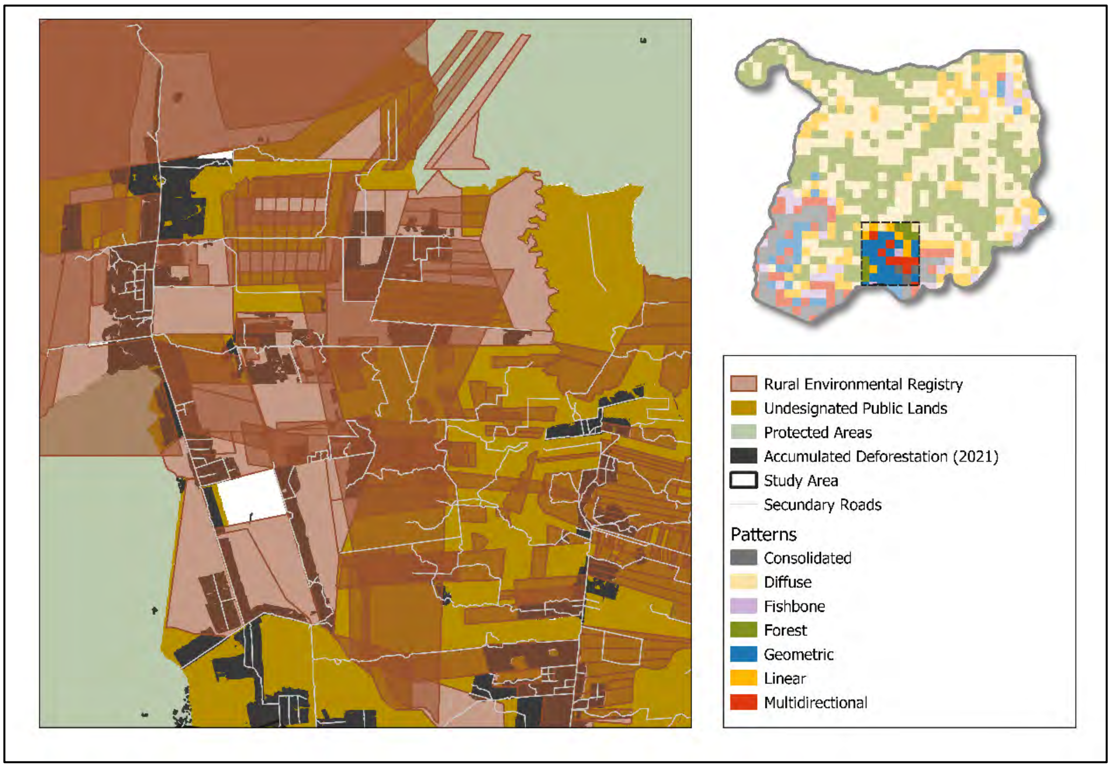

Figure S.4. Rural Environmental Registry (CAR) claims overlapping undesignated public lands in 2021, showing concentrations of the geometric deforestation pattern.

Reference

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