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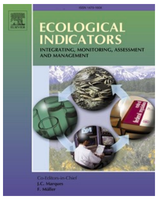

Diversity of frontier processes in Amazonian subnational jurisdictions: Frontier metrics reveal major patterns of human–nature interactions

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ABSTRACT

Deforestation, degradation and regrowth of the tropical forests of the Amazon clearly alter forest cover. These changes in space and over time generate diverse landscape use (archetypes). Identifying the differences and similarities between units and associated changes in forest cover due to deforestation, degradation and regrowth is crucial for context-specific management and planning. Methods for quantitatively characterizing this complexity across large agricultural frontiers are still underdeveloped. This article presents a new method to study the archetypes resulting from forest cover changes in Amazonian subnational jurisdictions by integrating spatial and temporal analysis techniques for deforestation, degradation and regrowth. The weighted k-means approach was linked to nine metrics covering the period 1990–2021 in three subnational jurisdictions of the Brazilian and Colombian Amazon: 1. baseline forest, 2. percentage forest loss, 3. remaining forest, 4. speed of forest loss, 5. active deforestation, 6. percentage forest degradation, 7. speed of forest degradation, 8. active degradation, and 9. percentage regrowth. Four optimal archetypes were chosen using k-means classification: a. consolidated frontier, b. vulnerable frontier, c. past gradual frontier and d. rampant frontier. Consolidated frontiers are areas with high and long term deforestation. Vulnerable frontiers have high forest cover but show signs of previous or recent deforestation and degradation. Past gradual and rampant frontiers show medium to high levels of deforestation associated with degradation. The importance and spatial distribution of each archetype varies at a territorial scale depending on colonization history and on the drivers of deforestation and degradation. This approach provides valuable insights for stakeholder to target interventions and policies adapted to each archetype, for example, payment for ecosystem services, command and control policies, land tenure regulations, land restoration strategies or land use intensification.

1. Introduction

Agricultural expansion takes diverse forms in different tropical social-ecological contexts, leading to deforestation frontiers characterized by differences in severity, speed, and spatial patterns of forest cover changes (Laurance et al., 2014). These changes have resulted in complex mosaics of large- and small-scale agricultural areas, croplands and pasture, and areas of intensive extraction of resources such as timber, minerals and hydrocarbons. Frontiers are defined here as areas with rapid land use expansion where the relative abundance of land and forest resources contrasts with a relative lack of capital or labor needed to exploit them (Rindfuss et al., 2007).

Understanding these frontier dynamics is crucial for designing effective, context-specific policies (Foley et al., 2011; Rounsevell et al.,

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2012) and for assessing the impacts of land use changes on biodiversity and ecosystem services. This knowledge can support land use planning policies, for example, by identifying areas to be conserved and others to be put into production, and to promote different ecosystem services, for example carbon storage and soil erosion control. As methods for quantitatively characterizing these dynamics across large agricultural frontiers are still underdeveloped, capturing and describing frontier dynamics is essential for supporting land governance and addressing sustainability challenges (Pacheco et al., 2021).

Recent studies emphasize the need for an integrative approach to better understand the diversity and interplay of frontiers (Buchadas et al., 2022; Levers et al., 2018; Oberlack et al., 2023, Oberlack et al., 2016). Characterizing and mapping typical patterns and trajectories of land system changes that consider both extent and intensity, are powerful tools for understanding this complexity. One such integrative approach is archetypical analysis, which identifies recurrent patterns in land systems. Archetypes are defined as patterns, processes, or combinations of variables, actors, situations, or outcomes (Levers et al., 2018; Oberlack et al., 2016; Schellnhuber et al., 1997; Valbuena et al., 2008) that occur repeatedly in space and over time. These archetypes can provide a holistic understanding of land system processes. Archetype analysis identifies configurations of attributes that are shared across cases, which is crucial for describing system dynamics or causal effects. This approach is particularly useful when dealing with heterogeneous cases, as it facilitates comparison, generalization, and the transfer of insights across multiple cases (Oberlack et al., 2019; Václavík et al., 2013). The number of applications of archetype analysis has recently increased (Brasil et al., 2023; Mengxue et al., 2022; Oberlack et al., 2019).

The archetype approach has already been successfully used to identify and characterize deforestation frontiers (Baumann et al., 2022; Buchadas et al., 2022) in tropical dry forests but only based on the deforestation process. In this study, we used an integrative approach to analyze tropical deforestation frontiers in the Amazon region. The originality of our study is that we account for three distinct processes of forest cover change: deforestation, forest degradation and forest regrowth, whereas land use dynamics in the Amazon are usually only analyzed through the deforestation lens (Richards, 2015; Rodrigues et al., 2009). Deforestation, usually defined as a permanent switch from forest cover to other land uses, has been the target of many national policies and international commitments, and a significant reduction has been achieved in some countries, including Brazil (Arima et al., 2014; Nepstad et al., 2014). Most Amazon countries have committed to combating deforestation and have built legal frameworks and public policies to support this objective. However, forest cover patterns are also the result of two other processes: forest degradation and forest regrowth. Evidence that forest degradation is an important process in forest cover changes has increased in recent years (Bourgoin et al., 2024; Lapola et al., 2023; Vancutsem et al., 2021). As new technologies and data emerge, the degradation process is better measured and analyzed, thereby revealing significant impacts on ecosystem structure and functioning (Berenguer et al., 2021; Lapola et al., 2023, Aragão et al., 2018; Reygadas et al., 2023). The importance of regrowth as secondary forest in forest change analyses highlights their great potential for restoration in priority areas, especially forests that have regrown naturally in areas that were once occupied by pasture (Nunes et al., 2022, Nunes et al., 2020, Brasil et al., 2023). Secondary forests in the Amazon region host significant biodiversity, store carbon and improve soil conditions (Ayala-Orozco et al., 2018; Heinrich et al., 2021; Martin et al., 2013).

In this paper, we present a new approach for representing human–environment interactions based on archetypes, i.e. unique combinations of the full range of the three processes of forest cover changes. Archetypes can be defined as forest cover changes or frontiers types that are characterized by a similar set of metrics related to the three processes. The main objective of the present study was to assess how different spatiotemporal patterns of forest cover changes in three subnational jurisdictions in Amazonia result in a variety of archetypes. We hypothesize that (i) subnational jurisdictions can be systematically characterized using a limited set of archetypes, defined as distinct landscape typologies that encapsulate varying spatiotemporal dynamics of forest cover changes and (ii) the three subnational jurisdictions exhibit significant variation in both the relative prominence and spatial distribution of archetypes. Characterizing these archetypes is a powerful tool to design specific and appropriate policies to prevent deforestation and forest degradation and to promote forest regrowth at the scale of subnational jurisdictions. We propose a data-based, operational and reproducible method that can be upscaled and applied to other frontier areas. We applied our analysis in three contrasted areas of subnational jurisdictions of the Amazon, two in Brazil (municipality of Paragominas and Cotriguaçu) and one in Colombia (department of Guaviare). We used the Tropical Moist Forest (TMF) dataset of the European Commission's Joint Research Centre (EC-JRC), the only worldwide dataset that includes data on deforestation, forest degradation and forest regrowth.

2. Materials and methods

2.1. Study sites

The study sites are three Amazon subnational jurisdictions (Fig. 1): two municipalities in Brazil (Paragominas and Cotriguaçu) and one department in Colombia (Guaviare) where stakeholders have committed to improving forest resource management (see below). The main geographical and socioeconomic features are provided for each territory hereafter.

- Municipality of Paragominas (state of Pará, northern Brazil): This municipality covers 19342 km^2, the population density is approximately 5.45 inhabitant/km^2 (IBGE, 2023). Colonization started with the opening of the Belem-Brasilia highway in the 1960 s (Uhl and Guimaraes, 1989). Paragominas municipality experienced high rates of deforestation and degradation from the 1960 s to 2005 (Tritsch et al., 2016). The majority of deforested land has been converted into pasture for cattle ranching. Until the 2010 s, cattle ranching was extensive, and fire was used to limit regrowth (Osis et al., 2019). Wood harvesting and fires were first associated with deforestation during the period 1983–1999 (Alencar et al., 2004; Verissimo et al., 1992). Since 2005, with the sharp decrease in deforestation rates, timber harvesting and fires have become direct drivers of forest degradation. In the 2000 s, commercial agriculture, mainly soya, began to appear on land located close to the main roads that had already been deforested (Osis et al., 2019; Piketty et al., 2015a,b). The establishment of agrarian reform settlements (*assentamentos*) with the development of agriculture and livestock raising also had a significant local impact on forest cover (Osis et al., 2016). The municipality initiated the Green Municipalities Program in 2009, that was subsequently applied throughout Para State, and in 2024, launched the Paragoclima program targeting carbon neutrality by 2030.
- Municipality of Cotriguaçu (state of Mato Grosso, Central West Brazil): This municipality covers 9123 km^2, the population density is approximately 1.21 inhabitants/km^2 (IBGE, 2023). A total of 18.5 % of the territory is indigenous land (*Escondido*), and 14.7 % is a national park (*Parque Nacional do Juruena*). Cotriguaçu has traditionally been occupied by indigenous peoples (Rikbaktsa group) (Sills et al., 2014). The first immigrants from Parana state (southern Brazil) arrived in Cotriguaçu in 1984 (Sills et al., 2014). Cotriguaçu was first a district and became a municipality in 1991, and four rural reform settlements were created, *Cedere*, *Nova Cotriguaçu*, *Juruena* and *Sonho Meu*. The main rural economic sectors in Cotriguaçu are cattle ranching and timber extraction (Guerra, 2016). The municipality of Cotriguaçu is part of an innovative proposal that brings together civil

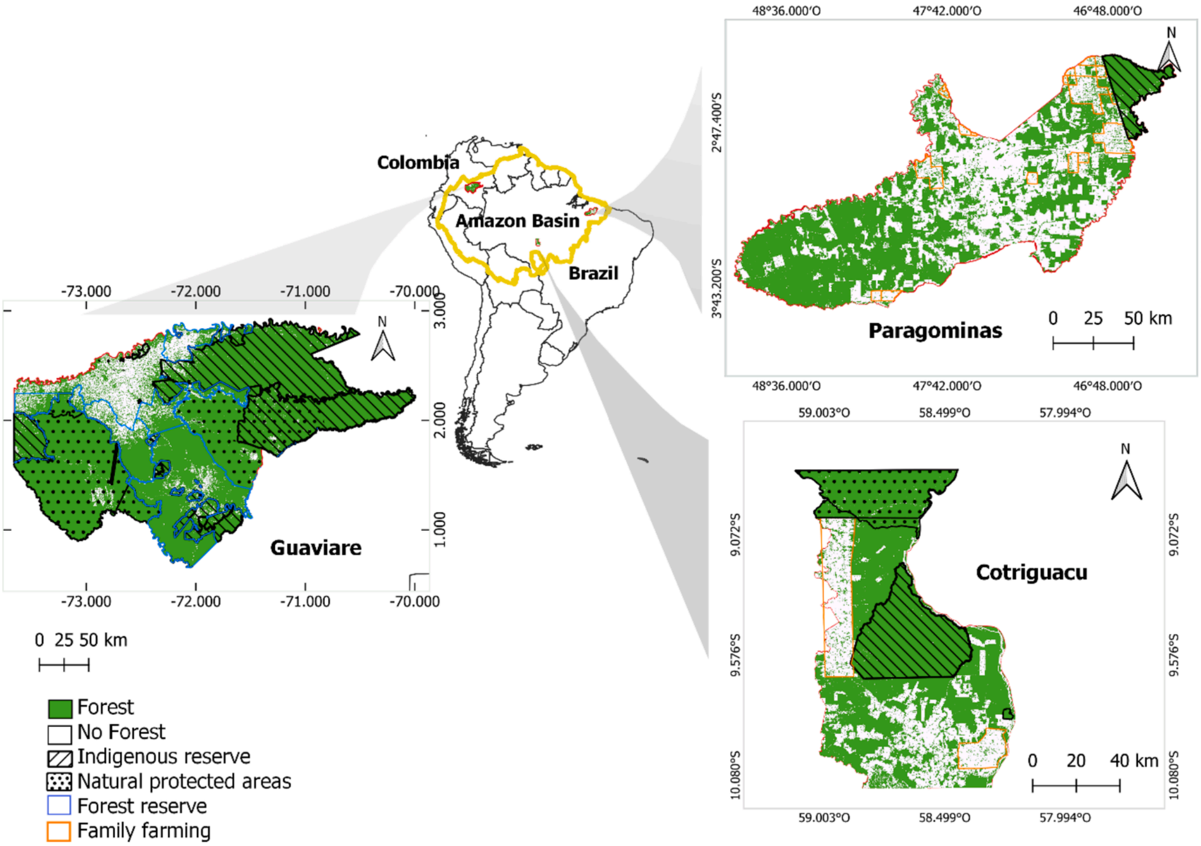


Fig. 1. Location of the three study sites: the Department of Guaviare in Colombia and the municipalities of Cotriguaçu and Paragominas in Brazil. Forested and non-forested areas are those recorded in 2022 (.
Source: European Commission's Joint Research Centre, EC-JRC)

society actors focused on reducing emissions due to deforestation and forest degradation in a strategy called "Produce, Conserved and Include" (PCI), led by the State of Mato Grosso (Rodrigues and Garcia, 2020).

- The Department of Guaviare (Colombia): This department covers 56 460 km^2, the population density is approximately 1.55 inhabitants/km^2 (DANE, 2018, Acosta, 1993; Arcila et al., 1999; Molano, 1987). The population is mainly located in the northern part of the department, in the main city of San José de Guaviare. In 1982, an area of 3011 km^2 was deforested, corresponding to 5.4 % of the province. Over the period of 1982–2020, deforested areas (3494 km^2) were mainly concentrated in the northwestern and southern regions. Since the 1980 s, the coca economy, subsistence farming and, more recently, extensive cattle farming have been the three main drivers of deforestation in Guaviare (Armenteras et al., 2019; Dávalos et al., 2014; Murcia and Guariguata, 2014). Illegal crops and pastures are also the two main drivers of forest degradation through the creation of fragmented forestland in the Colombian Amazon (Armenteras et al., 2006; Navarrete et al., 2016).

2.2. Methodology

Our framework analysis involved three main steps (Fig. 2): (i) data collection, (ii) metrics computation, (iii) archetype classification.

2.2.1. Data collection

Among all the databases containing data on changes in forest cover, we chose the TMF-JRC source for three reasons. Firstly, because it is the only dataset that provides information on the three forest change processes: deforestation, degradation and forest regrowth. TMF-JRC uses LANDSAT long-term satellite images to map disturbances with 91.4 % accuracy (Vancutsem et al., 2021). Each pixel was classified in one of the following categories: undisturbed forest, deforested, degraded forest, or regrowth forest. Secondly, using the TMF-JRC ensures reproducibility and operability of our approach, since it provides data for all moist forests worldwide whereas other data sets (*e.g.* INPE-Prodes, TerraClass, SAD Imazon and the dataset on forest degradation used by Matricardi et al., (2020) for Brazil and Ideam for Colombia) only contain national data. Thirdly, the JRC-TMF dataset contains updated annual data for the period 1990 to the present, whereas SAD-Imazon only contains data on the Legal Amazon from 2008 on. Annual deforestation, forest degradation and forest regrowth trends from 1990 to 2021 are detailed in Appendice section (see Fig. A.1). For the two Brazilian study sites, we compared the JRC-TMF deforestation data with data from three other sources (SAD-Imazon, INPE and MapBiomass). All four data sources showed the same trends, but JRC-TMF showed higher yearly deforestation areas rates after 2010. Unlike the other data sources, JRC-TMF classifies forest that was very severely burned over a period of more than 2.5 years as deforested area (see Fig. A.2).

We used the 'Annual change collection' of the Tropical Moist Forest (TMF) dataset developed by the European Commission's Joint Research Centre (EC-JRC), which is based on a 32-year Landsat time series (1990–2021) (Vancutsem et al., 2021). The 32 maps contain information at 30 m resolution on forest extent, disturbances (deforestation and degradation) and recovery (or forest regrowth) for each year. Each disturbance, whether deforestation or degradation, has its own distinct timing and intensity. Deforestation implies a change in land cover from forested to non-forested, whereas degradation includes temporary disturbances to a forest that nevertheless remains predominantly forested, such as selective logging, fires, and extreme weather events such as hurricanes, droughts, and blowdowns. Undisturbed forest is considered a closed evergreen or semi-evergreen forest with no disturbance

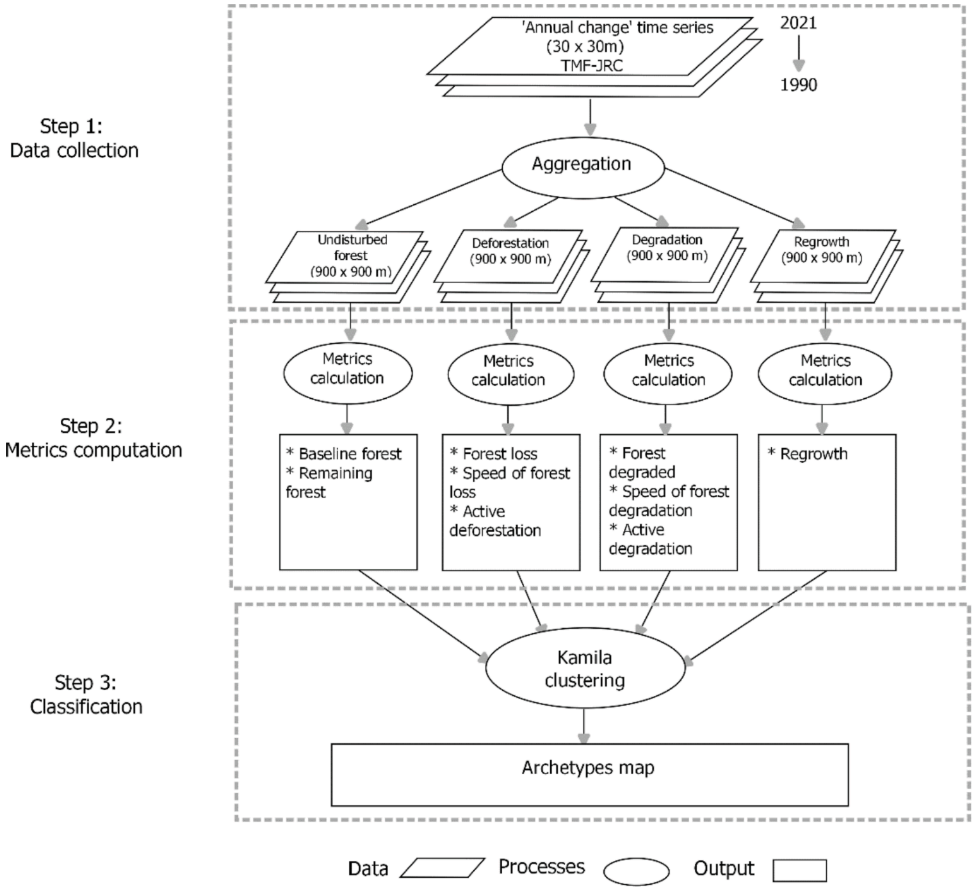


Fig. 2. Methodological framework to identify archetypes based on changes in forest cover.

observed over the full observation period.

2.2.2. *Metrics computation*

Following Buchadas et al., 2022, we developed a set of nine metrics (Table 1). Two are related to the extent of the forest (baseline forest in 1990, and remaining forest). Three metrics are related to deforestation (the percentage of forest loss, the speed of forest loss, and the degree of deforestation). Three metrics are related to forest degradation (percentage of forest degradation, speed of degradation and activity of degradation). We focused on independant degradation (i.e. logged, burned, logged and burned) as it was defined by Matricardi et al., 2020. One metric is related to forest regrowth (percentage of forest regrowth). Except for the baseline metrics forest (percentage of forest cover in 1990) and remaining forest (percentage of forest cover in 2021), all the metrics were calculated for the period 1990–2021. The metrics were calculated in an approximately 1 km^2 cell grid (0.81 km^2 cell of 0.9 km × 0.9 km). The cell size was established in relation to the size distribution of forest patches and deforested areas. A 1 km^2 cell was selected because it captures 99 % of the variability of the sizes of both forested and deforested patches. Seven of the nine metrics are continuous (baseline forest, remaining forest, percentage of forest loss, speed of forest loss, percentage of forest degradation, speed of forest degradation, percentage of forest regrowth), and two are categorical metrics (active deforestation and active degradation).

2.2.3. *Archetype classification*

To identify and map archetypes summarizing homogeneous forest cover changes, we conducted an unsupervised classification of the nine metrics. We used the Kamila clustering method, which is based on the k-means, since this algorithm is particularly suitable for large datasets and mixed continuous and categorical variables (Foss and Markatou, 2018). We performed the classification using 10 random initializations and a maximum of 20 iterations per initialization. We chose the number of initializations and iterations because they were sufficiently large to produce stable results. To determine the optimal number of clusters, we used the prediction strength criteria developed by Tibshirani and Walther (2005). We estimated the prediction strength criteria over 15-fold cross-validation runs, computed for a number of clusters ranging from 3 to 9. We used the function calcNumClust available in the 'kamila' package (Foss and Markatou, 2018). According to the prediction strength criteria, the optimum number of clusters was 4.

We used the Adjusted Rand Index (ARI) to analyze the sensitivity of the initialization of the KAMILA classification. We ran 100 Kamila classifications using 10 random initializations and a maximum of 20 iterations per initialization for each one. We then computed the ARI to assess agreement between results (Hubert and Arabie, 1985) using the 'mclust' package (Scrucca et al., 2023).

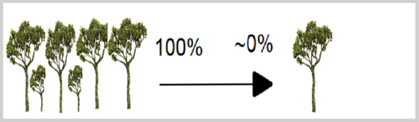
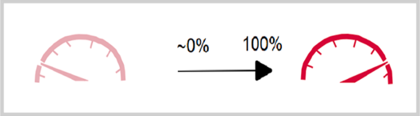
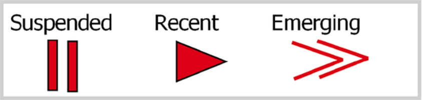
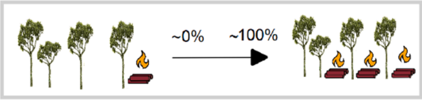
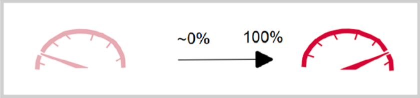
We classified the three sites simultaneously to be able to compare the results between them. Each cluster was then interpreted as an archetype and labeled on the basis of the median values of the nine metrics. All the steps were conducted in R version 4.1.2, which uses the following packages: terra (Hijmans, 2020), data.table (Barrett et al., 2006), stringr (Wickham, 2009), kamila (Foss and Markatou, 2018), ggplot2 (Wickham et al., 2007).

3. Results

3.1. *Four archetypes summarized forest cover changes*

Cluster analysis based on 9 metrics, identified four distinct archetypes. The ARI (sensitivity analysis) shows very high concordance between the results of the 100 classifications with a median value of 0.9.

Table 1
Characteristics of the nine metrics computed in a grid with cells of 0.81 km^2 (0.9 km × 0.9 km).

Forest characteristics and processes	Name of metrics	Definition	Representation scheme
Forest extent	Baseline forest	Percentage of forest cover (undisturbed and degraded forest) in 1990 computed for each cell of the grid	
Forest extent	Remaining forest	Percentage of forest cover (undisturbed and degraded forest) in 2021 computed for each cell of the grid	
Deforestation	Forest loss	Percentage of forest lost between 1990 and 2021 (deforestation area in 2021/Baseline forest * 100) computed for each cell of the grid	
Deforestation	Speed of forest loss	Maximum rate of deforestation (km^2/year) calculated for the period 1990–2021. For each cell, the surface area of annual deforestation was fitted using a LOESS regression. The speed of forest loss is the maximum value of the first derivate (corresponding to the highest annual velocity of forest loss). The speed of forest loss of deforestation was scaled as a percentage based on the highest value in the 3 sites.	
Deforestation	Active deforestation	Period between 1990 and 2021 when the frontier is considered as 'recent', 'consolidated' or 'emerging'. To calculate active deforestation, we considered only cells with 5 consecutive annual rates of deforestation higher than 0.5 %. The active deforestation metric was classified as suspended, recent or emerging, depending on a reference date for each site. The year 2016 was selected to identify the suspended deforestation (deforestation continued for more than 6 years), active and recent (deforestation lasting less than 6 years). Active deforestation is defined as suspended if the 5 consecutive years occurred before the reference date; as recent, if the 5 consecutive years included the reference date; and as emergent, if the 5 consecutive years occurred after the reference date. If 5 consecutive annual rates of deforestation occurred several times over the time period, the most recent active period was used.	
Degradation	Forest degraded	Percentage of forest degraded in 2021 computed for each cell of the grid	
Degradation	Speed of forest degradation	The same computation as the speed of forest loss using degradation data	
Degradation	Active degradation	The same computation as active deforestation using degradation data	
Regrowth	Regrowth	Percentage of forest regrowth in 2021 computed for each cell of the grid	

Archetype 1 (Fig. 3a) was characterized by a high baseline forest (almost all cells had a median percentage of baseline forest of more than 90 %), high and rapid deforestation (75 %) associated with a medium level of degradation (median values ranged between 34.1 % for Guaviare and 22.0 % for Cotriguaçu). The speed of forest loss was the highest of the four archetypes. In this archetype, in 2021, less than 20 % forest remained at all three sites. This archetype started emerging in 2016 in Guaviare and occurred during the study period in Paragominas and Cotriguaçu. Hereafter his archetype is termed 'rampant frontiers'.

Archetype 2 (Fig. 3b) shared some characteristics with rampant frontiers, but deforestation was less intense. Approximately 60 % forest cover remained in 2021 and the speed of forest loss was slower than in rampant frontiers. Similar percentages of forest loss and of forest degradation (between 25 % and 30 %) were found in Guaviare and Paragominas, whereas in Cotriguaçu, the percentage of forest loss was slightly lower than that of forest degradation (approximately 25 % and 50 %, respectively). Like in rampant frontiers, this archetype started emerging in Guaviare in 2016 and occurred during the study period in

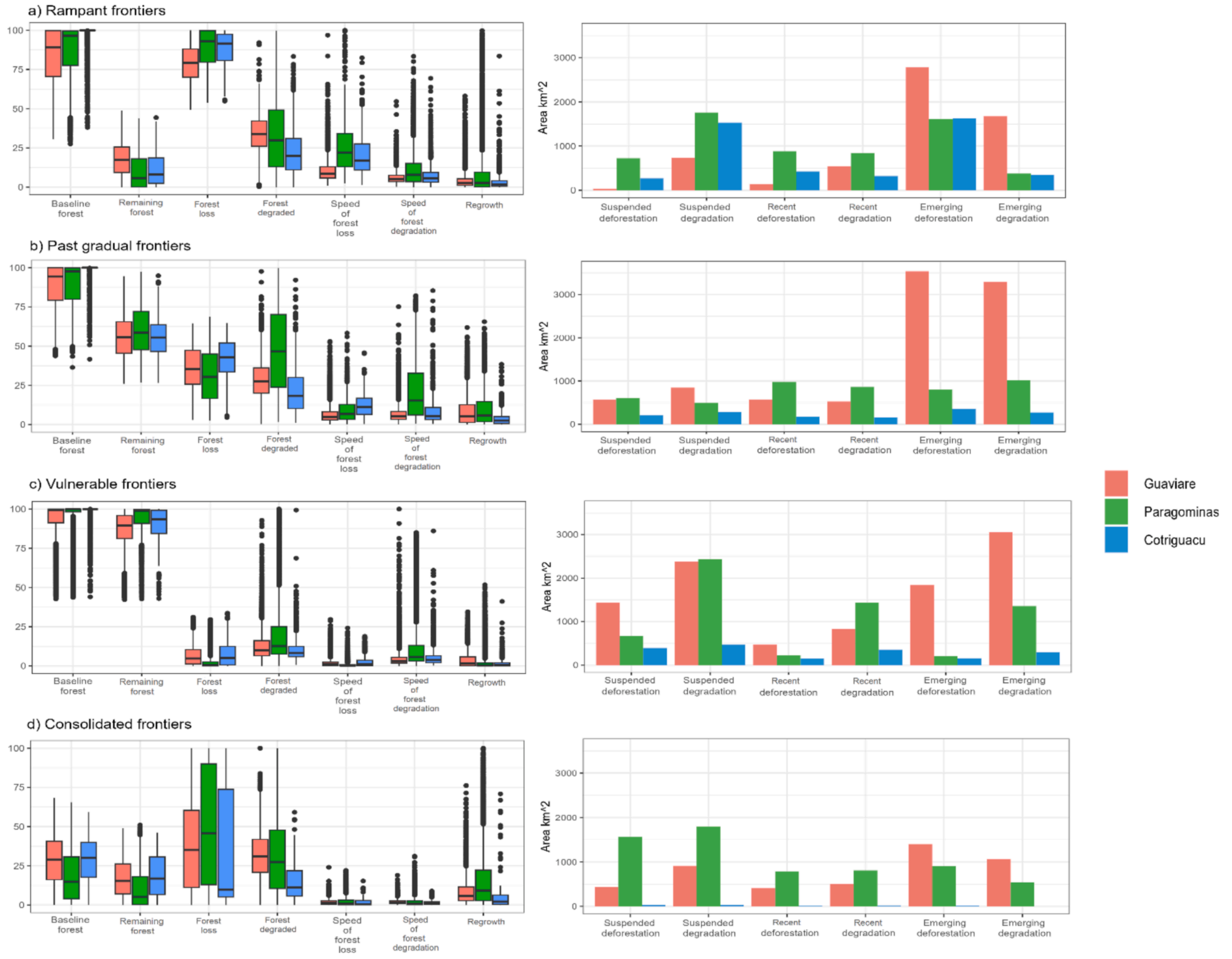


Fig. 3. Distribution of the 7 continuous metrics (left) and the 2 categorical metrics (right) related to deforestation, degradation and regrowth for the four archetypes at each study site.

Paragominas and Cotriguaçu. Hereafter this archetype is termed ‘past gradual frontiers’.

Archetype 3 also had a high baseline forest (approximately 99 %) but underwent low forest degradation (< 15 %) and even lower deforestation (< 5 %). In this archetype, remaining forest in 2021 covered 87 % of Guaviare, 93 % of Paragominas and 91 % of Cotriguaçu. At all three sites, this archetype occurred during the study period. Hereafter this archetype is termed ‘vulnerable frontiers’ with high forest extent and the first signs of disturbances.

Archetype 4 was characterized by low baseline forest (< 30 %). These areas were subject to high deforestation until 1991. Less than 20 % forest remained in 2021 at all three sites. These areas are still suffering from a moderate percentage of forest loss and forest degradation, with high variability within each site. Forest regrowth is an important process in some areas in Paragominas and Guaviare. This archetype occurred during the study period at all three sites. Hereafter, this archetype is termed ‘consolidated frontiers’.

In Paragominas, from 2010 to 2020, areas of degraded forest were larger than the deforested areas. Forest degradation in Paragominas increased from 1138.8 over the period 1999–2009 to 1296.4 km^2 over the period 2010–2020 (Fig. A1). Deforestation in Paragominas decreased from 2137.1 km^2 between 1999 and 2009 to 1090.1 km^2 over the period 2010–2020. Over the same periods, a decreasing trend was also observed in Cotriguaçu, where deforestation fell from 1533.5 km^2 to 613.9 km^2 and forest degradation from 435.9 to 238.7 km^2. In Guaviare, deforestation over the period 1999–2009 was 1289.45 km^2 and increased to 2 246 km^2 over the period 2010–2020 whereas forest degradation fell from 1530.18 km^2 to 1232.26 km^2. In Cotriguaçu and Guaviare secondary forests represented small areas of the territory and between 2010 and 2018, the mean annual areas of secondary forests were 8.14 km^2 and 21.33 km^{2,} respectively. In Paragominas, between 2010 and 2015, the annual area of secondary forests was 12.3 km^2 and increased to 77.0 km^2 in 2016, 140.3 km^2 in 2017 and to 252.4 km^2 in 2018.

3.2. *Distribution of the four archetypes at the study sites*

Forest cover changes affected 29.9 % of the total area in Guaviare, 74.5 % in Paragominas and 48.2 % in Cotriguaçu (Table 2). Vulnerable frontiers accounted for the largest areas of each territory in Guaviare and Paragominas (12.0 % and 27.6 %, respectively) and the second largest area in Cotriguaçu (13.7 %). The main archetype in Cotriguaçu was rampant frontier (25.4 %).

In Guaviare, the archetypes showed a clear spatial pattern in the northern part of the territory with three successive layers: the old settlement areas in the northern and east–southern parts of the territory

Table 2
Area and percentage of the total area represented by each archetype at the three study sites.

Changes in forest cover						No changes in forest cover
	Rampant frontiers	Past gradual frontiers	Vulnerable frontiers	Consolidated frontiers	**Total area**	Total area
Guaviare	2 952.3 km^2	4 677.1 km^2	6 813.5 km^2	2 556.6 km^2	**16 999.50** km^2	39 460.50 km^2
	5.2 %	8.2 %	12.0 %	4.5 %	**29.9 %**	70.1 %
Paragominas	3 207.7 km^2	2 372.7 km^2	5 450.3 km^2	3 699.3 km^2	**14 730** km^2	4 612.00 km^2
	16.2 %	12.0 %	27.6 %	18.7 %	**74.5 %**	25.5 %
Cotriguaçu	2 320.3 km^2	735.9 km^2	1 252.9 km^2	80.1 km^2	**4 389.20** km^2	4 733.80 km^2
	25.4 %	8.2 %	13.7 %	0.9 %	**48.2 %**	51.9 %

were mainly consolidated frontiers (Fig. 4). The surrounding layer was a mix of rampant and post gradual frontiers. This mixed layer covered the largest area in the northeastern part of Guaviare. The third layer was a vulnerable frontier located at the interface with undisturbed forests. Vulnerable frontiers were also located along rivers. A hot spot with rampant and past gradual frontiers was located in the eastern part of Guaviare.

In Paragominas, all four archetypes were well represented, the past gradual frontier covered 12.0 % and the vulnerable frontier 27.6 %. The spatial pattern of the archetypes differed significantly from that in Guaviare. The central and eastern parts of the municipality were dominated by consolidated, rampant and past gradual frontiers (Fig. 4). The western part was dominated by vulnerable frontiers and undisturbed forests. A large patch of rampant and past gradual frontiers was found in the eastern part of the municipality, which is also associated with consolidated frontiers. This patch is concerned by the reform of rural settlements.

Cotriguaçu was dominated by rampant frontiers (25.4 % of the total area) and vulnerable frontiers (13.7 %, Table 2). Consolidated frontiers accounted for only 0.9 % of the territory. Rampant frontiers dominated in rural reform settlements in the western and southeastern parts of the territory. Vulnerable frontiers were located mainly at the interface between rampant frontiers and undisturbed forests as well as along the Juruena River (Fig. 4).

3.3. *Active degradation and active deforestation in the vulnerable frontiers*

In this section, we analyze degradation and deforestation in the vulnerable frontiers at the three study sites. Our objective was to understand what kind of changes to the forest cover are beginning to occur in this archetype. Vulnerable frontiers were dominated by degradation in Paragominas and by degradation and deforestation in Guaviare and Cotriguaçu (Fig. 5). Small areas of vulnerable frontiers were characterized by very low rates of degradation and very low rates of deforestation (no active deforestation, see Table 3). Only 4.1 % (Guaviare), 3.0 % (Paragominas) and 2.2 % (Cotriguaçu) of the vulnerable frontier areas presented low rates of forest change (Table 3).

Indeed, in Paragominas, degradation occurred in the absence of deforestation in 77 % of the vulnerable frontiers (Table 3). These areas were mainly characterized by suspended degradation (36 % of vulnerable frontiers) but also by significantly recent degradation (21 %) and emergent degradation (20 %). Deforestation only impacted a very small proportion of vulnerable frontiers (69.1 km^2, i.e., 1.3 %).

In both Guaviare and Cotriguaçu, the degradation process occurred without deforestation in respectively, 41 % and 44 % of the vulnerable

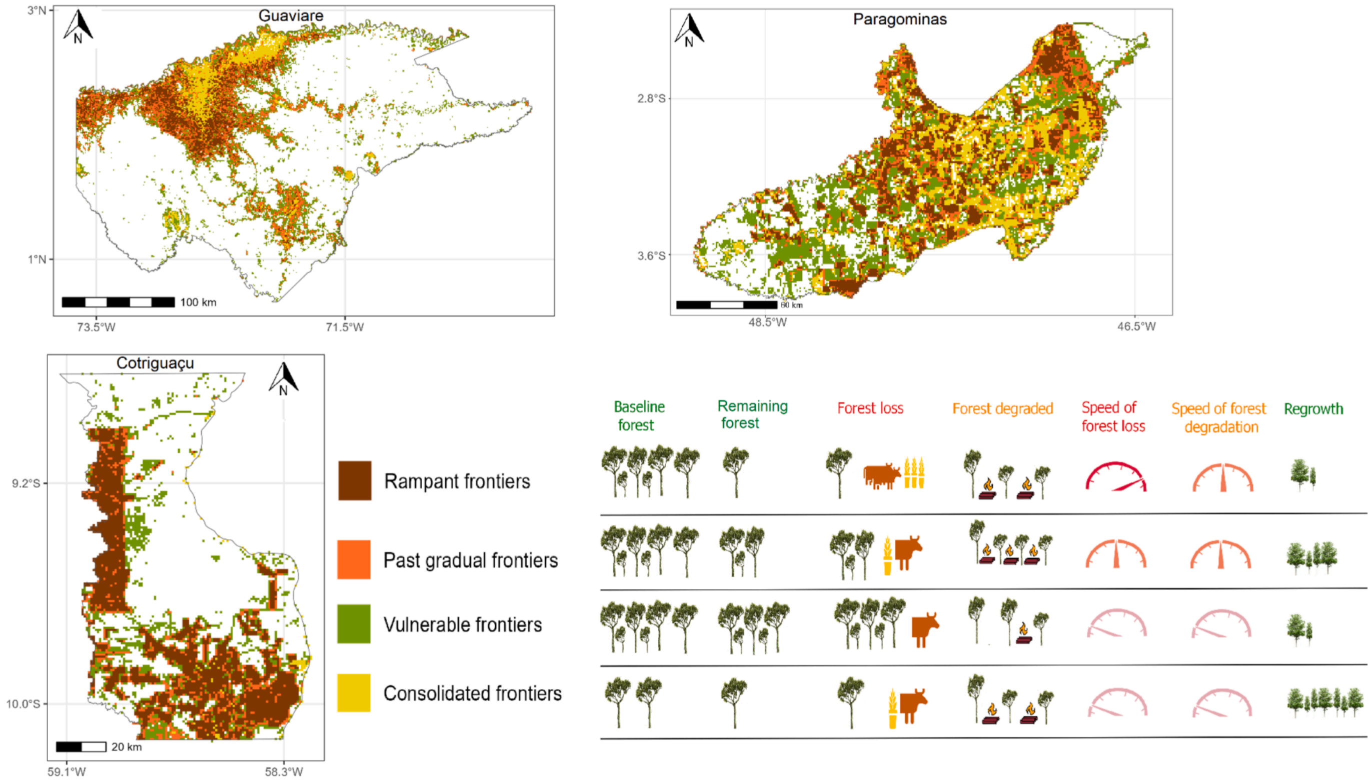


Fig. 4. Archetype maps for each study site: a) Guaviare, b) Paragominas and c) Cotriguaçu.

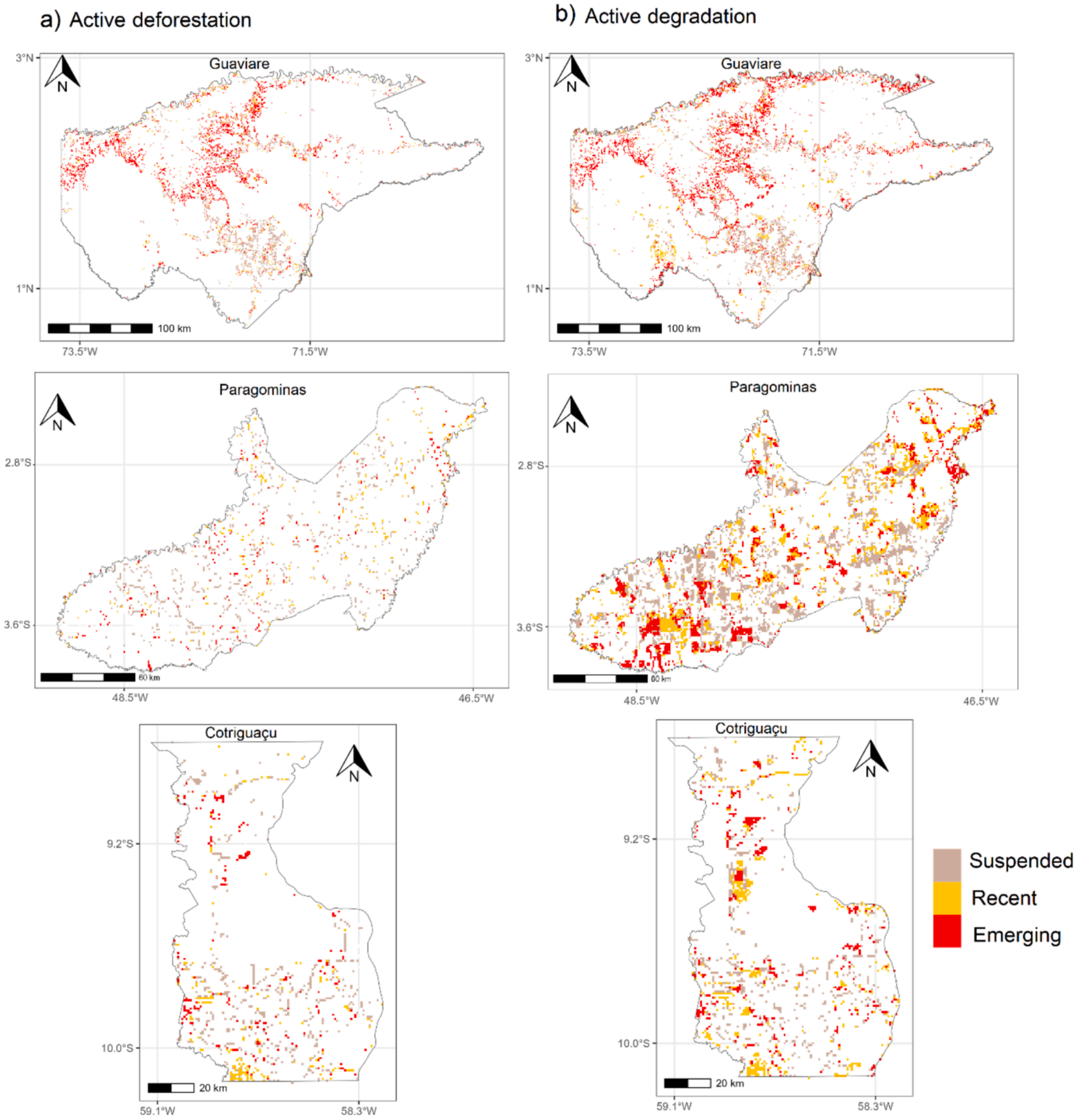


Fig. 5. Active deforestation (a) and active degradation (b) in vulnerable frontiers at each study site.

frontiers. In other words, degradation and deforestation processes acted together in respectively, 51 % and 46 % of the vulnerable frontiers in Guaviare and Cotriguaçu. In Guaviare, both emergent (20.3 % of the vulnerable frontier area) and suspended (14.7 %) degradation and deforestation were found. In Cotriguaçu, both processes were suspended (19.9 %), but an emerging front was observed in 7.8 % of the vulnerable frontiers.

In Guaviare, the vulnerable areas were located in three distinct areas (Fig. 5). The biggest area was in the northern part of the department and along the main river (Inirida River), where deforestation and degradation were mainly emerging. Significant areas are also vulnerable in the southern part of the department, where deforestation and degradation were mainly suspended. A third area with a significant number of patches classified as vulnerable was located in the eastern part of the territory characterized by recent degradation. In Paragominas, areas of vulnerable frontiers associated with active degradation were mainly located in the eastern part of the municipality (Fig. 5). In Cotriguaçu, diffuse vulnerable areas were observed in the southern part of the municipality. Larger patches classified as vulnerable frontiers were located in the center of the municipality, mainly associated with recent and emerging degradation processes (Fig. 5).

3.4. Distribution of undisturbed forests in the four archetypes at the three study sites

The distribution of undisturbed forests in 2021 within the four archetypes shows that in all three territories, the great majority of undisturbed forest was located in vulnerable frontiers and to a lesser extent in past gradual frontiers, notably in Guaviare and Paragominas (Fig. A.3): 3842.4 km^2, 4031.4 km^2 and 1052.6 km^2 in Guaviare, Paragominas and Cotriguaçu respectively. To a lesser degree, undisturbed forests were also observed in past gradual frontiers (1549.5 km^2, 614.8 km^2, 349.0 km^2, respectively). Undisturbed forests accounted for only a small area in rampant frontiers ($<$ 277.6 km^2) and in consolidated frontiers ($<$ 182.3 km^2)

4. Discussion

We developed an operational and reproducible data-driven approach to identify archetypal patterns of long-term changes in forest cover. We applied our method to three subnational jurisdictions of the Brazilian and Colombian Amazon. The three main processes were analyzed jointly, and, to our knowledge, this is the first study that uses

Table 3

Area and percentage of active deforestation and active degradation at the three. study sites.

Guaviare Area (km^2)						
		Degradation				
		Suspended	Recent	Emerging	No	**Total**
Deforestation	Suspended	1 003.9 km^2 (14.7%)	120.5 km^2 (1.8%)	210.9 km^2(3.1%)	99.1 km^2 (1.5%)	**1 434.5** km^2 **(21%)**
	Recent	133.2 km^2 (2.0%)	127.7 km^2 (1.9%)	182.4 km^2(2.7%)	18.2 km^2 (0.3%)	**461.5** km^2 **(7%)**
	Emerging	189,6 km^2 (2.8%)	91.2 km^2 (1.3%)	1 385.4 km^2 (20.3%)	172.9 km^2 (2.5%)	**1 839.1** km^2 **(27%)**
	No	1 050.7 km^2 (15.4%)	483.7 km^2 (7.1%)	1 262.5 km^2 (18.5%)	281.5 km^2 (4.1%)	**3 078.4** km^2 **(45%)**
	Total	**2 377.4** km^2 **(34.9%)**	**823.1** km^2 **(12.1%)**	**3041.1** km^2 **(44.6%)**	**571.7** km^2 **(8.4%)**	**6 813.5** km^2 **(100%)**
Paragominas Area (km^2)						
		Degradation				
		Suspended	Recent	Emerging	No	**Total**
Deforestation	Suspended	396.5 km^2 (7.3%)	150.7 km^2 (2.8%)	69.0 km^2(1.3%)	49.2 km^2 (0.9%)	**665.3** km^2 **(12.2%)**
	Recent	42.8 km^2 (0.8%)	111.0 km^2 (2.0%)	69.8 km^2(1.3%)	3.2 km^2 (0.1%)	**226.8** km^2 **(4.2%)**
	Emerging	52.3 km^2 (1.0%)	29.3 km^2 (0.5%)	107.8 km^2(2.0%)	16.7 km^2 (0.3%)	**206.2** km^2 **(3.8%)**
	No	1942.1 km^2 (35.6%)	1144.3 km^2 (21.0%)	1103.1 km^2 (20.2%)	162.6 km^2 (3.0%)	**4 3520** km^2 **(79.8%)**
	Total	**2 433.7** km^2 **(44.7%)**	**1 435.3** km^2 **(26.3%)**	**1 349.7** km^2 **(24.8%)**	**231.5** km^2 **(4.2%)**	**5 450.3** km^2 **(100%)**
Cotriguaçu Area (km^2)						
		Degradation				
		Suspended	Recent	Emerging	No	**Total**
Deforestation	Suspended	249.02 km^2 (19.9%)	46.78 km^2 (3.7%)	20.61 km^2(1.6%)	72.16 km^2 (5.8%)	**388.6** km^2 **(31.0%)**
	Recent	30.92 km^2 (2.5%)	81.67 km^2 (6.5%)	19.82 km^2(1.6%)	13.48 km^2 (1.1%)	**145.9** km^2 **(11.6%)**
	Emerging	16.65 km^2 (1.3%)	14.27 km^2 (1.1%)	98. km^2(7.8%)	26.16 km^2 (2.1%)	**155.4** km^2 **(12.4%)**
	No	169.70 km^2 (13.5%)	207.76 km^2 (16.6%)	158.60km^2 (12.7%)	26.96 km^2 (2.2%)	**563.0** km^2 **(44.9%)**
	Total	**466.3** km^2 **(37.2%)**	**350.5** km^2 **(28%)**	**297.4** km^2 **(23.7%)**	**138.8** km^2 **(11.1%)**	**1 252.9** km^2 **(100%)**

deforestation, forest degradation and regrowth metrics together to map forest cover change archetypes in the Amazon. Our analysis revealed that the three study sites shared the same archetypes, but that there were marked differences in their spatial and temporal distributions. Here, we first discuss how our approach can be applied in other forest regions to enable wider generalizations and abstractions of frontier dynamics. We then discuss the importance of each forest cover change process in defining archetypes. Finally, we discuss specific policies that could be prioritized for relevant actions to improve the conservation and restoration of forests

4.1. An operational and reproducible approach

Our operational and reproducible approach can be applied to other regions and other topics as it is open and flexible. Although we selected typologies for the purpose of the present study, the methodology can be adjusted to produce other typologies and archetypes for different applications. Our approach is operational because the TMF-JRC dataset covers all tropical moist forests worldwide. The dataset delineates the three processes independently, with separate databases on deforestation, forest degradation and forest regrowth, thereby preventing concordance issues. The approach is also scalable, since new metrics can be added. In the present study, we focused on independent degradation (i.e. logged, burned, logged and burned) as it was defined by Matricardi et al., (2020). In the future, it would be interesting to consider dependent degradation (i.e. fragmentation, edge effects), by integrating landscape metrics, for example, computed at different scales (Kim et al., 2013). Future studies could explore additional geographical factors, such as road networks, proximity to infrastructure projects, distance from protected areas, or even governance factors like the presence of law enforcement. Our approach is reproducible since it does not require the same level of expertise as that required in other studies (Baumann et al., 2022; Buchadas et al., 2022), in which archetypes are identified by the combination of measurements and the knowledge of the researcher. Our approach, which is based on the k-means weights of the Kamila algorithm, organizes the archetypes without the need for specialized knowledge. This represents a fundamental distinction from other data-driven classification approaches which integrated data of deforestation, land-use and socio-economic data (Arvor et al., 2013, DeFries et al., 2004, Thalês et al., 2021) but relied also heavily on the authors expert's knowledge for the definition of typologies.

This unsupervised approach can be easily replicated across different regions and at various scales, ranging from individual landscapes to entire regions, by leveraging existing databases. However, one limitation of this automated classification method is its potential to overlook certain changes. This includes recent shifts that may signal significant emerging trends or smaller-scale changes that, despite their limited spatial extent, hold considerable importance for the jurisdiction. Another challenge lies in validating the resulting typologies, as they are derived from retrospective analyses. Nonetheless, engaging with local stakeholders could provide valuable insights and help verify whether the identified archetypes align with their perceptions of change.

4.2. Importance of each forest cover change process in defining archetypes

Archetypes are driven by three main metrics: "baseline forest", "remaining forest" and "percentage of forest loss". These metrics are related to the deforestation process. High baseline forest areas are associated with three archetypes: rampant, past gradual and vulnerable frontiers. The low-baseline forest distinguished consolidated frontiers that characterized the oldest deforested areas in Paragominas and Guaviare. Low values of remaining forest in rampant and consolidated frontiers were distinct from past gradual and vulnerable frontiers, which presented medium to high values, respectively. The highest values of forest loss were characterized by rampant frontiers. In past studies, forest cover changes were analyzed mainly based on deforestation (Geist and Lambin, 2002, 2001). For example, Buchadas et al., (2022) used four deforestation metrics and two metrics of forest cover in tropical dry forests to detect five deforestation frontier archetypes: inactive frontiers, consolidated frontiers, fragmented frontiers, looming frontiers and rampant frontiers. These authors used a slightly shorter time series (2000–2020) but much larger areas (pantropical dry woodland, i.e., 1044.13 Mha in 2000). Rodrigues et al., (2009) also classified Brazilian municipalities in seven groups relative to the deforestation frontier in 2000 defined using two deforestation metrics: deforestation activity (the percentage of forest lost between 1997 and 2000) and deforestation extent (the percentage of original forest that had been lost by 2000). The classes ranged from prefrontier municipalities, with essentially intact forest cover, through progressively deforested classes, with increasing and then declining active deforestation, through heavily deforested postfrontier municipalities that were again almost inactive. Both studies analyzed deforestation frontiers at large scales and incorporated a wide range of deforestation dynamics, whereas our study analyzed frontier dynamics at a relatively fine scale and focused on the dynamic heterogeneity of forest cover changes within each study site in order to compare the dynamics at territorial scale.

In Brazil, the annual rate of deforestation has sharply fallen since 2004 as a result of public policies (PPCDAM was launched in 2004), local agreements (such as the "Green Municipalities Program"), private sectoral agreements (such as the soja memorandum), the drop in commodity prices, and unfavorable currency exchange rates (Fearnside, 2017a, Fearnside, 2017b; Nepstad et al., 2014; Ricketts et al., 2010; West et al., 2020). The sharp reduction in deforestation has further highlighted the role and importance of forest degradation, which has recently been the main process of forest cover change. Degradation metrics are comparable in rampant, past-gradual and consolidated frontiers (approximately 25 %) but were lower in vulnerable frontiers. Even if degradation metrics are less discriminating in identifying archetypes, they provide useful information to characterize the different frontiers. For example, in Guaviare, the emerging past-gradual and vulnerable frontiers were highly impacted by degradation. In Paragominas, degradation was higher in the past gradual frontiers than in the rampant frontiers. We also demonstrated that in the vulnerable frontiers, degradation had more impact on forested areas than deforestation at all three study sites in the three study periods (suspended, recent and emerging). Research on deforestation and forest degradation in the Brazilian Amazon has demonstrated that selective logging, fire, and deforestation are all correlated (Asner et al., 2006, 2005; Cochrane, 2003; Morton et al., 2013). Dependent degradation due to deforestation that causes edge effects and fragmentation has been analyzed (Brinck et al., 2017). Additionally, it is acknowledged that between 1990 and 2014, the extent of forest degradation exceeded that of deforested areas in the Brazilian Amazon, accountying for respectively, 337 km^2 and 308.31 km^2, (Matricardi et al., 2020). Importantly, forest degradation involves multiple spatial patterns (Tritsch et al., 2016), making its identification and mapping more complex than deforestation. Although significant progress has been made in the data mapping of forest degradation in tropical forest areas (Vancutsem et al., 2021), some limitations remain in terms of accuracy. This was evidenced in the northern municipality of Cotriguaçu where JRC data may overestimate degradation along rivers.

Finally, regrowth is not truly discriminating for the four archetypes. Deforestation frontiers are quite recent in Cotriguaçu, with a very small area of consolidated frontiers (0.9 % of the territory) and are still emerging in Guaviare. Neither site has started a transition in which areas that are less suitable for cattle ranching and agriculture are abandoned to allow the forest to regrow. This process is starting in Paragominas (see Fig. A1), where the percentage of regrowth is slightly higher at rampant, past-gradual and consolidated sites than at the other two sites.

The archetypes revealed three different spatial forest cover change dynamics on the basis of the relative importance of each archetype and their spatial organization. In Guaviare, in 2021, primary forest covered 88.5 % of the department. Primary forest can also be divided into 18.4 % of the forest area located in one of the four archetypes and 70.1 % of the archetypes (Table 2). The archetypes are mainly located in the northern and east–southern parts of the territory, with a spatial sequence of archetypes ranging from consolidated in the most ancient deforestation areas, to emerging vulnerable archetypes elsewhere in the most forested areas. This hotspot of emerging degradation and deforestation fronts is expanding from the Integrated Management District to the Amazon Forest Reserve, where deforestation is illegal (Katz-Asprilla et al., 2024). This hotspot reveals the increase in the deforestation rate between 2013 and 2019 during the negotiation and signing of the Peace Agreement with the FARC (Bautista-Cespedes et al., 2021; Murillo-Sandoval et al., 2023; Murillo-Sandoval et al., 2022; Negret et al., 2019; Prem et al., 2020; Rodríguez-de-Francisco et al., 2021). To address deforestation, vulnerable archetypes at the edge of this front should be prioritized through specific actions (see 4.3). The other colonization area located in the southern part of Guaviare was a former (now abandoned) coca production area (Armenteras et al., 2009; Davalos et al., 2021; Dávalos et al., 2016). However, this area is a vulnerable archetype meaning deforestation has stopped and that land use has stabilized.

In Cotriguaçu, rampant frontiers mainly dominated (25.4 %) in the southern and eastern regions of the municipality. These rampant areas were mainly related to the creation of settlement projects at the beginning of colonization in 1990, and were mainly used as pasture for cattle ranching (Guerra, 2016). Similar results were reported by Caviglia-Harris and Harris, (2011), who showed that the design of a settlement (radial, fishbone) has a significant impact on the rate of deforestation. In their study, Alves et al., (2021) also evaluated the effect of settlement design on deforestation and landscape fragmentation in four settlements in the state of Rondônia, where more than 50 % of the forest cover was lost by 2015. In cotriguaçu, the second most important archetype is vulnerable frontiers, with 13.7 % of these areas scattered in the southern and eastern regions of the municipality associated with selective logging areas.

The spatial pattern in Paragominas differs significantly from that at the two other study sites, with the four archetypes scattered almost throughout the territory. The primary forest area covers 54.8 % of the departments and is split into 29.3 % of the forest area embedded in one of the four archetypes and 25.5 % with no archetype classification. The latter area is located in the eastern (forestry farm, Cikel Verde) and western (indigenous reserve) parts of the municipality. A particular feature of the Brazilian Forest Code is that all properties must include legal forest reserves that represent a significant proportion of their land. This is not the case in Colombia. This means that in Brazil a significant proportion of the remaining primary forest is indeed conserved by landowners.

4.3. *How can archetype analysis help define public policies?*

The characteristics of archetypes provide a basis for determining and prioritizing relevant actions to improve the conservation and restoration of forests. It is possible to target priority policies for each archetype by cross-referencing the policy instruments with the question of the legality

Table 4
Suggestions for targeting public policies according to the defined archetypes.

Archetype frontiers	Legal frame	Public policies based on:
Vulnerable frontiers	Legal	- Incentives for sustainable forest management - Strong additionality for PES aimed at conserving forests
	Illegal	- Incentives and involvement of local populations to strengthen command-and-control policies
Past gradual frontiers	Legal	- Strong additionality for incentives aimed at avoiding further risk of forest degradation (eradicate the use of fire as a tool in agricultural and cattle ranching practices)
	Illegal	- Urgent clarification of the land tenure issue, legal obligation of forest restoration and sustainable land use intensification and strict control of the use of fire as a tool in agricultural and cattle ranching practices
Rampant frontiers	Legal	- Strong additionality for PES aimed at forest conservation
	Illegal	- Targeting those areas for command-and-control policies against land mafia
Consolidated frontiers	Legal	- Strong additionality for PES aimed at restoring forests
	Illegal	- Urgent clarification of the land tenure issue, legal obligation of forest restoration and land use intensification

of deforestation (Table 4). To achieve this objective, it is necessary to identify areas in which deforestation is legal and illegal for each archetype based on data sourced from national authorities, as already done by Katz-Asprilla et al., (2024) in the Colombian department of Guaviare.

It is critical to consider whether deforestation is legal or illegal because, theoretically, policy instruments for tackling legal deforestation differ from those used to combat illegal deforestation (Gregersen et al., 2010). For example, incentives, such as Payment for Ecosystem Services (PES), should primarily target regions where deforestation is legal, whereas efficient command-and-control policies are required where deforestation is illegal.

The policies developed should consider the relative extent of legal and illegal deforestation zones in conjunction with the archetypes characterizing a specific jurisdiction. Nonetheless, some general recommendations can be outlined.

In vulnerable frontiers, when deforestation is still legal, large areas of primary forest nevertheless remain. Incentives for the sustainable management of forest resources and PES aimed at forest conservation are required to avoid deforestation and PES have more opportunity for additionality (Gregersen et al., 2010; Karsenty et al., 2017). Typically, in the vulnerable frontiers of Guaviare and Cotriguaçu, incentives for community-based forest management are particularly suitable, as the landscapes are less fragmented, making it easier to organize farmers around continuous forest areas. However, these incentives must also consider the limited accessibility of these regions, and to make community-based forest management plans viable, it is essential to ensure access to profitable markets (Piketty et al., 2015a,b, Sist et al., 2014). Incentives for the sustainable management of forest resources could also target vulnerable frontiers where deforestation is illegal if the legal framework authorizes the sustainable harvesting of timber and non-timber forest products. In these areas, it is also important to involve and strengthen local populations to avoid possible illegal intrusion. As we have demonstrated in this study, these areas are often located at the colonization fronts and are thus very difficult to control efficiently without the involvement of surrounding communities. In Guaviare, for example, one strategy is grouping villages located on deforestation fronts with which priorities for action are defined not only with a view to stabilizing the agricultural frontier, but also with a view to preserving peace and social services.

In past gradual frontiers, large areas of primary forest but agriculture and cattle ranching can increase the risk of forest degradation. This often occurs through uncontrolled fires (Aragão et al., 2008; Barni et al., 2021; Bourgoin et al., 2020; Brasil et al., 2023). The risk of further degradation can be reduced by prohibiting fire use in agricultural practices. Incentives such as subsidies and farmer training can promote the eradication of fire in agriculture and cattle ranching. However, even without deforestation, fire is still commonly used, for example, to clear quickly cultivated or grazed areas. Several alternatives, like rotational pastures and slash-and-mulch methods (Kettler, 1996), are already available but need wider dissemination. Eliminating fire use is a priority for preventing further degradation in the Amazon. When deforestation is illegal, but has been happening for many years, it is also often impossible to systematically remove farmers who have established their properties. In addition to forbidding the use of fire, decisions must be made at the local level to redefine the status of *de facto* property rights in the many areas that have already been deforested, even illegally, and, most importantly, reach binding agreements targeting restoration between the inhabitants of the territory and the State (Katz-Asprilla et al., 2024).

In rampant frontiers, where deforestation is still legal but the forested area is small in size, forest restoration is a priority and could be encouraged by incentives like PES. Where deforestation is completely illegal but nevertheless continues, the areas concerned must be targeted by command- and-control policies against deforestation.

In consolidated frontier areas, where deforestation is still legal and forest regrowth already significant, farmers have already started to engage in land use intensification trajectories that allow the passive regeneration of forests. In Paragominas, for example, in cattle ranching farms, clearing and restoring pastures is increasingly mechanized with the cessation of the use of fire. However, due to their biophysical characteristics, many areas such as buffer strips along watercourses, springs, swamps, steep slopes, cannot be mechanized and are consequently spontaneously abandoned to forest regeneration. What is more, cattle ranchers may seek to protect them in order to ensure they continue to provide ecosystem services (Plassin et al., 2017). Specific incentives are needed to boost such land use intensification practices. The situation becomes more complex in areas where deforestation is illegal and land tenure is weak. The urgent clarification of land tenure, especially in regions like Guaviare, is crucial and could involve linking land rights with forest conservation and restoration obligations to prevent further loss of legally protected forest areas. The Colombian Ministry of Environment is currently working on new models for smallholder concessions as a strategy to stabilize agricultural frontiers.

5. Conclusions

This paper presents an operational and reproducible data-driven framework for identifying archetypal patterns of long-term forest cover changes across three subnational jurisdictions in the Amazon Basin. We demonstrate that the complexity of forest cover dynamics can be effectively captured through the use of four distinct archetypes. Furthermore, the simplicity and accessibility of our approach, which relies on open data and does not require specialized expertise, make it easily replicable in other tropical forest regions facing deforestation challenges. Characterizing these areas through archetypal patterns can help inform targeted public policies in regions where deforestation and forest degradation persist. In our three subnational jurisdictions, primary forests are predominantly located in vulnerable and gradual frontiers. We highlight the need for public policy discussions with local stakeholders to implement incentive-based projects, improve monitoring, and protect forest resources for sustainable management, thereby promoting sustainable forest management and reducing forest degradation from threats such as fire and over-logging. In particular, community-based forest management could be a viable option in Guaviare (Colombia) and Cotriguaçu (Brazil), where landscape is less fragmented. Conversely, in areas characterized by low forest cover like in rampant frontiers and consolidated frontiers, identifying abandoned lands with potential for natural forest regrowth presents an opportunity. Engaging local stakeholders to reach a consensus on strategies such as land rehabilitation or the planting of native tree species could enhance forest restoration efforts. However, the urgent clarification of land tenure remains a critical prerequisite, particularly in Guaviare, Colombia. Establishing clear land rights, coupled with obligations for forest conservation and restoration, is essential to prevent further encroachment on legally protected forest estates.

CRediT authorship contribution statement

Guido Briceño: Writing – original draft, Investigation, Formal analysis, Data curation. **Julie Betbeder:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization. **Agnès Bégué:** Writing – review & editing, Supervision, Conceptualization. **Guillaume Cornu:** Writing – review & editing, Formal analysis, Data curation. **David Katz-Asprilla:** Writing – review & editing. **Marie-Gabrielle Piketty:** Writing – review & editing, Resources, Funding acquisition. **Solen Le Clech:** Writing – review & editing. **Vinicius Silgueiro:** Writing – review & editing. **Hélène Dessard:** Writing – review & editing. **Lilian Blanc:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

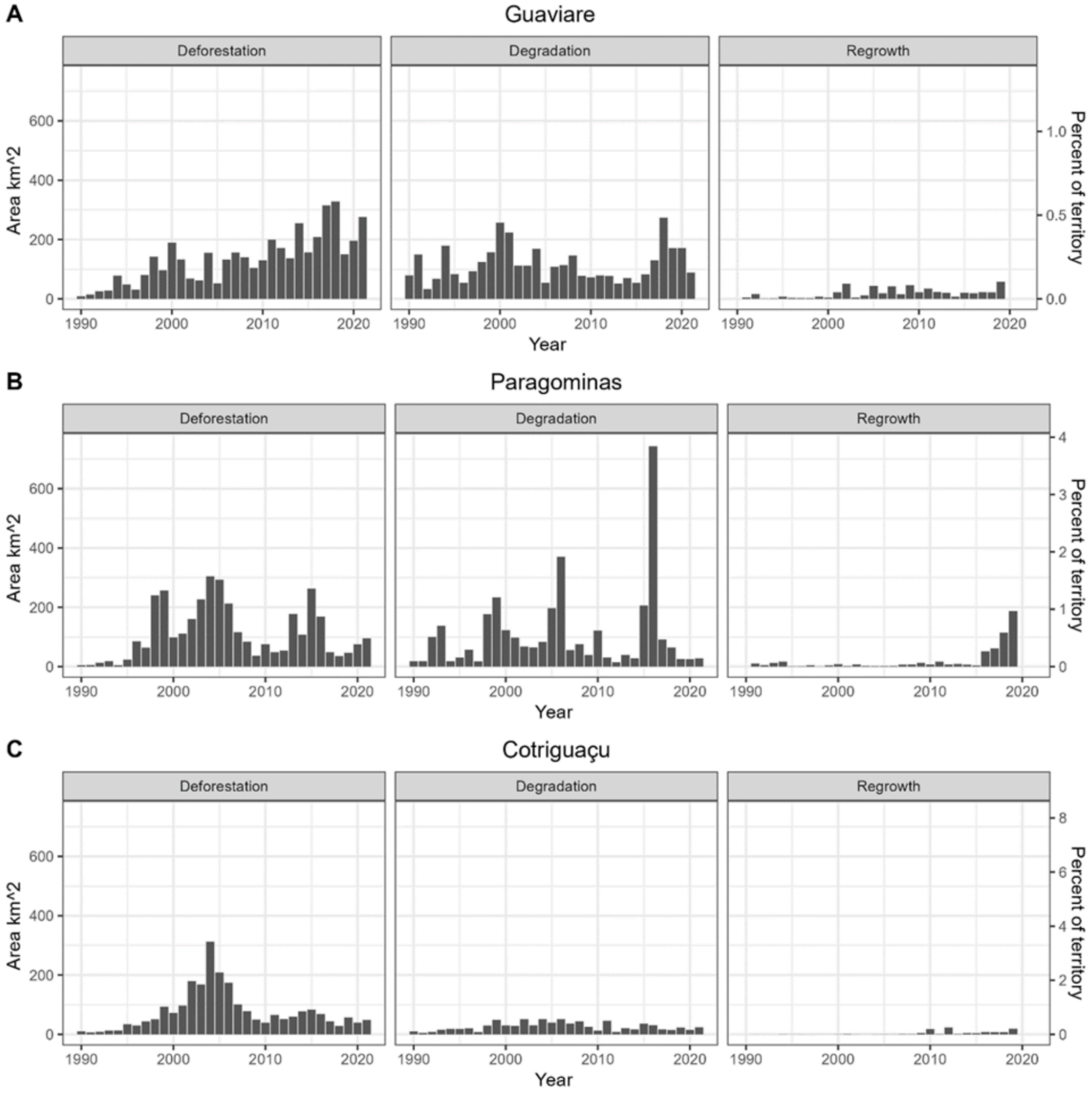

Fig. A1. Trends in annual deforestation, forest degradation and forest regrowth from 1990 to 2021, according to JRC-TMF data, at the three study sites (Guaviare, Paragominas and Cotriguaçu).

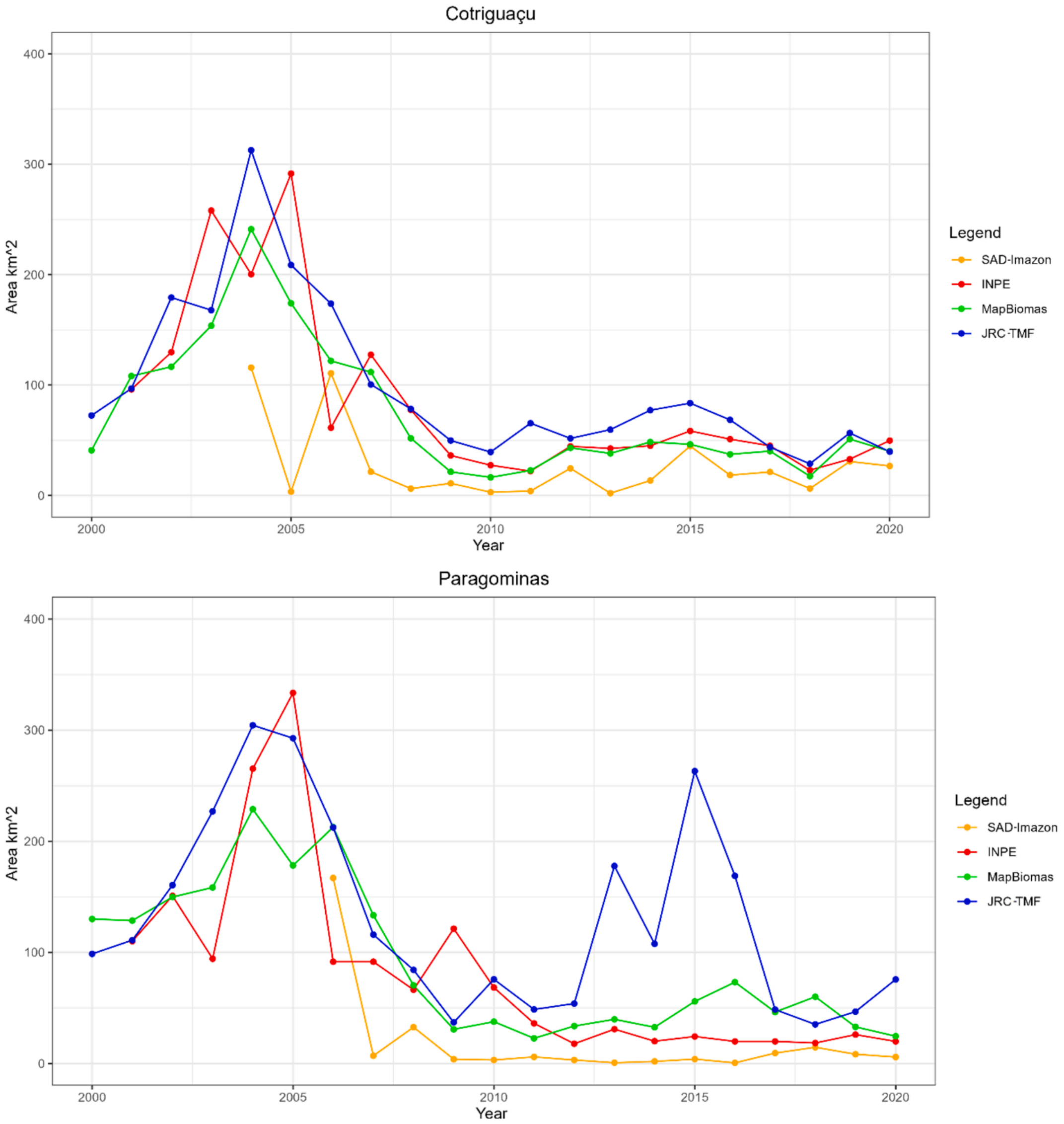

Fig. A2. Yearly deforested area in the municipalities of Cotriguaçu and Paragominas (Brazil) according to four data sources (SAD-Imazon, INPE, MapBiomas and JRC-TMF).

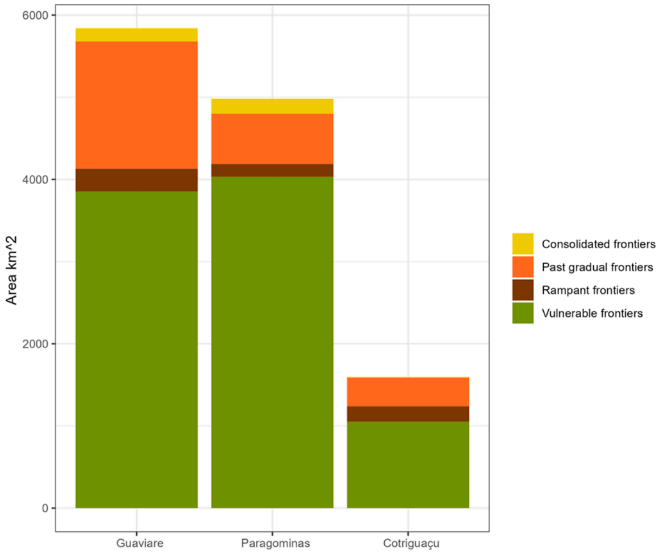

Fig. A3. Distribution of the remaining primary forests across archetypes in Paragominas, Cotriguaçu and Guaviare (2021).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113198.

Data availability

I have shared my code in Supplementary Material Files 1 and 2

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